DESIGN OF DENSE GRADED COLD BITUMINOUS EMULSION MIXTURES AND EVALUATION OF THEIR ENGINEERING PROPERTIES

by

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To my beloved and ever memorable

Father

Στόν πολυαγαπημένο καί ἀείμνηστο

Πατέρα μου

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ABSTRACT

A stable slow setting cationic emulsion has been developed, suitable to coat dense graded mixtures high in fine aggregate content, in particular gap graded rolled asphalt type and dense graded macadam mixtures. The slow setting emulsion, NH-10, is the outcome of an investigation into five different formulations using two surfactants, two adhesive agents and a water shading compound.

The rheological studies of the NH-10 emulsion have shown that it possesses a thixotropic behaviour. The thixotropic behaviour has been justified by the "complex flow" coefficient, a technique proposed by Traxler for bitumens. The viscosity of the emulsion is greatly influenced by the amount of binder and level of temperature. The hardness of binder does not change appreciably the viscosity value of the emulsion.

The highly stable mildly cationic emulsion has been used to prepare two types of dense bituminous mixtures containing limestone aggregate, river sand and limestone filler, blended in appropriate proportions.

The study presents information regarding the properties of two dense graded bituminous mixtures i.e. a gap graded "Cold Rolled Asphalt" (C.R.A.) and a continuously graded "Dense Emulsion Macadam" (D.E.Mc). A design procedure based on a modified Marshall method and the evaluation of permeability and creep stiffness is proposed as a laboratory method for the design of the bituminous mixtures developed. The evaluation of permeability and creep stiffness is carried out with equipment designed and developed specially for this investigation.

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CHAPTER ONE - INTRODUCTION

During the last decade, the Road Construction Industry has paid increasing attention to the development and use of bituminous emulsions for the construction of road pavements, in particular, for the production of cold bituminous mixtures.

The advantages of using cold Bituminous Emulsion Mixtures (D.E.Ms) are related to:

a) they can be prepared using relatively inexpensive plant,
b) they can be transported longer distances and,
c) they can be stored for use at convenient times, specially for maintenance work.

In addition to the operational flexibility given by the advantages listed above, savings may be made on the actual production cost by reducing part of the expenditure corresponding to fuel for heating the aggregate and binder. This saving may reach 20 to 25% of the overall production cost (214).

Despite all the advantages, the use of B.E.Ms is limited in this country to surface dressing. Other countries like America, France, Belgium and Brazil are now using them as road base material for lightly trafficked roads. The common feature of all the existant B.E.Ms is that they are open graded mixtures with relatively low percentage of fine aggregate and filler. This implies that coarse aggregate is selectively used which may cause serious problems in the future as regards the conservation of the natural aggregate resources.

The suitability of cold B.E.Ms is still doubted by a number of engineers. This is because the mixtures do not develop their full strength soon after construction like the conventional hot mixtures. Full strength is developed with time which may be extended to two or three years. Their suitability is in doubt also due to a small number of repeated failures which occured apparently due to lack of knowledge, regarding the preparation and properties of bitumen emulsion mixtures and not due to inherent defects in these mixtures.

During the last few years design methods have been developed by various agencies, mainly in America and France. However, all the methods exclusively refer to open graded mixtures. Bituminous emulsion mixtures have not been used for preparation of dense mixtures with high percentage of fine aggregates, such as, gap graded mixtures used extensively in the UK for construction of road surfacings and road bases.

The incorporation of high percentage of fine aggregate and filler requires a very stable and slow setting emulsion, in order to provide sufficient mixing time for good coating of all the aggregates. Emulsions of the level of stability required for this purpose are not available commercially. The development, therefore, of a suitable emulsion, on a commercial basis, which can be stable enough to be mixed with aggregates containing relatively large proportion of fines would be an advantage because it will extend the use of emulsions in the preparation of dense graded bituminous mixtures.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The review of literature falls into five main parts. These are: fundamental properties of bituminous emulsions, rheological properties of bitumous emulsions, emulsified bituminous mixtures, current mix design methods for base course layers, and permanent deformation of emulsified bituminous mixtures.

2.2 Fundamental properties of bituminous emulsions

2.2.1 Historical background

In broad terms an emulsion is a two-phase system consisting of two immiscible liquids, one which is dispersed in the other. In the case of a bituminous emulsion the two-phase system involves bitumen and water. The dispersed phase (also called the internal phase) is broken into finite globules which are dispersed into the surrounding liquid (known as the continuous or external phase). Emulsions used in road construction have water as the external phase and bitumen as the internal phase. The globules of binder stay in suspension with the help of a surfactant called the emulsifier. Depending on which emulsifier is used the emulsions are classified as Anionic, Cationic or Non-Anionic.

Anionic type emulsions were developed in 1869, but it was not until 1910 that they were first used (in America) in road construction (1). During the early stages of development, emulsions were mainly used as dust palliative, as soil stabilising agents (2, 3) and as slurry sealing material for the lightly trafficked residential roads. Despite the advantages of these emulsions over conventional binders, i.e. cold application, low thermal susceptibility, safer usage in terms of fire hazards and less environmental pollution - anionic emulsions suffered from three main drawbacks. They could not be used with all types of aggregates, they were highly susceptible to rain water and the breaking time was too long.

During the early 1950s, cationic type emulsions were introduced in France and promised to solve the problems associated with the anionic type. They indeed provided better adhesion with all the aggregates, they were less susceptible to rain due to shorter breaking time, furthermore, higher percentages of binder could be dispersed in water without altering the viscosity of the emulsion appreciably. As a consequence, their application was extended to the production of coated stones and chippings for resurfacing and also to base-course mixtures (4, 5). It has also been reported that cationic emulsions have been used in skid resistant surface dressings on main roads and motorways (6).

Following the development of cationic emulsions, the production of emulsions used in road construction steadily increased. The use of bituminous emulsions became more attractive after the energy crisis in 1973. Various countries started to recommend the use of bituminous emulsions instead of cutback bitumens, the use of which became very uneconomical and wasteful in energy terms (9, 10). Today the use of cutback bitumens has almost been phased out and a high percentage of the collapsed cutback market has been taken over by cationic emulsions.

2.2.2. Types and formulations of emulsifiers

The role of the emulsifier is very important not only because it promotes emulsification and keeps the emulsion stable but also because the physical and chemical properties of the emulsion are mainly dependent on the chemical type and molecular weight of this component.

All emulsifiers consist of two molecular groups: the hydrophobic, non polar part, which is dissolved in the bitumen, and the hydrophillic group, the polar part which is dissolved in water. Depending on the polarity of the hydrophillic group, emulsifiers can be classified accordingly.

The older type of emulsifying agent, the anionic, is generally a soap consisting of a sodium or potassium salt of carboxylic acid namely fatty acids and rosin acids. The newer, cationic type of emulsifiers are amine (mono or polyamine) or quaternary ammonium bases, neutralised with a strong organic or mineral monoacid (the most frequently used being hydrochloric acid) (1, 11).

The emulsifiers can be added separately as a base and acid, or together as salts to either binder or water (12). Nevertheless it is now common practice to add the emulsifier agent (salt) to the water phase. When the emulsifier comes into contact with the bitumen-water system, orientation of its molecules takes place. The hydrophobic part of the molecular chain (non polar) is dissolved into the globules of bitumen leaving the hydrophillic part (polar) exposed to the water phase (13). The similarly charged bituminous globules stay in suspension until they come into contact with the surface of mineral aggregate.

It is interesting to note at this stage that the cation, being inorganic in the case of anionic emulsion, imparts no hydrophobic properties while in the case of cationic emulsion the organic cation possesses hydrophobic properties. This is the main factor that gives cationic emulsions the great superiority over the anionic in terms of adhesion, with almost all aggregates.

2.2.3. Chemical stability and breaking mechanism

Stability can be considered in terms of: chemical, storage, mixing, mechanical and freezing stability. In the following discussion the chemical and the mixing stability in particular will be examined.

The importance of chemical stability of an emulsion has been recognised ever since the development of the emulsions so as to enable them to be stored, transported and applied without coagulation of the particles of the binder. Stability is provided by the emulsifier and a minimum amount is required for the formation of micelles, known as Critical Micelle Concentration (CMC) (13).

When the emulsion comes into contact with the aggregate surface the droplets of the bitumen coalesce and produce a continuous film of bitumen. This coalescence is known as 'the breaking' and the rate at which this occurs is referred to as the 'rate of breaking'.

The breaking mechanism of an anionic emulsion is relatively simple. Various investigators (13, 14, 15, 16, 17) have stated that the excess amount of inorganic cation is adsorbed on to the surface of the aggregate so that breaking, due to the attractive forces between the bitumen droplets and the aggregate surface occurs, exclusively due to evaporation of water.

The breaking mechanism of a cationic emulsion is more complicated. Early explanations (14) were similar to the anionic type, with the only difference being that the breaking was not exclusively due to evaporation. This of course could not satisfactorily explain the fact that cationic emulsions could coat successfully almost any aggregate including limestones. Martens and Wright (13) explained the above by accepting the fact that most limestones contain elements with negative surface charge and thus the overall surface charge of the limestones is a mixture of electropositive and electronegative charges.

Vogt (17) and Borgfeldt and Ferm (15), suggested that breaking was caused by two phenomena: the attractive forces between the bitumen droplets and the aggregate surface, and the transfer of the emulsifier from the emulsion to the aggregate surface. This adsorption of the emulsifier on the aggregate surface may destroy the stability of the emulsion.

Gaestel (18) proved and clarified the above theory. He found that ion exchange between surfactant molecules and aggregate surface occurs only at a concentration of emulsifier below the critical micelle concentration (CMC). Above CMC, although some ion exchange takes place, physical adsorption of the emulsifier governs the breaking of a cationic bitumen emulsion. He also concluded that between the anions and cations in solution only the cations are adsorbed on the aggregate surface. These findings explained satisfactorily the breaking of a cationic emulsion.

Further experimental work by Lane (19, 20) was in agreement with Gaestel's work, and went on to show that it is the emulsifier that is adsorbed first, followed by the emulsion droplets, due to their differences in electrophoretic mobility. Lane further stated that although at low concentrations of binder (approximately 5%) the diffusion of surfactant ions and droplets of the emulsion governs the breaking mechanism, at higher and more realistic binder contents (50-60%) physical contact of the droplets may govern the breaking process and dehydration of the emulsion will bring the droplets even closer.

Finally, Scott (21) summarised the breaking mechanism and concluded that the breaking of a cationic emulsion takes place in three phases. During the first phase adsorption of emulsifier and emulsion droplets take place, during the second phase flocculation and coagulation (always in this order) takes place and finally, during the third phase dehydration takes place overriding any other factor affecting breaking, and causing further coagulation and final breaking.

2.2.4. Factors affecting the mixing stability and rate of breaking

As was mentioned earlier, the stability of an emulsion depends principally on the concentration of the emulsifier, and a minimum amount is required to reach stable emulsion. This minimum amount varies from one type of emulsifier to another. Lane (19) found that the longer the chain length of the surfactant the lower will be the concentration (CMC) at which a stable situation is reached. He also stated that maximum stability occurs at the maximum zeta potential of the emulsion. Zeta potential is related to the electrophoretic mobility of the particles in the solution. The type and concentration of emulsifier affect the level of zeta potential while the presence of an electrolyte (sodium or calcium chloride) affects the level of concentration at which zeta potential reaches its maximum (19, 20). In other words maximum zeta potential can be reached at lower concentrations of emulsifier if an electrolyte is present. Zeta potential is obviously related to the pH of the solution, and some emulsifiers are more pH dependent than others and, therefore, for better performance, emulsifiers that are less pH sensitive should be preferred. Nevertheless, it was found (21) that a combination of changes in the emulsifier concentration and in the pH of the emulsion has a greater effect on the stability of the emulsion than a change in pH alone.

When an emulsion comes into contact with the aggregate's surface breaking occurs the rate of which depends on the following factors:

i) Type and amount of emulsifier
ii) Nature and specific area of the aggregate
iii) Nature of fine aggregate
iv) Water added to the aggregate
v) Environmental temperature (evaporation rate)
vi) Percentage of binder and size of droplets

The type and amount of the emulsifier affect , as stated above, the zeta potential of the emulsion. The higher the zeta potential the more stable the emulsion but the quicker the breaking of the emulsion. Depending on the level of zeta potential an emulsion can be classified as "quick", "medium", or "slow" breaking (or setting) (22).

The surfaces of different types of aggregates possess different ion exchange capacities and aggregates with a high ion exchange capacity will cause the emulsion to break faster. This can be seen more clearly when the aggregate is wet with water prior to mixing (21). The water neutralises some of the surface ions and hence reduces the ion exchange capacity of the aggregate. Of course the addition of water plays another, two-fold role. Its presence guarantees firstly that the original water content in the emulsion remains constant at the early stage of mixing, and secondly that the excess amount of water retards the effect of evaporation on the breaking of the emulsion and therefore longer mixing time is achieved which may result in better coating of the aggregate. Scott (21) found that the effect of additional water on the breaking rate was more profound on limestone and gravel than basalt and quartzite when cationic emulsion was used.

Environmental temperatures affect the rate of evaporation which in turn causes flocculation and coagulation and final breaking. Work by Pinilla and Agnusdei (23) showed that the rate of breaking, when quick breaking emulsions are used, increases proportionally to the temperature increases between 5°C to 50°C; the range for the slow breaking emulsions was 5° C to 30° C. Temperature increases outside this range have no significant effect. In the same work it was concluded that at the lower end of the above ranges siliceous aggregates show longer breaking time than calcareous but at the top part of the range both aggregates, regardless of the type of emulsion, break fast.

Finally, an increase in binder content will increase the rate of breaking. As Lane suggested (19) this is due to denser packing, while the coarseness of the droplets will cause further increase in breaking rate due to excess flocculation.

2.2.5. Other use of emulsifiers

Emulsifiers, particularly cationic ones, due to their inherited adhesive properties, may also act as an agent which can be added to either the binder or aggregate in order to prevent excessive weather damage in surface dressings. Extensive work carried out by Mathews (24) showed encouraging results and demonstrated the importance of the way of application and the concentration of the emulsifier depending on the type of aggregate. An interesting work carried out by Plancher et al (25) investigated the components of bitumen that are strongly adsorbed on the aggregate surface. It was found that although carboxylic acids were most selectively adsorbed by all aggregates, ketones and nitrogen compounds were the ones that were selectively retained by all aggregates during a moisture damage test. The above finding will certainly lead to a development of more suitable emulsifiers to be used,for this purpose.

2.3. Rheological properties of bituminous emulsions

2.3.1. Evaluation of the consistency of bituminous emulsions

Unlike the ordinary bituminous binders the consistency of a bituminous emulsion is not only dependent on the type and origin of the bitumen, but also on the bitumen content, the particle size distribution of the dispersed bitumen globules and the nature and concentration of the emulsifier. Therefore, because of the complexity of the material, simple tests like Penetration and Ring and Ball would not necessarily be very informative, for their consistency and hence more fundamental tests have to be employed.

Viscosity measurements on ordinary binders at elevated temperatures give valuable information for controlling the thickness of the binder around the aggregate. Similarly, viscosity tests on bituminous emulsions may provide this information. Viscosity measurements may also give information about the handling and storage of a particular emulsion and furthermore viscosity measurements may be used as another technique for ranking the emulsions.

An emulsion which is going to be sprayed over a road surface must have a minimum and maximum limit of viscosity at a certain temperature.

The minimum limit is to permit spraying and the maximum is to prevent the emulsion flowing to the sides of the road (6).

Furthermore, an emulsion which exhibits non-Newtonian flow may require considerable agitation before use and it may be susceptible to a high degree of ageing.

2.3.2. Factors affecting the viscosity of an emulsion

Factors affecting the viscosity of an emulsion may be classified as chemical and physical. The chemical factors are: the type and nature of binders, the type and concentration of emulsifier and the presence of electrolyte. The physical factors are, the binder content, the particle size and distribution of the binder, and the environmental temperature.

Early work carried out by Broughton and Squires (26) confirmed the significance of the different types of emulsifiers and stated that emulsifiers producing the best emulsification give emulsions of the lowest relative viscosity.

Lyttleton and Traxler (27) using two types of binder (Venezuela steam refined and Texas air-blown), and various types of anionic emulsifiers found that emulsions produced by using a protein type emulsifier possess non-Newtonian flow, while the presence of an alkaline inorganic salt produced a Newtonian emulsion.

It is obvious that the higher the binder content the higher the viscosity, and, for the same binder content, the particle size distribution has a predominant effect on the viscosity. Traxler (28, 29) examined the effect of the particle size of the droplets, and found that emulsions having uniform size droplets of one micron in diameter possess higher viscosity than those with a uniform size of three microns. When the uniformity of the particle size was destroyed, the emulsion had lower viscosity. This was due to the degree of packing of the particles; the smaller the size and the particle size distribution the denser the packing and the higher the viscosity.

The effect of temperature on the viscosity of an emulsion was investigated by Jimenez (30). He found that viscosity decreases as the temperature increases, but he failed to justify why some of the emulsion with a higher binder content than others, had lower viscosity than the ones with lower binder content at the same temperature. Gaestel (6), also examining the effect of temperature, concluded that the effect of temperature is more pronounced on cationic emulsions which have high percentage of binder.

It is interesting to note that the very limited work done on the viscosity of emulsions is mainly based on anionic emulsions, therefore there is a need for further research, particularly in relation to the Rheological behaviour of cationic emulsions.

2.3.3. The effect of emulsification on the binder

The emulsification process and the type of emulsifiers have a marked effect on the consistency of a binder. This is because the introduction of the emulsifier to the molecules of binder causes chemical changes in the molecular structure and also because, to a lesser degree, high temperatures during emulsification (up to 160°C) may cause evaporation of the volatile oils.

Early studies (30) showed that temperature causes hardening of the binder when hardening is expressed in terms of changes of absolute viscosity measured on a recovered binder. Hardin et al (31) confirmed the above and added that the rate of hardening is a function of emulsion grades (ie Rapid, Medium or Slow). It could not be said which emulsion grade causes a slow rate of hardening, but it was shown that specially formulated emulsions, called High Float, had a very slow rate of hardening and as a consequence the overall hardening was negligible.

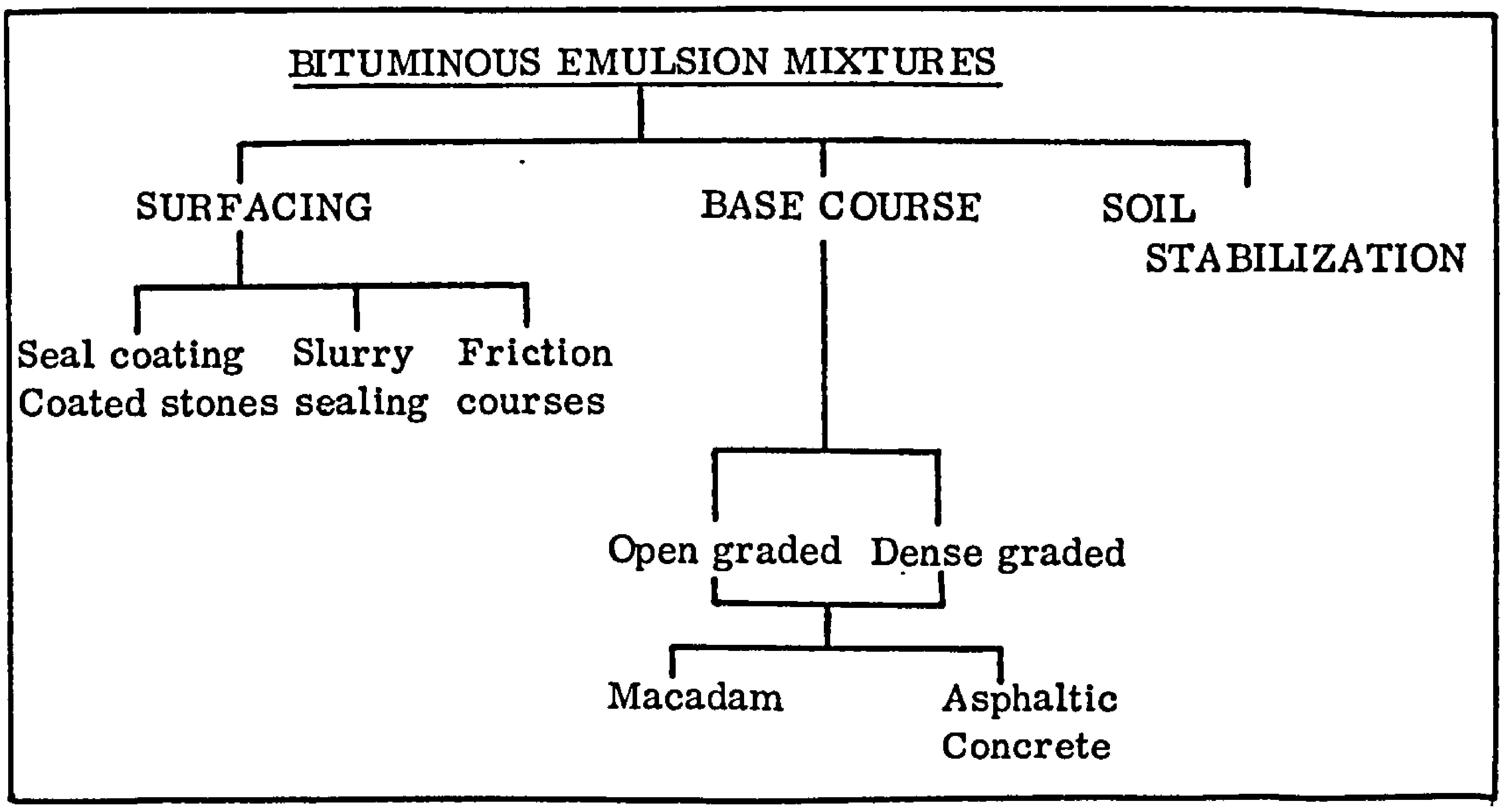
From the above it could be suggested that the type of emulsifier greatly influences the rate of hardening. Hardening of the binder, after final breaking of the emulsion, also occurs due to polymerization, oxidation, volatilization, photo-oxidation, thixotropy, syneresis and separation (32).

2.4 Bituminous Emulsion Mixtures (B.E.Ms)

2.4.1. Use of Bituminous Emulsion Mixtures

B.E.Ms started to be used in road construction as early as 1910 but their use was limited to surface treatments which included dust prevention and seal coating (1, 33). Later on, emulsions were used in soil stabilization (2) and slurry sealing (35). After the development of cationic emulsion, the use of emulsion was extended to the base course mixtures and skid-resistant surface dressings (6, 36, 37). Table 2.1 summarises the use of B.E.Ms in road construction.

TABLE 2.1 USE OF BITUMINOUS EMULSION MIXTURES IN ROAD CONSTRUCTION



For the purpose of this project emphasis will be given to the use of BEMs as base course material, while some consideration will be given to its use as surfacing material. Soil stabilization falls outside the area of this research and therefore no particular reference to this will be given. Nevertheless, soil stabilization has been covered, in more detail elsewhere (2, 3, 39, 40, 41).

2.4.2. Bituminous Emulsion Mixtures used in road surfacing

Seal coat surface treatment was the earliest form of application of emulsions in road construction and is still in use today. It is a three stage operation involving spraying of the emulsion, application of the aggregate, and compaction of the aggregate. During the early projects it was preferable to apply the aggregate in two layers sandwiched between layers of emulsion (33). Later on with the development of quick breaking cationic emulsions, a single layer of aggregate was found to be adequate. This was because this type of emulsion allowed the use of harder binders, the incorporation of higher binder content and the quick development of the properties of the binder.

The factors effecting the performance of seal coating are as follows: the viscosity of the emulsion, the type of emulsion, the size and type of aggregate and the type of binder.

Viscosity affects the uniformity of spraying, and together with the type of emulsion further effects the coating and compaction of the aggregate. Kari (43), after extensive field and laboratory work, established limiting values of viscosity to achieve adequate coating and compaction and to prevent 'runoff'. The rate of spraying the emulsion and the aggregate has also been established and is given elsewhere (45, 46, 49). Cohesion between the aggregates found to be affected by the type of binder and cleanliness of the aggregate (43, 50, 51), the harder the binder and the cleaner the aggregate (free of dust) the better the adhesion and the lesser the degree of stripping.

The spraying of emulsion can be carried out at ambient temperatures but it is a common practice now to carry this out at higher temperatures of 80-90^{o}C (7, 50, 51). This is due to incorporation of higher binder contents, which causes blockage of the jets of spraying machines.

Although seal coating traditionally uses single size aggregate, attempts have been made to use open graded aggregate gradation (44), by employing a specially formulated emulsion known as high float, and the results have been very successful.

Another form of surface treatment very similar to that of seal coating, is the use of coated stones. As in seal coating the aggregate is of single size and free of dust, the only difference being that they are precoated prior to spreading and rolling over the treated surface.

An alternative to coated stones is the open-graded mixtures sometimes referred to as friction courses. These are well graded, coarse, (greater than 2.36mm BS sieve), and precoated aggregate mixes with a very low percentage of fine aggregate and filler (to a maximum 10 percent). These types of mixtures have been used for quite a long time and the results are mostly satisfactory (4, 6, 7, 52). Excellent results have been reported from France (6) where not only rutting of the pavement was not observed, but skid resistance two years after construction was as good as or even higher, in some sections, than as at construction. It must be noted that the project carried out in France used the old technique of two layers of aggregate sandwiched between a thin layer of emulsion.

The slurry seal coats, unlike other surfacing mixtures, employ only fine aggregate (passing 2.36mm sieve). This is used as pavement seal in a temporary wearing course, as a crack filler or as a pre-treatment prior to overlay. The service life has been reported to last from two to three years (15, 35).

The other distinct feature of the slurry seal is that it contains a high percentage of water and uses exclusively slow setting emulsions. Hence, the breaking time solely depends on the evaporation of water.

The mechanism and the stability of a slurry seal is similar to any other emulsified mixture and has been covered in section 2.2.4. of this chapter. In addition, work carried out by Kari and Coyne (35) has shown that the wear of slurry seals, measured with the Wet Track Abrasion test, is increased as the binder content decreases and also as the percentage of clay is above permissible. It was also shown that cationic slurries possess less wear than anionic type and that the effect of binder penetration was not appreciable. The over all performance of slurry seals is affected significantly by the gradation of fine aggregate, and an excessive amount of coarse aggregate causes streaking of the slurry, an excessive amount of filler results in a brittle mixture, while mixtures with a low percentage of filler possess application difficulties and tend to segregate during laydown (35).

Further work was carried out by Cliffton (53) and Cliffton et al (54) on the effect of aggregate type on wear of slurry seals. Working with a particular cationic emulsifier, called Redicote E-11, Cliffton (53) and Cliffton et al (54), concluded that slurries with 'basic' aggregate wear more than slurries with 'acid' aggregate. On the other hand, using this particular emulsifier, the stability of the emulsion increases with the presence of Portland cement or Hydrated lime. This could not be explained properly at that time, but taking into account Lane's work (19) it is now known that this is due to the fact that this type of filler acts as an electrolyte, increases the zeta potential of the emulsion and hence the stability.

2.4.3. Bituminous Emulsion mixtures as base course material

The successful application of bituminous emulsions in road surfacing and the development of more stable emulsions lead to the investigation of their properties when mixed with well graded aggregates to produce base course material. The first comprehensive study of the performance of pavement using BEMs as a base course material was carried out in America by San Diego county (56). The project consisted of 35 test sections of emulsion treated bases, five bitumen treated and two untreated granular bases (for comparison). The emulsion was a slow setting cationic type and the aggregate marginal-quality sandy gravel well graded to produce a dense mixture. The results after seven years were very encouraging and in some cases were better than the bitumen treated mixtures. Similar results were reported from other surveys, carried out independently, in America (37) and South Africa (57).

In all the above projects however, little thought was given to the actual design of the mixtures. They simply followed soil stabilization procedures and the main interest, apart from monitoring the pavement's performance, was to develop structural design formulae to obtain equivalent depth of pavements, it was not until a few years later that investigators started to examine the factors affecting the behaviour of BEMs for base course mixtures (58-68).

Depending on the aggregate gradation BEMs, as conventional bituminous mixtures, can be classified into two categories: the Open graded and the Dense graded, with the Dense graded being subdivided into two further categories, the Continuous dense graded and the Gap dense graded. Typical gradation specifications can be found elsewhere (45, 49, 69, 70).

2.4.4. Factors affecting the behaviour of open and dense graded mixtures for base course

The factors affecting the behaviour of these mixtures are:

i) Type of emulsifier
ii) Binder
iii) Type of filler
iv) Water content and curing
v) Degree of compaction
vi) Permeability of the final compacted mixture

i) Type of emulsifier

The type of emulsifier affects the rate of breaking and the cohesion between the aggregate. In Open and Dense graded mixtures, only the slow setting and medium setting emulsions can be used. These are designated as K3 and K2 by the BS434 for slow and medium cationics, and A3 and A4 for the slow and medium setting anionics respectively. The American equivalent is CSS, CMS, SS and MS respectively (45, 47, 48). Dense graded mixtures use exclusively slow setting emulsions while for Open graded mixtures both types are suitable.

ii) Binder

The penetration value of the binder and its content in the emulsion has a direct effect on workability (59), Marshall stability, stiffness, fatigue and permanent deformation of the mixture (58 - 67). The binder used for all graded mixtures varies between 70 and 300 in terms of penetration grade, and its minimum recommended content in the emulsion is 55 percent (45, 47 & 48). High penetration binders and high binder contents, normally tend to be used for Open graded mixtures, while low penetration binders and low binder contents are used with dense mixtures (59). The use of a high percentage of hard binder increases the viscosity of the emulsion and as a consequence reduces the workability of the mixture. The workability of the mixture has been reported to be improved by the incorporation of oil distillates (56) but emulsions containing oil distillates require considerably longer time to develop their ultimate strength, and stripping may occur. Harder binders produce mixtures with higher Marshall stability (58, 59) and higher Resilient modules (63, 68).

Unlike conventional hot mixtures, an increase in binder content shows a decrease in stability when the specimens are tested dry and at room temperatures. It is only when the specimens are tested 'soaked' that the effect of an increase in binder content can be seen (60, 61, 62). An increase in binder content causes a decrease in resilient modules (71) and indirect tensile strength (60, 61, 67).

iii) Effect of filler

Most of the studies on the effect of filler have been carried out with respect to hot mixtures, but equally they can be applied to BEMs, since after final breaking BEMs behave in exactly the same way as hot mixtures.

The role of fillers in bituminous mixture has been studied by Puzinaskas (73) and Puzinaskas and Kallas (74). They stated that the filler had a dual role to play. One portion participates in the particle to particle contact, and the remainder floats in the bitumen forming a high consistency binder. Anderson and Goetz (75) extended the above and stated that two types of stiffening result from the portion of filler that is in suspension in the bitumen, one is due to volume filling by the filler (relatively small), and the other is due to physicochemical interaction between the binder and the surface of the mineral filler (large effect). Such is the effect of mineral filler on the stiffening of the binder that Tunnicliff (80) suggested that the filler should be included in the design calculations as part of the binder, instead of being part of the aggregate.

Early studies by Bollen (76) indicated that different type and size of fillers affect the stiffness of the mixture and Mitchell and Lee (77) related the expected stiffening to bulk volume in toluene measurement. A few years later Rigden (82) concluded that although the bulk density of filler in toluene (or benzene) is a good evaluation of the fineness of the filler it does not provide a satisfactory measure for the evaulation of the flow properties of filler-binder mixture. He demonstrated that the influence of filler in the flow properties was best assessed by measuring the fractional voids of dry compacted filler. Later on Huschek and Angt (85) proved that Rigden's approach was correct only at higher temperatures and concluded that at low temperatures (environmental) the hardness of the binder has a greater influence on the behaviour of the mixture. They also pointed out the importance of shape and grading of the filler at low temperatures.

Extensive laboratory work by Kallas and Puzinauskas (83) has shown that the filler gives the binder non-Newtonian flow properties. In the same report it was concluded that Marshall stability was greatly affected by the type and shape of filler. This was more profound in the poorly graded asphalt sheet mixture than in well graded asphalt concrete. Similar results relating to the effect of the type and shape of filler have been produced by other investigators (84, 86, 88). Craus et al (87), in a recent study, examined the physico-chemical aspects of the fillers and found that due to high geometric irregularity and surface activity, hydrated lime and limestone have a greater effect on binder stiffening than sandstone. Dukatz and Anderson (89) found that all fillers, particularly limestone, have a greater effect on the Creep compliance of the bitumen rather than the Resilient modulus.

BEMs contain a certain percentage of water at the early stages, and it is logical to expect a further effect of surface active fillers on the actual strength of the mixture. Terrel and Wang (90) investigated this and found that a small percentage of Portland Cement (1%), increases the resilient modulus of the bitumen-aggregate mixture at the early stage of curing. The effect of Portland Cement (P.C.) was almost negligible at the later stage of curing (one year). Furthermore, it was stated that the addition of P.C. was not as effective with slow setting emulsions as with quick setting ones. However, it was observed that the addition of P.C. had an adverse effect on the workability of the mixture and the degree of coating of the aggregates. From similar studies, Schmidt et al

(68) found that the addition of P.C. is more beneficial to anionic type emulsion mixtures than to canionic ones, or ones with soft binders as opposed to hard binders. In the same study it was shown that although the strength of the mixture (measured in Resilient modulus) and its water resistance improves, its flexular fatigue deteriorates. Similar studies were carried out by Head (58), Gadallah (61), Gadallah et al (62). Gadallah (61) and Gadallah et al (62) also showed that the effect of P.C. on BEMs further depends on the gradation of aggregate and binder content, while open graded and lean mixtures are benefited more.

Finally, the use of filler, and in particular Portland Cement, can affect the rate of breaking of the emulsion depending on which type of emulsifier is used.

Summarising the effect of filler on the BEMs, it must be stated that its effect is not as straightforward as with the conventional hot mixtures. Careful selection of filler, emulsifier, binder and aggregate is needed in order to obtain beneficial effects.

iv) The effect of water content and curing

Water added to the aggregates prior to mixing prolongs breaking time and allows better coating to be obtained. Unfortunately, this is the only advantage to be gained from water in the mixture, because after this stage the water in the mixture slows down the development of the strength of the mixture, and therefore can cause premature failure.

The determination of the optimum water content added to the aggregate was originally obtained by the coating test. This test is very subjective however, and does not provide a precise answer; hence there is always the danger of producing a very wet mixture, thus causing unnecessary delay in the development of strength. Obviously, a certain moisture content is required for compaction, unfortunately this amount of moisture is always lower than the moisture required for good coating

(63, 92). It has been reported (92) that for Dense grade mixtures the total fluid content for mixing (water and emulsion) was between 12 to 15 percent and 9 to 12 percent for compaction. It is therefore necessary that the mixture should be left to cure for a certain time, in order to allow some water to evaporate.

Obviously, after compaction, further curing causes development of strength of the mixture, the rate of which depends primarily on the permeability of the mixture, water table of the subgrade, and weather conditions (temperature, wind velocity and humidity). It is apparent that any prediction on the rate of development of the strength of the mixture is extremely difficult to make and can be misleading. Kari (63) has reported that in a certain project the strength of the mixture increased in three days by three times, but Williamson (92) found that in moist-full conditions and at temperatures of $5^{o}C$ development of strength was almost non existent.

This tremendous complexity in the development of strength on site makes it impossible to study the factors affecting the behaviour of the mixture after compaction, unless conditions are simplified and simulated in the laboratory. Nevertheless, the two full scale projects carried out (37, 57) have given invaluable information on how to handle the material.

In 1976, Darter et al (60) and Gadallah (61) published the first comprehensive laboratory reports on the factors affecting the behaviour of dense graded emulsified mixtures. Darter concluded that the optimum moisture content to be added can be sufficiently determined by observing the coating of the aggregate coating test. The moisture content at compaction has a significant effect on the structural response as well as the moisture content at testing. In terms of curing, he concluded that the rate of moisture loss and hence gain in strength is proportional to curing time and total voids in the mixture. A good agreement was also found between the Marshall stability and the Resilient modulus, which is significant because if a relationship is established, the Resilient modulus can be estimated from Marshall test and can be used for further structural design calculations. Finally, he recommended the use of the soaking test for determining the resistance of the mixture to water attack.

Gadallah (61) investigated the effect of the severity of soaking tests on the compacted specimens, and he recommended the soaking test proposed by the Asphalt Institute (94) for compacted bituminous mixtures. This test involves vacuum saturation for one hour and bath immersion for a further 24h at 22°C. Incidentally, Darter (60) also used the Illinois method described in (49) which involves capillary soaking of the specimens for 48h at room temperature and he concluded in a later report (66) that this test was much more realistic in terms of field representation, and also much simpler to use. Gadallah (61) also showed that the significance of binder content was not apparent at the early stage of curing (three days air curing).

Hicks et al (64) examined the effect of various laboratory conditions on the stress-strain behaviour of Open mixtures, using the indirect tensile test and repeated loading triaxial test. It was found that samples cured at 24°C and 38°C exhibited a more rapid gain in resilient modulus than those cured at 5°C, regardless of stress conditions. In fact, the gain in stiffness for the samples cured at 5°C was less than 50 percent of the ultimate modulus, after 90 days of air curing under normal humidity. This is in agreement with previous findings from a full scale project (92). Further studies carried out by Mamlouk and Wood (96), using an indirect tensile test concluded that indirect tensile strength is affected by test temperature, aggregate type, curing and initial added moisture content.

An interesting work was carried out by Darter et al (66) in which for the first time experimental curing conditions and results were compared with field experience. It was found that specimens tested after three days air curing and 48 hours soaking gave results equivalent to 3-4 months specimens cored from site.

v) Effect of compaction

Field results have shown that not only the compacting effort (60) but also the type of compacting machine used influences the properties of the mixture. The highest field densities were obtained by the Tandem vibratory roller and the lowest by using the multiple shoe vibratory compactor. In the same report it was recommended that a California kneading compactor should be used to simulate field compaction in the laboratory. In another report (59) however, objections were raised to this type of laboratory compaction because it was thought to cause crushing of the aggregate and stripping of the mixture.

Laboratory studies have shown (60) that as the compacted effort increases from 50 to 75 blows (Marshall compaction) so does the density, stability, resilient modulus and the indirect tensile strength. Mamlouk et al (67) compared the Marshall compactor with the Gyratory Testing Machine and found that at equivalent levels (50 blows and 20 revolution, at 1.38MPa pressure with one degree of angle of gyration) both machines produce the same results.

vi) Effect of permeability

BEMs used as base course material need to be sufficiently permeable so as to allow further evaporation of water to occur after construction and hence to reach their maximum stability in the least possible time. Permeable layers on the other hand allow the movement of water from either the top (in case of an open surfacing layer) or the bottom (in case of water table rise and poor subgrade drainage) which in both cases may not be desirable. The free water movement through the emulsified mixture will certainly cause extensive delay on the development of the final strength and possibly partial displacement of the binder. If none of the above happens excessive permeability will certainly cause extensive delay on the development of the final strength and possibly partial displacement of the binder. If none of the above happens excessive permeability will certainly cause hardening of the binder which might lead to premature fatigue failure (98, 99, 100, 101). On the other hand, if impermeable layers were constructed (associated with a very low percentage of voids) then bleeding might occur under further densification of the layers due to traffic (97) and possibly excessive rutting, as will be explained in Section 2.6.

In view of the above it can be said that permeability of BEMs is far more important and more complex than in conventional hot mixtures and should always be taken into consideration in mixture design.

Permeability of a bituminous pavement, in general, was considered to be directly related to air voids of the mixture (102, 103) and Heithaus and Johnson (100) have shown the relationship that exists between the air voids and the hardening. Typical examples of their findings are given in Figure 2.1 and 2.2. It is interesting to note in Figure 2.2 that most of the hardening takes place within four years for mixtures with a high percentage of voids. It was also found (94) that hardening due to oxidation and ageing was far more serious than hardening due to mixing and laying. In fact it was estimated that hardening due to the former was twice as much as for the latter. Similar findings reported by Simpson et al (104) who added that hardening also varies with pavement depth and its density.

Void content is a function of aggregate gradation, binder content and degree of compaction (102), and since permeability is related to void content all the above must affect permeability. Goode and Lufsey (101) and McLaughlin and Goetz (102) have shown that air permeability is indeed a function of aggregate gradation as well as air voids, and that the effect of gradation is more pronounced at high air voids than at low ones. The relationship between voids and permeability was influenced to a large extent by binder content, with permeability being more

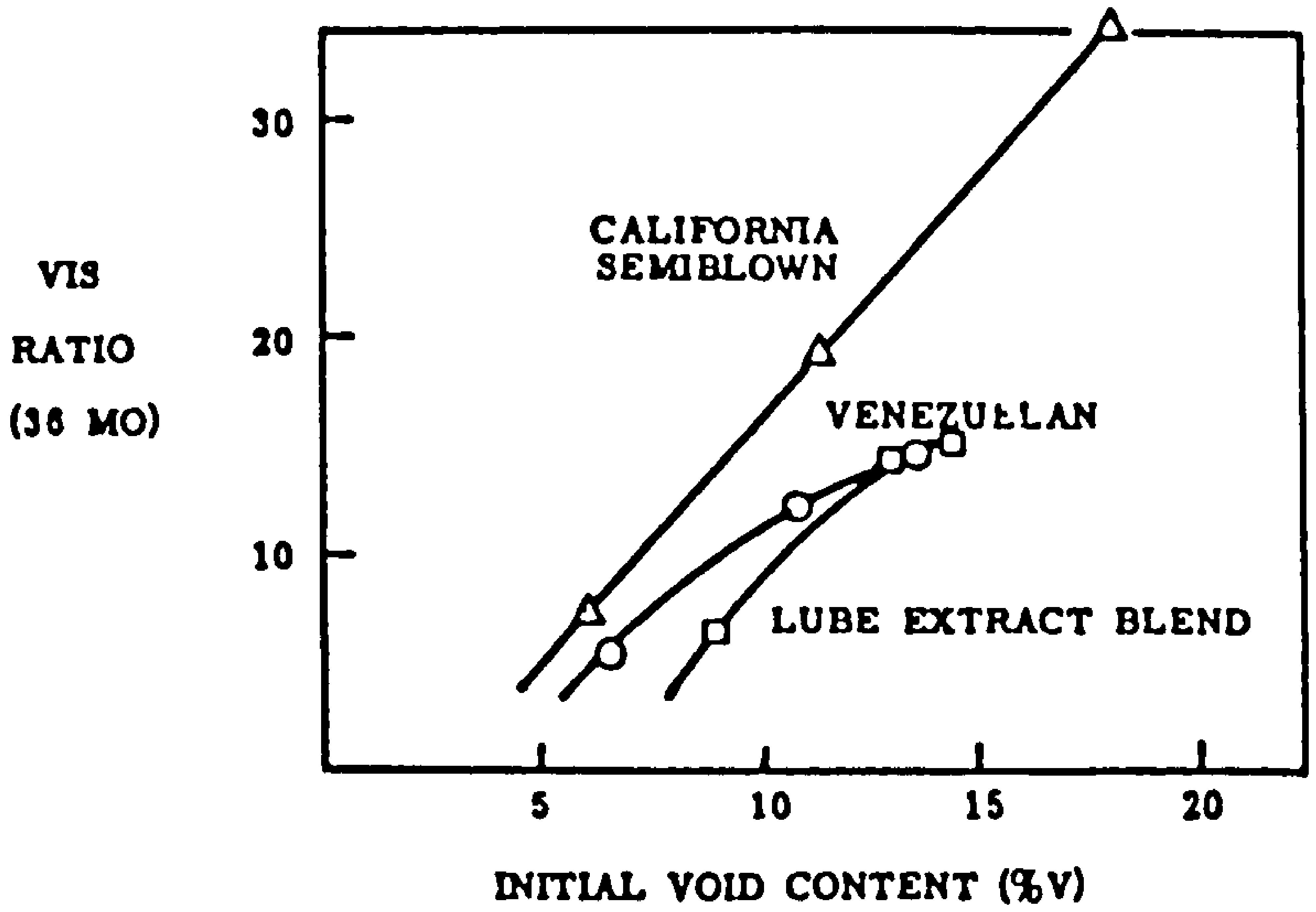


Fig. 2.1 AGEING OF VARIOUS TYPES OF BITUMEN WITH RESPECT TO VOIDS IN THE MIXTURE (after ref. 100)

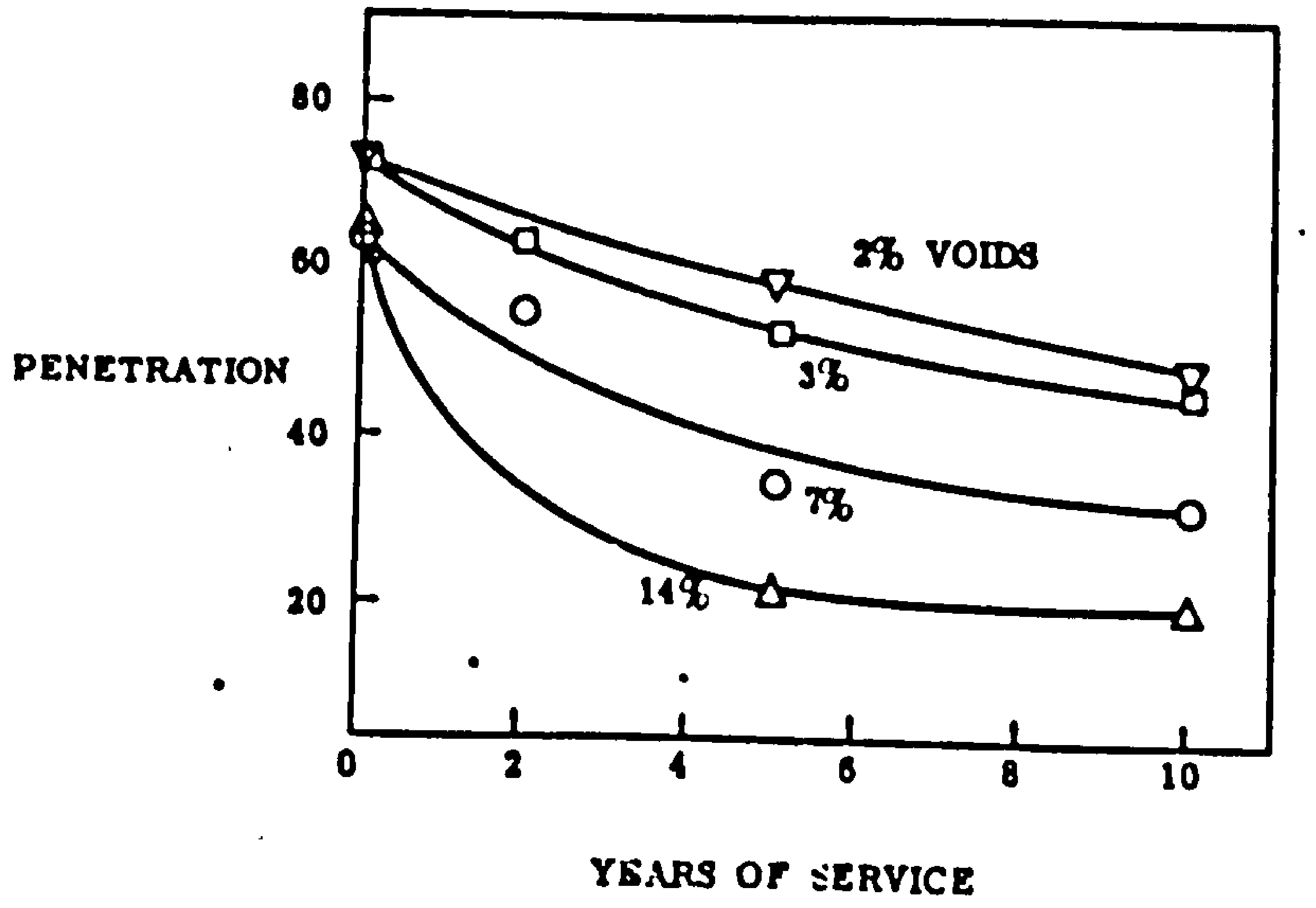


Fig. 2.2 HARDENING OF BITUMEN WITH TIME AND AIR VOIDS OF THE MIXTURE (ref. 100)

sensitive to void content at high binder contents (105, 109).

The effect of compaction was studied by Warner and Moavenzadeh (107). Marshall compaction was used at four different levels, and it was concluded that although permeability was decreased with compaction, the rate of decrease diminished after a certain compaction (60 blows) with a tendency to level off. Field studies (106, 108, 109) confirmed the above and showed that the type of roller and low speeds (approximately 0.720 Km/h) are essential for low air permeabilities.

Early field measurement of permeability (102) could not explain the fact that when all factors, such as compaction, gradation, binder content, aggregate type etc., kept constant, permeability readings were different between sections. There was a further factor involved and that was, as Kari and Santucci (106) and Zube (108) discovered, the seasonal period of construction. Pavements constructed during late Autumn have after a few months higher permeability than those constructed during early Summer. This was attributed to the overall lower environmental temperatures during Autumn and lighter Autumn-Winter traffic.

Although void content is related to permeability, measurements of voids only cannot give reliable information about the permeability of the mixture. This is because void measurements are only volume measurements and can give no information about the distribution of this volume and the interconnection of the voids. It is therefore necessary to measure permeability, and not to rely on void content measurements.

Permeability can be measured on site or in the laboratory with relatively simple apparatuses (97, 101, 102, 109, 110) which are described in Chapter 5. Typical values of the permeability of conventional bituminous mixtures are given below after (102, 105) which can be classified according to Cassagrante's (109) classification given in Table 2.2.

Dense graded mixtures	1 x E-9 to 1 x E-5
Gap graded mixtures	1 x E-8 to 1 x E-3
Sand sheet mixtures	1 x E-4 to 1 x E-2

TABLE 2.2 PAVEMENT CLASSIFICATION IN TERMS OF PERMEABILITY

Permeability, K (cm/sec)	Pavement
1×10^{-9} to 1×10^{-6}	Impervious
1×10^{-6} to 1×10^{-4}	Partially impervious
1×10^{-4} to 1×10^{-2}	Poor drainage
1×10^{-2} to 1×10^{-1}	Fair drainage
1×10^{-1} to 1×10^{2}	Good drainage

It must be noted that permeability data for emulsified bituminous mixtures could not be found throughout the literature review despite the importance of this measurement. This absence could be because the majority of projects used open graded mixtures which are highly permeable. It must be appreciated that when dense continuous and gap graded mixtures are used as base courses, permeability measurements are vitally important for the reasons given above.

2.5 Current Mix Design methods for base course mixtures

The widespread use in the last few years, of the BEMs has led to a demand in the development of a mix design procedure, so as to avoid mishandling of the mixtures. Some countries more than others have responded quickly to the acute demand and developed standardised procedures for the design of these mixtures.

Britain, among other countries, throughout the history of bituminous emulsions has maintained a sceptical attitude to the usefulness of this material in road construction and therefore the latest specifications for bituminous emulsions BS434 part 1 and 2 1973 can only cover sufficiently the use of emulsions in surfacing. This allows individual contractors and Local Authorities to use the material at their discretion despite the great possibility of failure.

However, other countries like America and France, have taken a more positive approach and have developed design methods and performance tests. America alone has been reported to have to date eleven mix design methods on an operating basis.

2.5.1. Main features of BEMs designs

The failure to agree to one standardised design method may be attributed to the great number of parameters involved in design, and above all to the difficulty in duplicating field conditions in the laboratory. Unlike hot mixtures, BEMs do not develop their ultimate strength and other related properties soon after construction. Development of ultimate strength may take from a few months to a few years, which in turn may make it difficult to decide under what conditions the specimens should be cured before testing.

All the available mix designs can be classified into two categories depending on the type of equipment used for compacting and testing the specimens. These two categories are the Hveem and Marshall modified mix design methods.

The Hveem method was developed by the Asphalt Institute (49), and its main features are that the emulsion content in the mixture is calculated by using the Centrifuge Kerosen Equivalent (CKE) test, and that the properties of the mixture are determined in terms of Modulus of Resilience (Mr), Resistance R-value (using the Hveem stabilometer) and the Cohesiometer C-value (using Hveem cohesiometer).

The suitability of the emulsion and the determination of the optimum water content added to the aggregate prior to mixing was determined by using the Coating test (93, 115). Slightly different coating tests to the one proposed by the Asphalt Institute have been proposed by various bodies and are summarised in ref. (5).

The optimum fluid content (water and emulsion) at compaction was determined by compaction (kneading plus double plunger static compaction) for maximum bulk density. There were two curing stages of the specimens in order to simulate early curing and final curing of the pavement on site. Early curing was represented by 24 hours air curing (room temperatures) of the specimens in the molds, and the final stage by 72 hours air curing in the mold, followed by four days vacuum desiccation curing (room temperatures).

The mix design procedure also included a test for measuring the effect of prolonged exposure of specimens to subsurface water. In this test, the specimens, after being cured for 72 hours and 4 days in vacuum desiccator, undergo vacuum saturation for one hour and are then immediately tested for R-value and C-value (49). The proposed design criteria are given in Table 2.3. Similar to the above method, are the Chevron method, the U.S.Forest Service method, the F.H.W.A. Region and the Arizona method.

TABLE 2.3 DESIGN CRITERIA FOR MODIFIED HVEEM MIX DESIGN METHOD (after 49)

Test Method	Base Course Material	
	Dense graded	Open graded
Resistance R-value		
- early cure	70 minimum	N.A.*
- fully cured plus water soak	78 minimum	N.A.
Cohesiometer C-value		
- early cure	50** minimum	N.A.
- fully cured plus water soak	100** minimum	N.A.
Coating, percent	50 minimum	50 minimum
Runoff, washoff (both)	N.A.	0.5 maximum

*N.A. = Not applicable

** =Applicable to wearing surface only

The other method, the modified Marshall method, also known as the Illinois method is based on the widely used Marshall method, and the initial estimation of the emulsion content is done by using equation 2.1.

$$R= 0.00138\times A\times B+6.3581\log C-4.655 \qquad \ldots \text{ eq. } 2.1$$

where R=trial residual binder content (by wt. of dry agg.)

A=perc. of aggregate retained on 4.75mm sieve

B=perc. of aggregate passing 4.75mm sieve and retained at 75micron sieve

C= perc. of aggregate passing 75micron sieve

The suitability of the emulsion and determination of optimum water added was done, as in the Hveem method, by the Coating test, and the optimum moisture content at compaction was determined by compaction (Marshall compaction - 75 blows) for maximum bulk density. The two curing stages were for 24 hours and 72 hours at room temperatures and with the specimens out of the mould. To measure the effect of water, the specimens, after having been cured for 48 hours, underwent capillary soaking for 48 hours and were then tested immediately for Marshall stability. Table 2.4 shows the recommended design criteria using this method.

TABLE 2.4 LIMITING DESIGN CRITERIA FOR THE MODIFIED MARSHALL METHOD (after 49)

	Base Course Material
Mix Parameter	Limiting Criteria
Stability loss (%)	50 maximum
Total voids (%)	2-8
Moisture absorption (%)	4 maximum
Modified Marshall Stability (lbs)	500 minimum
(KN)	2.3 minimum
Aggregate coating (%)	50 minimum

It should be stated that all tests for all methods are carried out at room temperature of approximately 22^{o}C. Also, all methods have requirements as to the suitability of the aggregates. These requirements are in terms of Sand Equivalent (greater than 25 percent), material passing 75 micron sieve (not greater than 15 percent), Los Angeles abrasion value (maximum 40 percent), and percent of crushed faces (minimum 65 percent).

Finally, it must be noted that all the available methods make no provision for the design of Gap graded emulsified bituminous mixtures.

2.6 Permanent deformation of BEMs

Bituminous Emulsion Mixtures (BEMs), when used in base courses should be designed to provide good resistance to rutting and fatigue cracking. Rutting failure (due to permanent deformation) has been reported to be the most common type of failure in England (116), France (117) and Switzerland (118), while fatigue cracking failure is common in the United States (119). For the purpose of this literature review emphasis will be given to the permanent deformation rather than fatigue cracking.

Permanent deformation of pavements depends on a number of factors (118, 120): the intrinsic properties of the bitumen, the traffic loading, the aggregate gradation, the structure of the pavement and the environmental conditions. Wear due to studded tyres has been reported (118) to lead to permanent deformation in some countries, but it cannot be considered to be a major factor. All layers of a pavement, including the subgrade, undergo permanent deformation but is believed that adequate thickness of the bituminous layers should prevent permanent deformation of the subgrade.

Although the main concern of this section is the permanent deformation of the BEMs, no relevant work was found throughout the literature, and therefore all the subsequent discussion will be based on the bituminous layers in general. This complete absence of information may be due to the fact that only in the last few years have these types of mixtures started to be used as the main structural element (base course) of the pavement. However, there is no doubt that future use of BEMs will face the question of how they perform in long term deformation due to traffic loading.

2.6.1. Rheological response of bituminous mixtures

Bituminous mixtures behave, mainly due to inherited properties of binder, as a viscous-elastic material. In other words, unlike elastic materials, their stiffness modulus (similar to Young's modulus) is dependent on time and temperature as well as stress and strain. Therefore, viscoelastic materials have a mixed behaviour as shown on Figure 2.3. At short loading times (less than 10^{-4} secs) they are almost elastic and their stiffness (Smix) is equivalent to Young's modulus (E). After a longer period of time they behave as viscous materials, between these two extremes they possess a visco-elastic behaviour, sometimes known at Delayed or Retarded elastic behaviour (121, 122). Elastic and viscous behaviour have been represented by early investigators, by springs and dashpots respectively and different arrangements of these two elements may describe the visco-elastic behaviour (123, 124). This theoretical modelling was found to have an excellent correllation with the behaviour of the pure bitumen (125) under certain loading conditions. With the actual bituminous mixtures, and taking into account the frequency of loading, modelling of the behaviour becomes very complex and less correlated (126) and as Van der Poel pointed out " ... models with a finite number of springs and dashpots fail to give a representative picture over a sufficient large range of loading time frequencies" (121).

Van der Poel (121, 127) concentrated on a single stress and its resultant strain on pure bitumen, and working with a variety of bitumens he showed that there was no fundamental difference between static and dynamic loading. This enabled him to construct a nomograph in which both dynamic and static sitffness moduli are given as a function of loading time (or frequency), temperature, hardness of bitumen (Ring and Ball temperature) and rheological type of bitumen (Penetration Index). The equivalence of static and dynamic loading was also valid for bituminous mixtures and it was found by Van der Poel (121), again, that there is a relationship between stiffness of the mixture (Smix), and the stiffness of

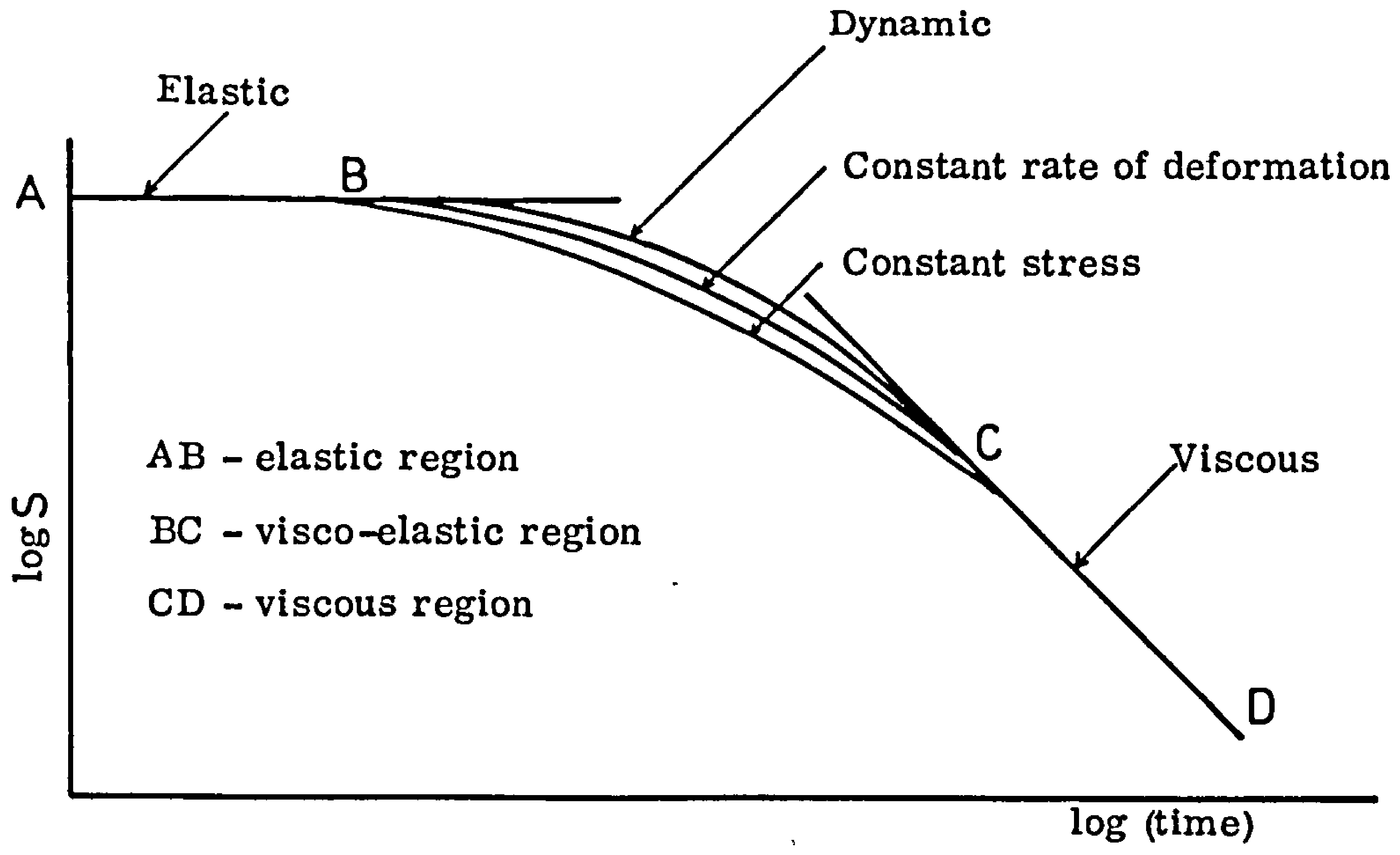


Fig. 2.3 STIFFNESS MODULUS (S) OF BITUMINOUS MATERIALS AS A FUNCTION OF TIME (t), FOR VARIOUS TYPES OF LOADING (after 122)

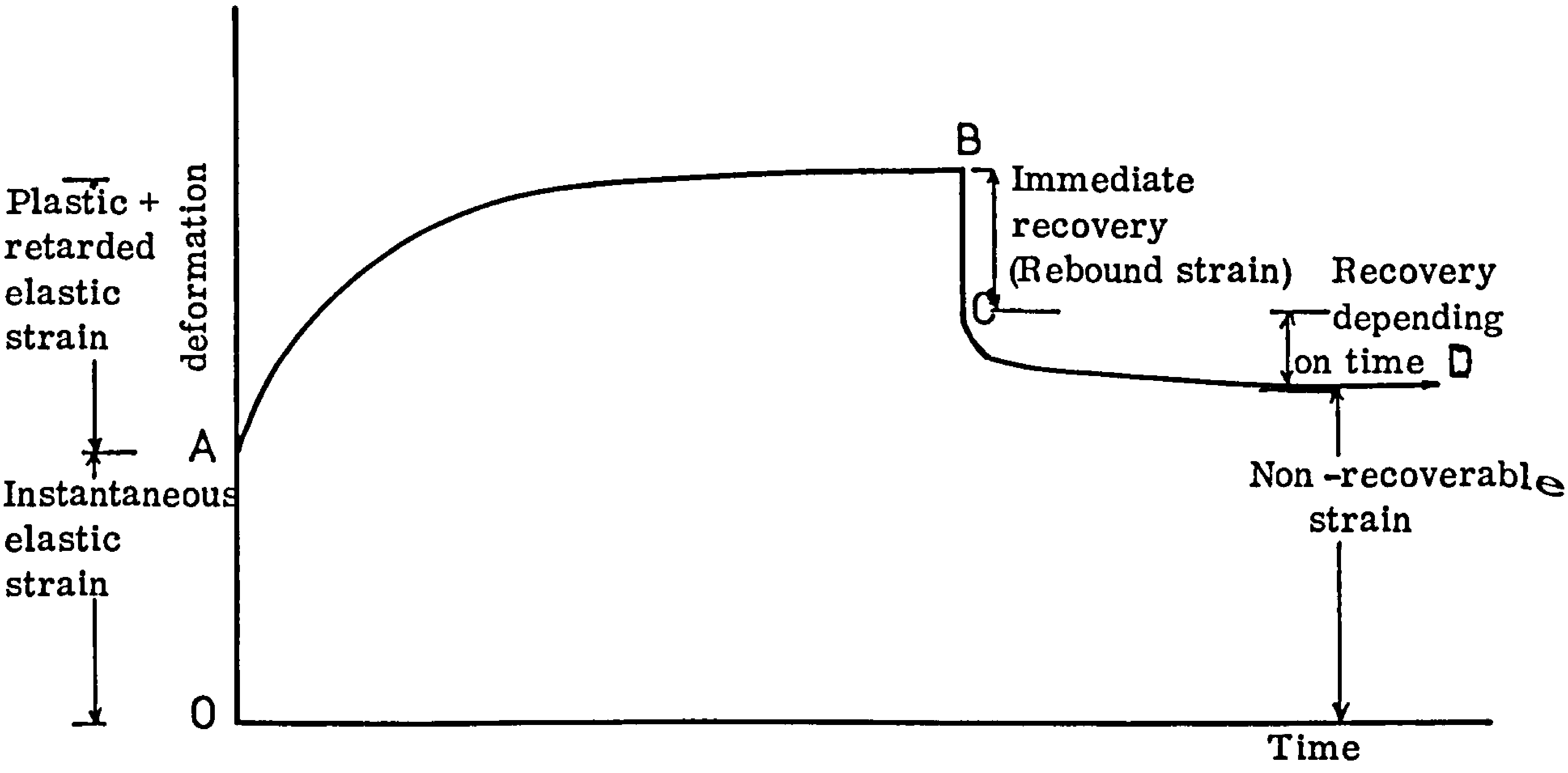


Fig. 2.4 THE DEFORMATION OF A BITUMINOUS MIXTURE AS A FUNCTION OF TIME FOR LOADING AND UNLOADING (after 132)

binder and volume concentration of minerals (Cv), irrespective of combination of loading time and temperature. This relationship was examined by Heukelom and Klomp (122), who suggested that equation 2.2 gives a reasonable estimation of the stiffness of the mixture, provided that the stiffness of the binder is determined from Van der Poel's nomograph.

$$Smix/Sbit= (1 + (2.5Cv/(n(1 - Cv)))^{n} \qquad \text{...eq. 2.2}$$

where $n = 0.83*\log\ 4 \times 10^{5}/Sbit)$

n dependent of voids

Smix and Sbit the stiffness of the mixture and the bitumen in units of Kg/cm^{2}

Pell and McCarthy (122) examined the validity of the above equation by comparing the results with the measured stiffness under dynamic loading and concluded that although it does not give accurate results under all the range of loading time it does give reasonable results for the range of loading equivalent to traffic loading.

Other investigators (128, 129, 131) have suggested different experimental methods of measuring the stiffness of the mixture i.e. by testing specimens under compression or/and tension, and flexure.

2.6.2. Permanent deformation of bituminous mixtures

Regardless of the type of loading, the deformation pattern of a bituminous mixture is similar to the deformation pattern of pure bitumen (123, 132). It consists of instantaneous elastic strain,Figure 2.4, which is independent of time, a retarded elastic strain which is a function of time, and a plastic strain whose rate decreases with time. When the load is removed,immediate rebound takes place followed by a retard rebound which is dependent on time.

Mack (132) in his early work experienced difficulty in modelling the behaviour of the bituminous mixtures, particularly the recovery stage, and he concentrated on the strength evaluation of the mixtures by using the uniaxial static compression test, known as the Creep test. He recommended the use of two types of deformation, the recoverable and the non recoverable. This was a move in the right direction because, if successful, ranking of the mixtures could be done in terms of their behaviour in permanent deformation, which could be related to actual rutting of the pavements.

Wood and Goetz (134) followed the recommendation of Mack, and studied the behaviour of sand-asphalt mixtures under static loading. They based the analysis of the data on modulus of Recovery (R), (stress over rebound strain), and modulus of mixture viscosity. The later modulus was obtained by dividing the applied stress by the slope of the strain v time curve, in the region where the rate of strain was constant. They pointed out that high values of both moduli are not desirable. Despite the fact that some of the tests carried on beyond failure point, they concluded that both the above moduli were independent of stress level.

Moavezadeh and Sendze (135), using the same type of material, followed the analysis of Wood and Goetz and found tremendous difficulty in measuring rebound strain, because they could not determine where the rebound ended. They therefore suggested using for the evaluation of the mixtures the Creep modulus, obtained from the recovery (relaxation) curve.

Parallel to the work of Moavenzadeh and Sendze, Pagen (131) studied the rheological behaviour of bituminous mixtures under static and dynamic loading. After extensive investigation he concluded that at low stress levels linear viscoelastic behaviour was applicable, and that the time-temperature superposition theory was valid. This means that experimental temperatures alter only the position of the viscoelastic functions on the time scale, and not the general shape of the curves. This was of great importance because it allowed a projection of experimental viscoelastic functions to loading times both shorter and longer than can normally be obtained experimentally and for any intermediate temperatures within the tested temperature range. Pagen developed his master Creep modulus (Ec) curve and Transverse Creep modulus (Tc) curve by using the temperature dependant Shift factor (aT). Other investigators (136, 137) also indicated that the time-temperature superposition theory is valid for bituminous materials, and added that the shift factor was influenced by the type of filler used (137), and was not too dependant on the binder content (136).

Further work by Pagen and Ku (138) on the influence of mixture parameters on creep showed that aggregate gradation had more influence than the type of aggregate. Pagen (139, 140) also examined the influence of the size of the specimen and found that its length and the diameter influenced its properties in a manner comparable to the effects of temperature on these properties. He therefore proposed a length/diameter ratio shift factor similar to temperature dependant shift factor aT.

Although the behaviour of bituminous mixtures under loading had been defined the question of how to relate permanent deformation to rutting depth of a pavement was still unanswered.

In 1973, Hills (141) published his theoretical model for the deformation of bituminous mixtures under a constant uniaxial static load. It was based on the hypothesis that any deformation in the mixture is the result of sliding displacements between adjacent mineral particles, separated by a thin film of bitumen. In this model the rate of strain was dependant on the magnitude of the stresses, the thickness of the bitumen film (which changes with time under the influence of the stress) and the properties of the binder. He compared a theoretical model with the Creep test and obtained excellent results. The main discovery, also, was that by plotting the stiffness of the mixture against the stiffness of the binder the effects of temperature, applied stress level, type of binder and size of specimen were completely eliminated (141, 142, 143), and therefore the determination of shift factor was unnecessary. The shape of Smix vSbit curves was only dependant on the composition of the mixture and its internal structure (aggregate gradation and type of aggregate). He stated though that the above is only true for values of binder stiffness of less than $10MN/m^2$. Above this value he recommended using the concentration of mineral aggregate formula proposed by Heukelom and Klomp (122).

Hills findings were of tremendous importance because as Van de Loo (143) stated, since Smix/Sbit curves are only dependant on the mixture and its internal structure, the quality of the material can be judged by the slope and the position of the curve.

Hills et al (142) compared the results of the Creep test with the rutting test (144, 148); results were obtained from five different laboratories and good correlation was found. The comparison was based on the stiffness of the mixture and the permanent deformation. The calculation of Smix from the creep test was straight forward but the calculation of Smix from the rutting test, because of the different stress pattern, was slightly complicated. Stresses and strains were calculated with the aid of a computer programme (BISTRO) which uses elastic layered system analysis. They finally proposed the following formula for estimating the rut depth from creep test:

Rut depth = H x Z x Stress/Smix, creep ...eq. 2 .3

where H = the initial depth of the pavement

Z = dimensionless parameter, function of geometry and stiffness moduli of the system

Smix, creep = corresponds to the value of Sbit equal to $3 \times \eta/(N \times Tw)$

Stress = stress due to traffic load , N/m^2

where η visoosity of the bitumen obtained by Van der Peol nomograph

N=no. of wheel passes

Tw=time of loading for one wheel passage

The results showed that rutting could be predicted from the creep test within a factor of about two for rut depths ranging from 0.1 to 10mm. This was a major breakthrough because for the first time there was a good evidence that actual pavement deformation could be predicted from a simple laboratory test and a knowledge of the site and traffic conditions, a true engineering approach to the acute problem of rutting.

Van de Loo (143) carried the above idea a bit further. To improve the accuracy of the formula he first proved that the difference in results between the rutting and the creep test was not due to the contrast of confined-unconfined conditions, but to the contrast between static-dynamic loading, and incorporated other factors into the formula such as temperature distribution through layers, variation of axial loads and their distribution; thus the new formula was modified as follows:

Rut depth (RD) = Cm×H×Stress/Smix ... eq. 2.4

where Cm = correlation factor for the dynamic effect, it depends on the type of mixture and is fixed empirically

H = layer thickness

Stress = weighed average stress in the pavement, under moving wheels related to wheel loading and its distribution within the layers and equal to $Z \times 6 \times 10^5$, N/m^2

Z = as in equation 2.3

Smix = value of stiffness of the mixture derived as in equation 2.3

All the above coefficients are given in the Shell Design manual (147) and explained further by Van de Loo (148, 149) and Claessen et al (150).

In his original paper, Van de Loo (143) also demonstrated the inability of Marshall design to rank the mixtures in terms of permanent deformation performance.

Hilster and Van de Loo (151) carried out another extensive investigation on the influence of test parameters to creep test results which enabled them to propose the final version of creep test procedure and test conditions, which was finally accepted by a Symposium in Geneva as the standard procedure of creep test.

At the same time as Van de Loo refined the method of estimating the rut depth, Brown and Snaith (153) investigated the experimental conditions suitable for predicting rut depths from repeated loading tests.

A year later Kirwan et al (155) developed a computer programme for the prediction of rut depth, using finite element analysis and based on Romain model (156). The results obtained were comparable to the unconfined repeated test at high values of vertical stress only.

The deficiency of Kirwan et al (155) programme, according to Brown and Bell (157) was that it ignored completely the effect of shear stress on vertical strain. They found that because of this, values obtained by using the programme were overestimated.

Further work by Brown and Cooper (158) showed that sinuisoidal load gives closer results to creep than square wave loading.

Similar work to that of Brown and Cooper (158, 159) was carried out by Francken (160), who derived a formula in terms of time stress and dynamic stiffness modulus. He also suggested that the existance of "plastic failure limit" could be used as a design criterion in a rational design method.

Lai and Huffered (161) developed a theoretical model for predicting rut depth, and this has been incorporated into VESYS IIM programme developed by Pennsylvania University (162, 165). The validity of this model was examined by Kenis and Sharma (163), but McLean and

Monismith (164) doubt its suitability for implementation in a design procedure.

A completely different approach to the estimation of permanent deformation was proposed by Meyer et al (166). They proposed a formula, based on monitoring the performance of pavements for a number of years, in terms of equivalent asphalt thickness, stiffness moduli of the layers, and number of standard axles applications. They eliminated the above factors by statistical analysis. This formula was modified later on by Meyer et al (168) for rutting results above 5×10^5 standard axles applications. This formula has not been tested for mixtures other than the ones used in the San Diego experiment (167) and its validity should be treated with caution.

Potter (169) developed a similar formula to monitor the performance of pavements built with Rolled Asphalt bases, in England, and found good correlation with practical measurements of rutting. The main finding from Potter's study was that all the already built pavements, according to RN29, exhibited a greater rate of deformation than expected, when the traffic was more than 8×10^6 standard axles. This shows the inadequacy of RN29 in designing pavements with good resistance to deformation.

The only relevant work to permanent deformation of BEMs was carried out by Akili and Monismith (170) using emulsion stabilised sand mixtures and repeated triaxial test. The proposed formula is in terms of the principal stress and its accuracy remains to be seen.

As was outlined, two experimental techniques can be used for predicting rut depth of pavements, the Creep test and the Repeated load test. Both of these give reasonably accurate results but the Creep test is undoubtedly more popular for its simplicity and reliability and when used with the Shell method can cover, effortlessly and economically, a much wider range of site conditions.

2.7 Summary

The literature review has shown that although enough is known about the behaviour of bituminous emulsions, their use is mainly restricted to surface treatments. However, some countries have started to use bituminous emulsion mixtures for base courses and surfacings for light trafficked roads. The disadvantage of these mixtures is that they are open graded mixtures, i.e. their porosity is high because the use of fine aggregate is restricted to small amounts.

The use of relatively large quantities of fine aggregates is precluded because the stability of commercially available emulsions is drastically reduced by the large specific area and nature of the surfaces of the fine aggregate. Production of dense graded mixtures is then restricted by the type of emulsions available. Various research projects, reviewed in the literature, have shown that the success of producing dense mixtures depends mainly on the nature of the emulsion. Emulsions for this purpose are still on the experimental stage and consequently the properties of dense bituminous emulsion mixtures have yet to be evaluated.

CHAPTER THREE

SCOPE OF THE INVESTIGATION

The review of literature has revealed that there is a need for developing a stable slow setting emulsion suitable to be used with dense graded mixtures. Consequently a mixture design method has to be established and the properties of the mixtures have to be evaluated.

The objectives of this investigation are as follows:

1. To develop a stable slow setting cationic emulsion suitable to coat dense graded mixtures and in particular gap graded (Rolled Asphalt) and dense graded Macadam.

2. To study the rheological properties of the cationic emulsion with respect to its viscosity and the factors affecting the viscosity. The investigation of the development of an emulsion, which may be successfully used for the production of dense graded mixture, is carried out on 5 different formulations, which required the use of two surfactants, two adhesive agents and a water shading compound. The evaluation of the properties of the emulsion involved normal BS434 Part 1 and 2 tests and the detailed study of their rheological properties, obtained by the use of the rotational viscometer (Epprecht Rheomat 15), the Engler viscometer and the glass capillary viscometer.

3. To develop a procedure for preparing and testing Cold Rolled Asphalt (C.R.A.) and Dense Emulsion Macadam (D.E.Mc) mixtures, in order to evaluate the engineering properties.

   The mineral aggregates, for the preparation of the mixtures, consist of limestone aggregate and filler, from a local quarry (Pately Bridge) and river sand from an industrial plant (Almington).

The mineral aggregates are carefully graded and mixed with the best emulsion developed during the first phase of the study and the mixtures are evaluated using a modified Marshall procedure, which includes the measurement of air permeability. The long term performance of the mixtures, in terms of permanent deformation, is evaluated using a static creep test.

CHAPTER FOUR

MATERIALS AND THEIR PROPERTIES

4.1 Introduction

This chapter gives a detailed account of the materials used in this study. The materials can be classified under the following headings: aggregates (coarse and fine), filler, bitumen and emulsion.

The coarse aggregate (retained on 2.36 mm B.S. sieve) was crushed limestones, the fine aggregate (passing 2.36 mm B.S. sieve) was washed sand and the filler was limestone dust of the same origin as the coarse aggregate. The bitumen was a Middle East type of three grades, hard, medium and soft, and the bituminous emulsions were all slow setting cationic emulsions.

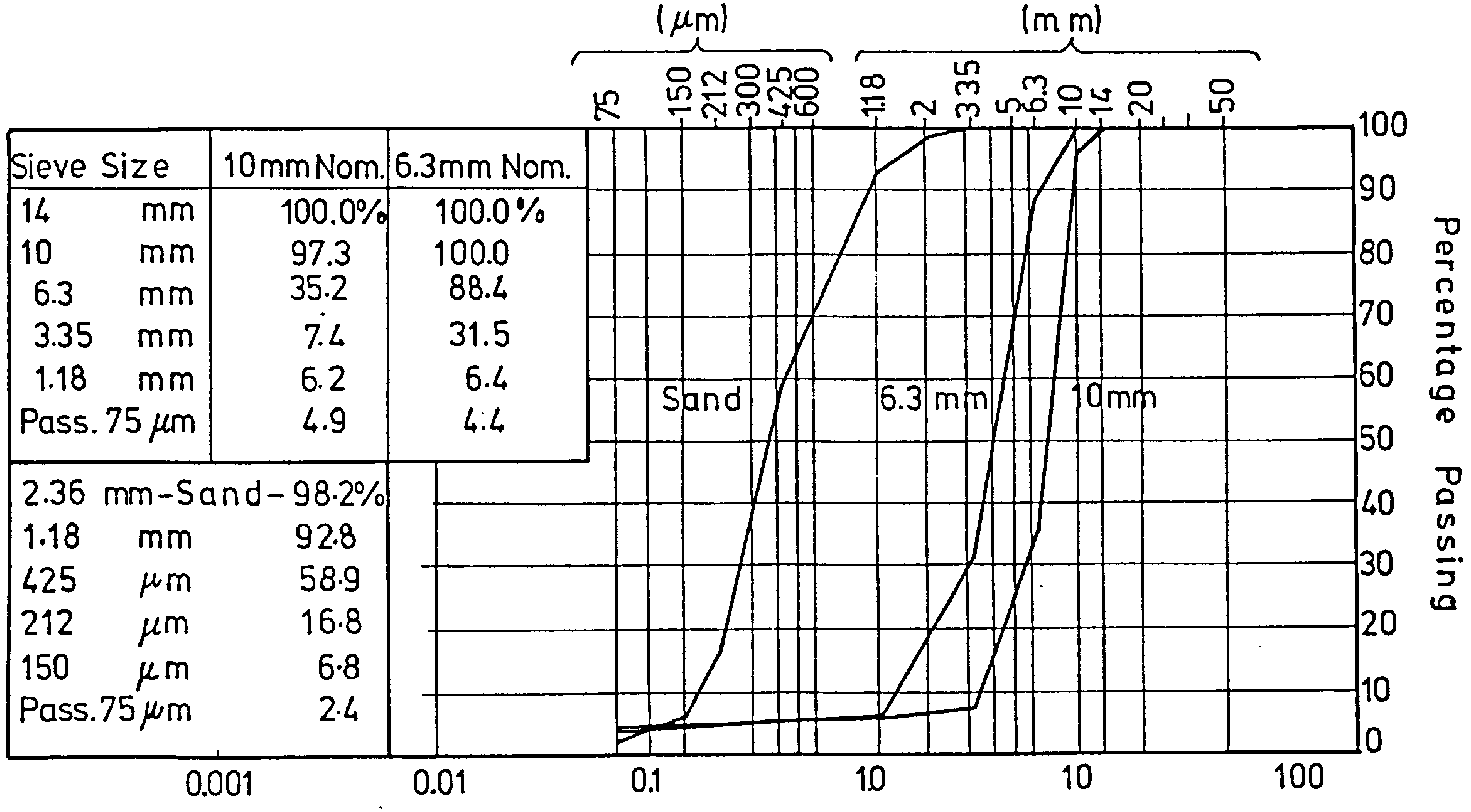
4.2 Description and properties of the material

4.2.1. Coarse aggregate

The crushed limestone coarse aggregate was supplied by Readymix Concrete (Yorkshire) Ltd from the limestone quarry at Pately Bridge (West Yorkshire). This limestone is commercially used for the preparation of base course and road base materials, mainly dense bituminous macadams.

The aggregate was supplied in two nominal sizes of 6.3mm and 10mm size. The gradation analysis after wet sieving and the resulted gradation curves is shown in Figure 4. 1.

The properties of the aggregate were determined according to appropriate British Standards and the results are shown in Table 4.1. It is interesting to note that the crushing value of the aggregate is close



Sieve Size	10mm Nom.	6.3mm Nom.
14 mm	100.0%	100.0 %
10 mm	97.3	100.0
6.3 mm	35.2	88.4
3.35 mm	7.4	31.5
1.18 mm	6.2	6.4
Pass. 75 µm	4.9	4.4

2.36 mm - Sand -	98.2%
1.18 mm	92.8
425 µm	58.9
212 µm	16.8
150 µm	6.8
Pass. 75 µm	2.4

Fig. 4.1 SIEVE ANALYSIS OF THE AGGREGATES (Wet sieving)

COARSE AGGREGATE, FINE AGGREGATE (SAND) AND FILLER			
MATERIAL	PROPERTY	BRITISH STANDARD REFERENCE	MEASURED VALUE
Coarse Aggregate (Limestone)	Specific gravity - apparent - oven dried - saturated, surface dried	BS812/1975 (38)	 $2.72g/cm^3$ $2.63g/cm^3$ $2.67g/cm^3$
	Water absorption	"	1.5%
	Crushing value	"	27%
	Impact value	"	20%
Fine Aggregate (Sand)	Specific gravity	"	$2.65g/cm^3$
Filler	Specific gravity	"	$2.78g/m^3$
	% Voids in dry compacted filler	"	33.81%
	Bulk density in toluene	"	0.63g/ml

TABLE 4.1 PROPERTIES OF AGGREGATES AND FILLER

to the upper limit of 30%. This suggests that this limestone may be crushed under heavy compaction or due to heavy traffic loading.

4.2.2. Fine aggregate - sand

The sand was supplied by Amey Roadstone Corporation (ARC West Midlands) Ltd., from Almington sand pit. It is washed sand and is mainly used for Hot Rolled Asphalt mixtures. Scanning electron micrographs obtained by Cabrera (201) have shown than it is angular in shape, in contrast to riversand.

The sieving analysis and gradation curve of the sand is shown in Figure 4.1 and its specific gravity in Table 4.1. It must be noted that due to the manufacturing process (washed sand) there was no trace of clay particles.

4.2.3. Filler

The filler was crushed limestone from the same quarry as the coarse aggregate. Its physical properties are shown in Table 4.1. It can be seen that its bulk density in toluene was within the specified range of BS594/1973 (69) for Hot Rolled Asphalt mixtures, i.e. 0.5 to 0.95 gr/ml.

4.2.4. Combined aggregate gradation for C.R.A. and DEMc mixtures

The coarse aggregate, sand and filler were combined to produce the desired gradation for the Cold Rolled Asphalt (C.R.A.) and Dense Emulsion Macadam (D.E.Mc) mixtures used in this study.

The gradation of the C.R.A. mixtures was equivalent to 10mm nominal wearing coarse mixture. It was obtained by combining the coarse aggregate (10mm nominal) with the sand and filler at percentages of 34.6, 57.6 and 7.8 respectively. The combining of the aggregates was carried out using the mathematical method as illustrated in reference (65). The resulting gradation curve, together with the specified limits by BS594/1975 is shown in Figure 4.2.

Similarly, the combined gradation curve of the DEMc mixtures was obtained by combining 50% of 10mm nominal aggregate, with 27.5% of 6.3mm nominal aggregate, and 22.5% of sand. The resulting combined curve is equivalent to 10mm nominal dense wearing coarse Macadam, as specified by BS4987/1973 (70), and is shown in Figure 4.3.

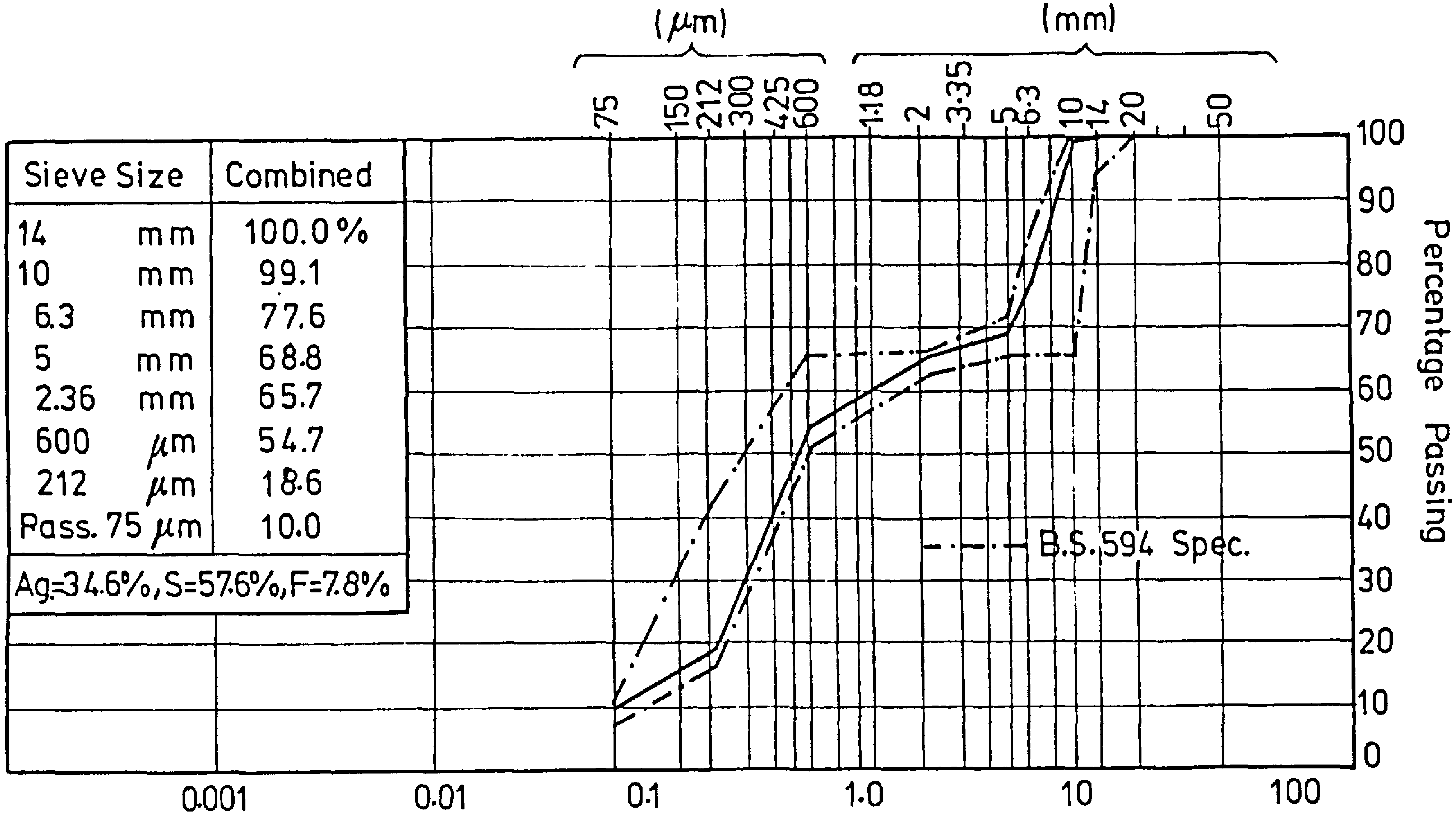
4.2.5. Binder

The binder used was a Middle East bitumen of three different penetration grades, 40/60 - hard, 80/100 - medium, and 200 pen - soft. The properties of the bitumens used are given in Table 4.2.

Type of Binder	Suppliers Specification	Test	British Standard Reference	Measured Value
Hard	40/60 pen	Penetration	BS 4691/1974 (114)	74 pen
		Ring and Ball	BS 4692/1971	$50^{o}C$
		Specific gravity	-	$1.03 gr/cm^3$
Medium	80/100 pen	-	-	-
Soft	200 pen	-	-	-

TABLE 4.2 THE PROPERTIES OF BITUMEN

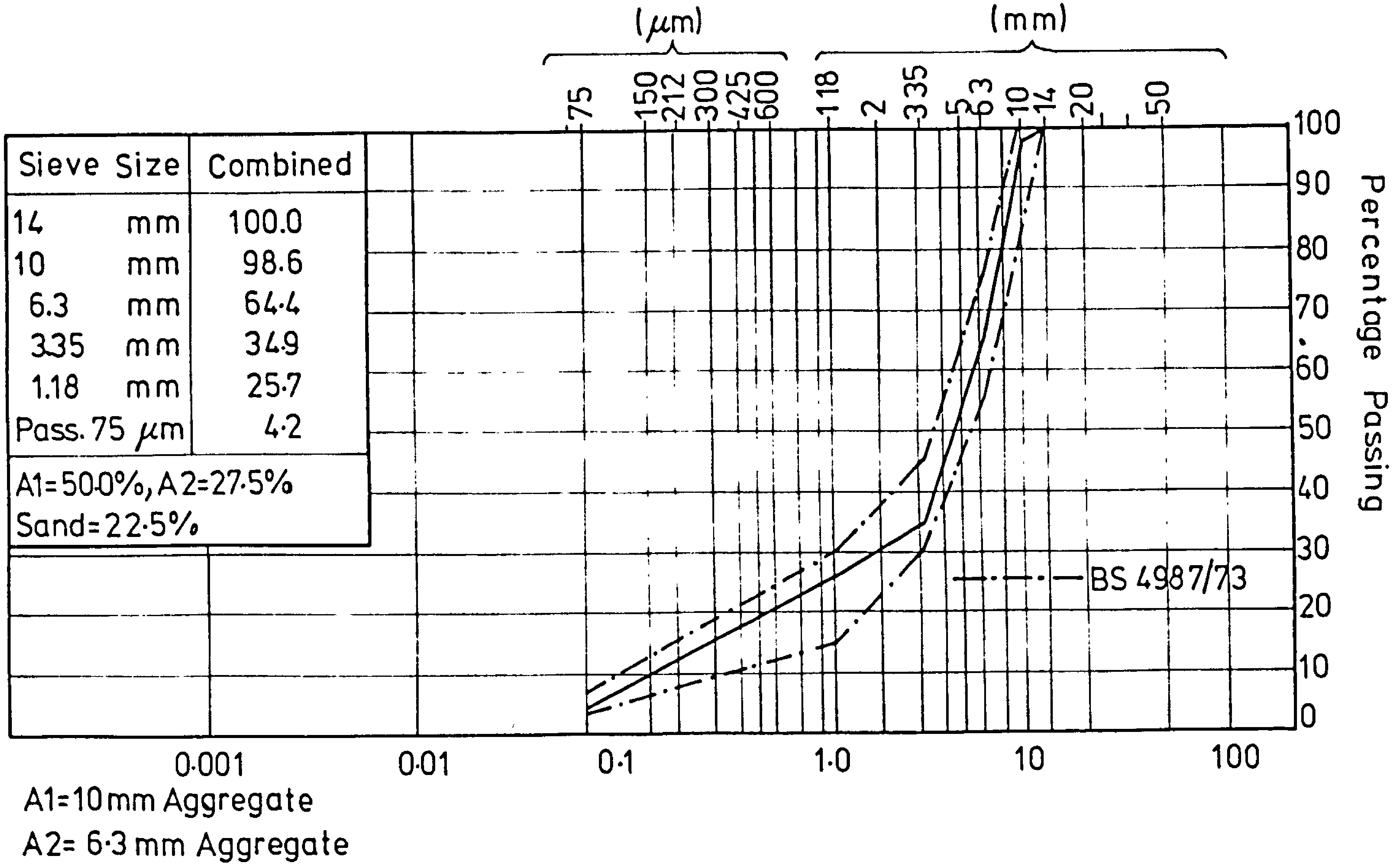
It must be emphasised that the medium and soft binder was used only for the limited study of rheological behaviour of the emulsions. The hard binder was used exclusively for all the investigation study.



Sieve Size	Combined
14 mm	100.0 %
10 mm	99.1
6.3 mm	77.6
5 mm	68.8
2.36 mm	65.7
600 μm	54.7
212 μm	18.6
Pass. 75 μm	10.0
Ag=34.6%, S=57.6%, F=7.8%	

Fig. 4.2 COMBINED GRADATION CURVE OF C.R.A. MIXTURES

(Combination of coarse aggregate - 10mm nominal, sand and filler, see also Plate 4.1).



Sieve Size	Combined
14 mm	100.0
10 mm	98.6
6.3 mm	64.4
3.35 mm	34.9
1.18 mm	25.7
Pass. 75 μm	4.2

A1=50.0%, A2=27.5%
Sand=22.5%

Fig. 4.3 COMBINED GRADATION CURVE FOR D.E.Mc MIXTURES

(Combination of 10mm, 6.3mm nominal aggregate and sand, see also Plate 4.1.)

Using the data given in Table 4.2, the Penetration Index, as defined by Van de Poel (127), was found to be equal to -0.14.

4.2.5. Cationic emulsions

The emulsions developed and tested as indicated in Chapter 6 were prepared by using a Hurrell emulsification unit machine (colloid mill). The three emulsifiers used were Redicote - E11, NH-10 and the KS-4. The first is currently used in slurry seals (22, 53, 54) and the last two are new formulations, especially designed for the preparation of slow setting emulsions of high stability. Details of the formulation and manufacture of emulsions are given in Chapter 6.

The emulsions contained 60, 65 and 70 percent binder of different grades, corresponding to low, medium and high binder content respectively. The properties of the emulsions were tested according to BS 434 Part 1 (45) and the results are shown in Table 4.3.

It must be noted that for the major part of the investigation, (determination of mixture properties) NH-10 emulsion was used with 74 penetration grade bitumen and with 70% binder content.

PROPERTIES	REDICOTE - E11			NH - 10					KS4	NH-10+A_1*	NH-10+A_2**	BS 434/Pt1 1973 (45) SPECIFICATIONS
	TYPE OF BITUMEN IN PENETRATION GRADE											
	74	80/100	200	74	74	80/100	200	74	74	40/60	40/60	
Average Binder content (%by mass)	65	65	65	60	65	65	65	70	70	70	70	min 56
Residue on 150 micron sieve (g per 100ml)	0.12	-	-	-	0.11	-	-	0.16	-	-	-	max 0.15
Viscosity (Engler) at 20^oC (^oE)	-	-	-	-	-	-	-	35.2	-	-	-	max 10^oE
Storage stability (long period - water content difference %)	0.6	-	-	-	0.35	-	-	0.30	-	-	-	max 2%
pH	2.40	2.26	2.00	4.06	4.13	4.08	4.05	3.95	4.30	3.99	4.00	-

*A_1 = NH-10 with Imidazoline

**A_2 = NH -10 with PN39

TABLE 4.3 PROPERTIES OF CATIONIC EMULSIONS

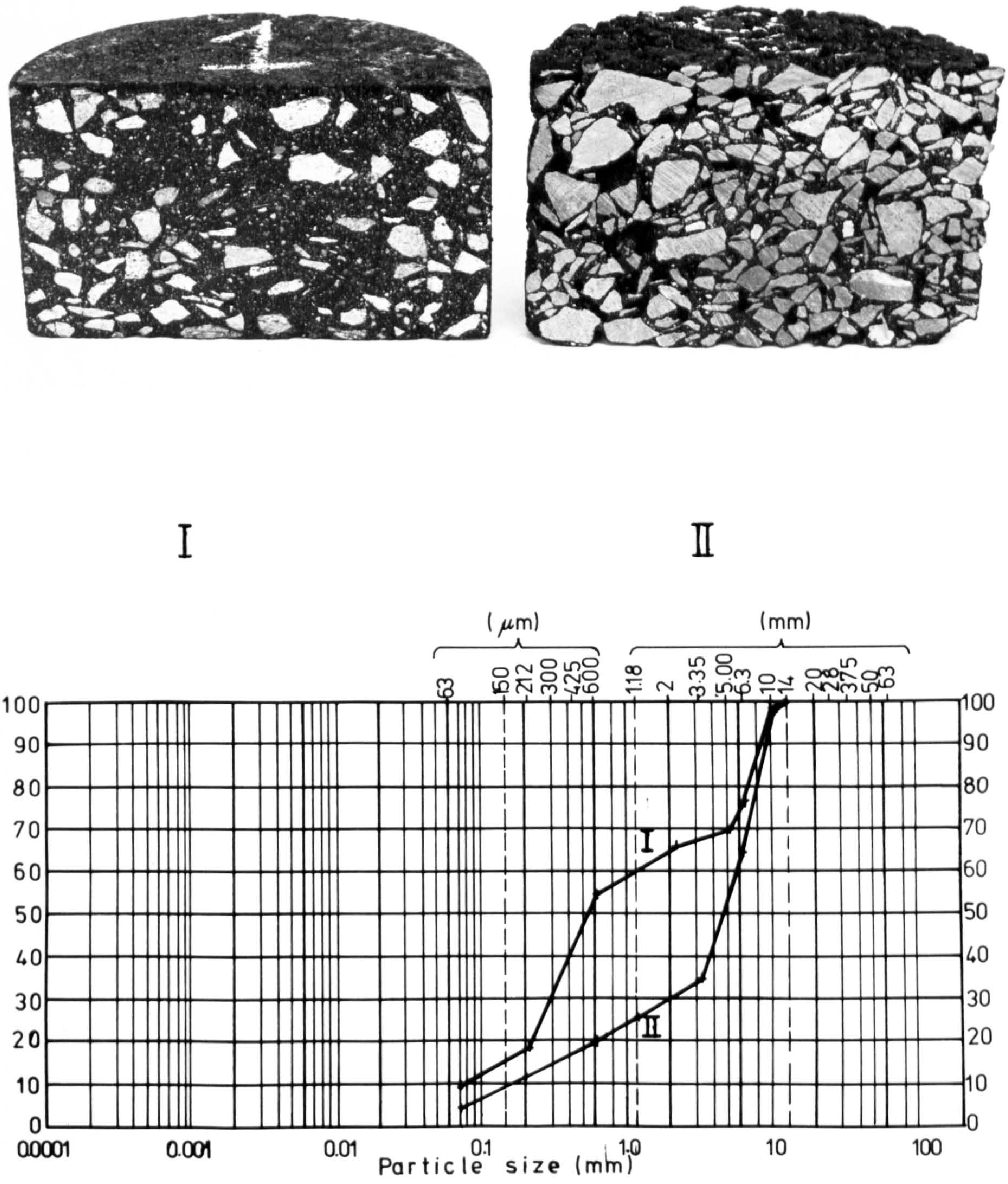


Plate 4.1 Gap graded (curve I) and Continuously graded (curve II) grad ation curves and the resulting mixtures

CHAPTER 5

TESTING PROCEDURES AND INSTRUMENTATION

5.1 Introduction

This chapter gives a detailed account of the procedures and equipment used for measuring the rheological properties of the emulsions, and for preparing and testing the specimens of the emulsion treated mixtures.

The viscosity measurements were carried out using the Epprecht rotational viscometer, the Engler viscometer and a glass capillary viscometer, conforming to specification of BS 188:1977 (180).

The evaulation of the properties of the emulsion treated mixtures was carried out following a modified Marshall method and by using an air permeability test on specimens of 101.6mm diameter by approximately 62.5mm high. The behaviour of the mixtures regarding permanent deformation was studied by employing the static Creep test.

The apparatus used in the modified Marshall method was the same as for the ordinary Marshall test; Permeability and Creep tests were carried out by using newly designed apparatus, details of which are given in the subsequent sections of this Chapter.

5.2 Rheological measurements

The rheological properties of the emulsions used in this study were determined in terms of viscosity. The dynamic viscosity (in centipoise, cP), was measured with the Epprecht Rheomat 15 rheometer (179), the kinematic viscosity (in mm^2/sec) was measured with the Glass capillary viscometer (180) and the Engler viscosity (^oE) with the Engler viscometer (45).

5.2.1. Epprecht Rheomat 15 (ER15)

The Epprecht Rheomat 15 rheometer, shown on plate 5.1, is a rotational viscometer designed by Contraves AG Zurich. It is capable of measuring viscosities within the range of 1 to 1 x 10^4 cP and is suitable for Newtonian and non-Newtonian fluids.

It consists of a cylindrical bob, with conical ends, rotating in a cup containing the material to be tested. The bob may rotate at fifteen different frequencies with the aid of a frequency generator unit, a switch panel unit, and a synchronous motor with gear box, freely suspended by a steel wire opposed by a calibrated spring. The torque, corresponding to the drag force on the measuring bob is taken by the calibrated spring, so that the drag will correspond to a certain deflection of the pointer attached to the torque-reactive motor (179).

The ER15 employs six different measuring systems of cups and bobs which enables viscosity measurements to be obtained within the range mentioned above. Shear rate values, corresponding to different measuring systems and speeds used, were provided in a table form by the manufacturers.

5.2.1.1. Testing procedure

All emulsions were tested at five different temperatures (12, 16, 20, 25 and 30°C) using two measuring systems (system A and B). The measuring system used depended on the number of points considered sufficient to plot the shear stress/shear rate curve. (Ten points were assumed to be adequate).

The emulsions were heated or cooled to the required temperature by placing them, for a sufficient time (not less than one hour), in an oil bath. They were then transferred to the appropriate measuring cylinder and after 10-15 minutes period of rest they were tested at various shear rates.

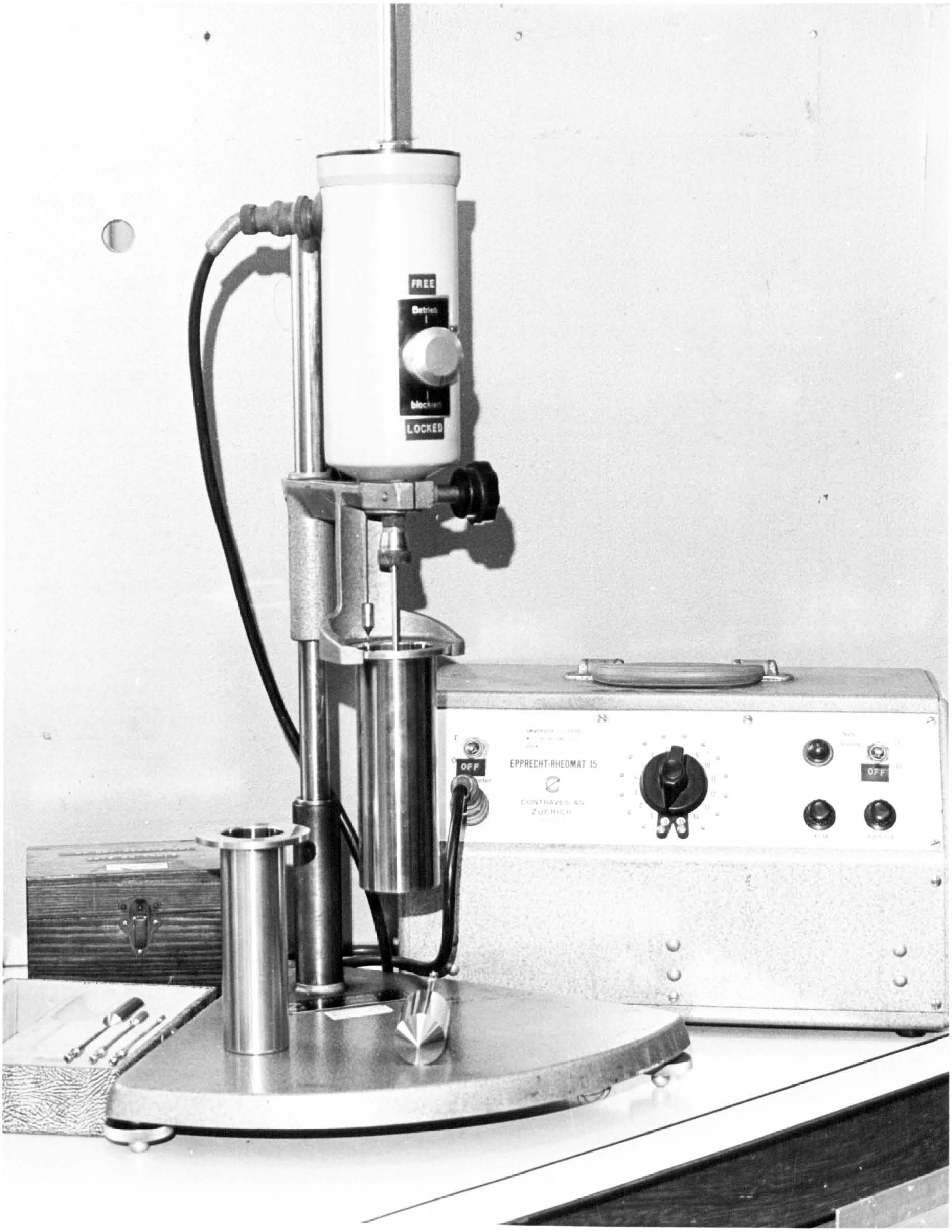


Plate 5.1 The Epprecht Rheomat 15

The shear rates were applied according to the following shearing cycles:

Cycle 1. The shear rate was increased from zero to a maximum shearing force allowed by the system at intervals of 30 seconds and it was then decreased to zero again at the same intervals. Readings of the shear force in the system's scale units were taken at each of the above intervals.

Cycle 2. This cycle was carried out after 15 minutes of rest, allowing thixotropy, if any, to build up again. Readings were taken at the same intervals, starting from the maximum shear rate obtained in the previous cycle.

Cycle 3. A further 15 minutes of rest was allowed before cycle 2 was repeated.

The above shearing cycles were applied in order to examine the effect of shearing rate and time on the viscosity of the emulsion and hence to determine their Newtonian or non-Newtonian behaviour.

5.2.2. Glass capillary viscometer

Kinematic viscosity measurements were carried out by using the Reverse flow U-tube viscometer. The test procedure, the calibration of the tubes and the calculations of the viscosities were carried out in accordance to BS 188:1977 (180).

Plate 5.2 shows two glass capillary viscometers assembled in an oil temperature controlled bath. The one on the right hand side is the reverse flow type, used for the viscosity measurements, and the one on the left is a glass viscometer used for calibration purposes.

5.2.3. Engler viscometer

The Engler viscometer is the standard viscometer used by the road

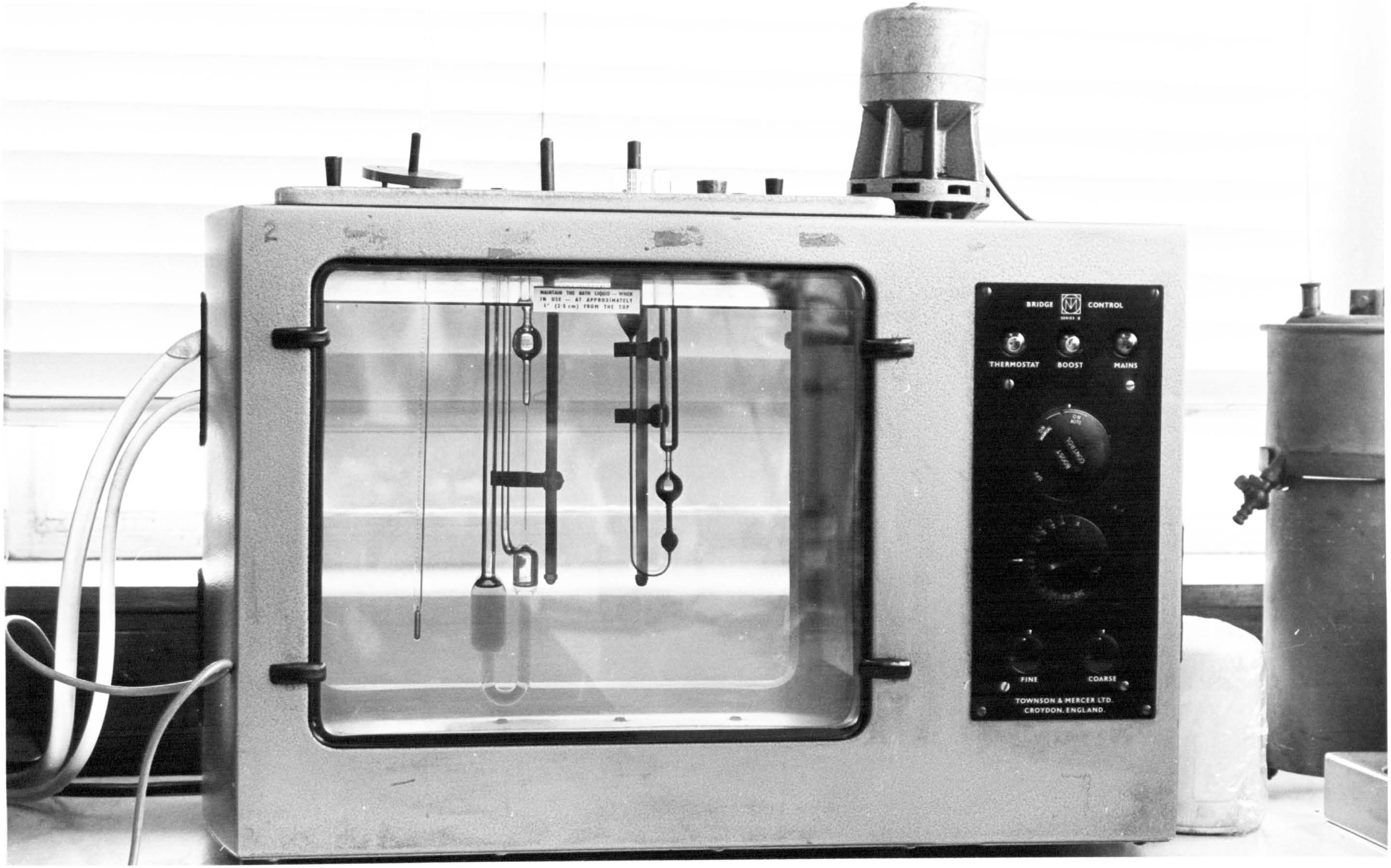


Plate 5.2 Glass capillary viscometers

industry for the classification and determination of the viscosity of the emulsions, in arbritary units of Engler degrees (^{o}E).

The test procedure which has been followed in this part of the research study is the same as the one proposed by British Standards BS 434 Part 1 (45).

5.3 Preparation and testing of the emulsion treated mixtures

The preparation and testing procedure was divided into three stages and is shown in Fig. 5.1. In the first stage the suitability of the emulsion was examined and an estimation of the amount of water needed to be added to the aggregate was obtained. In the second stage the chosen emulsion was mixed with the aggregates. The mixture was dried at 60^{o}C in a forced draft oven for a certain period of time until the desired moisture content for compaction was reached and finally compacted into specimens of 101.6mm in diameter and approximately 62.5mm in height. In the third and final stage, the evaulation of the properties of the mixture was carried out, leading to the determination of an optimum binder content.

5.3.1. Suitability of the emulsion - Stage one

The suitability of the emulsion, for a given aggregate type and aggregate gradation was judged in terms of the degree of coating of aggregates and the breaking time of the emulsion.

5.3.1.1. The coating test

Batches of 250gr. of the aggregates, carefully dried and blended to the required size distribution, were prepared for the coating test.

Each batch was then placed into a mixing bowl of 200mm in diameter, water was added to the aggregate and mixed thoroughly. Mixing was

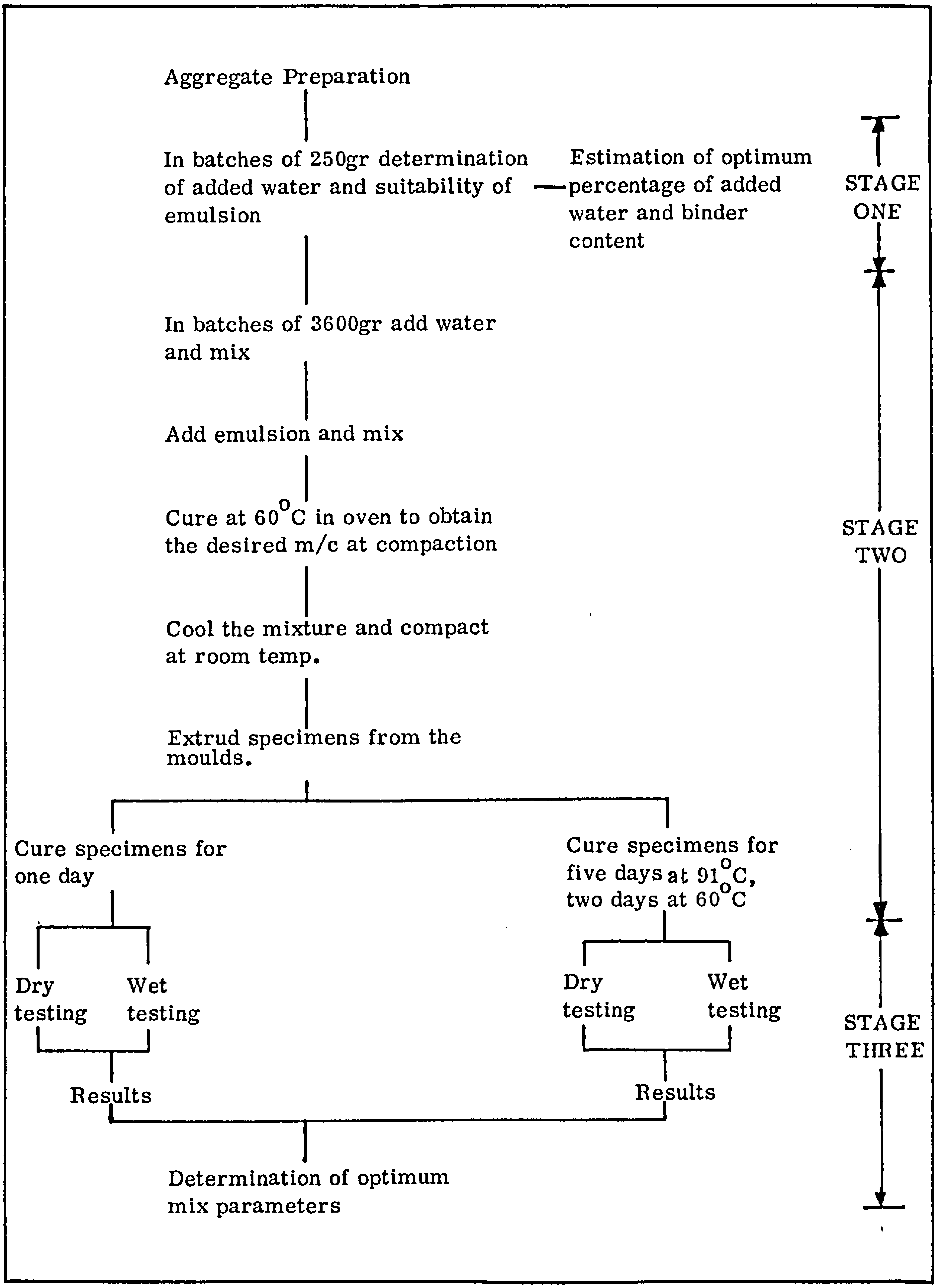


FIG. 5.1 FLOW CHART FOR PREPARING AND TESTING THE EMULSION TREATED MIXTURES

carried out manually, using a spoon, for a minimum time of one minute. The required amount of bituminous emulsion was then added to the wet aggregate and mixed thoroughly for a minimum of 30 seconds. Immediately after mixing, observations were made on the percentage of coating of the aggregate by a visual inspection of the aggregate surface. Any mixture with less than seventy five percent (75%) coating was rejected at this stage. Successful mixtures were then divided into five, approximately, equal parts and placed on a flat non-absorbant plate or container. The containers were left at room temperature and checked at hourly intervals for final breaking of the emulsion. The final breaking was determined by washing off the mixture with tap water and observing the colour of the water. When the water was clear, final breaking had occurred. The time taken for final breaking to occur was recorded. Mixtures which required more than six hours for final breaking to occur, under the above-mentioned conditions, were rejected.

The percentage of water added to the aggregate was varied, for all tests, from zero to six percent by weight of dry aggregate.

The percentage of binder and hence the percentage of emulsion added to the aggregate was varied around the estimated optimum binder content, as if the mixture was a conventional hot bituminous mixture. Mixtures which required more than five percent binder above the estimated optimum were rejected as being uneconomic.

All the above requirements made it possible not only to eliminate the number of theoretically suitable emulsions to one but also to reduce the great number of combinations between percentage of water and emulsion to a manageable size.

5.3.2. Mixing, Curing and Compaction of the Cold Rolled Asphalt C.R.A.) and Dense Emulsion Macadam (DEMc) mixtures

5.3.2.1. Mixing

The aggregate, sand and filler, dried for 24 hours at 110°C, were blended in suitable proportions so as to produce 3600 gr batches with particle size distribution satisfying the specifications. Each batch was then placed in a mechanical mixer and water was added. The contents were mixed thoroughly for between 2 and 3 minutes. (It should be noted at this stage that care should be taken not to continue mixing for more than 5 minutes since this may result in evaporation of water).

Emulsion was then added to the wet aggregate and mixing continued for a further 1½ to 2 minutes. After the first 30 seconds, mechanical mixing was interrupted for a short period and a hand scoop was used in order to prevent segregation of the aggregate. Mechanical mixing was then resumed and the mixture was checked at 30 second intervals.

Excessive mixing time - i.e. longer than 2 minutes - should be avoided due to the possibility of "balling" and "stripping". It was found that certain mixtures, particularly those with a high binder content were prone to "balling".

The mixture was then transferred into pre-weighed trays of 330 x 280 x 50mm in dimensions and was assessed for degree of coating.

5.3.2.2. Curing prior to compaction

Curing prior to compaction was necessary due to the excessive amount of total liquid present in the mixture. It has been shown, Table 6.1, that the minimum total liquid content for 75 percent coating was 11.10 percent, for CRA mixtures, and 6.70% for DEMc mixtures. If a better coating was required these total liquid contents could go as high as 21.50 and

11.90 percent for CRA and DEMc mixtures respectively.

The low voids mixtures, in particular, could not accommodate such a percentage of total liquid in their voids. When C.R.A. mixtures were compacted at various liquid contents it was found (Fig.5.2) that after a certain liquid content, at a given binder content, compaction became very difficult, and there was an increase in total voids. The difficulty in compaction could be seen in terms of rate of change in total voids. It can be seen that for 12% binder content any increase in total water above 3% reduced the rate of reduction in total voids and the mixture after final compaction possessed a higher percentage of total voids. Similar results, but to a lesser degree, could also be seen at 9% and 7% binder content mixtures. This is because the water quickly filled up the available air voids, at the early stages of compaction, and the excessive amount resulted in hydrostatic pressures. These pressures resisted compaction, pushing away the aggregate particle, resulting in higher voids mixtures.

The effect of total liquid content (water + binder) at compaction on the bulk density of C.R.A. mixtures can be seen on Fig.5.3. This figure shows that a maximum bulk density may be obtained at approximately 11% total liquid content. This value is lower than the range of total liquid content required for optimum mixing (12.95% to 21.58%). It must be noted that compaction at a lower total liquid content was not attempted ? because the reduction in total liquid content would require longer periods of drying the mixture, to remove the moisture, and this would not be economically feasible. ?

The behaviour of D.E.Mc mixes, however, was different than the behaviour of the CRA mixes. These mixtures, in general, have higher percentage of air voids and consequently should be able to accommodate more liquid. The total liquid content at mixing was found to vary between 8.16 and 11.9 percent. When mixtures were compacted at the above total

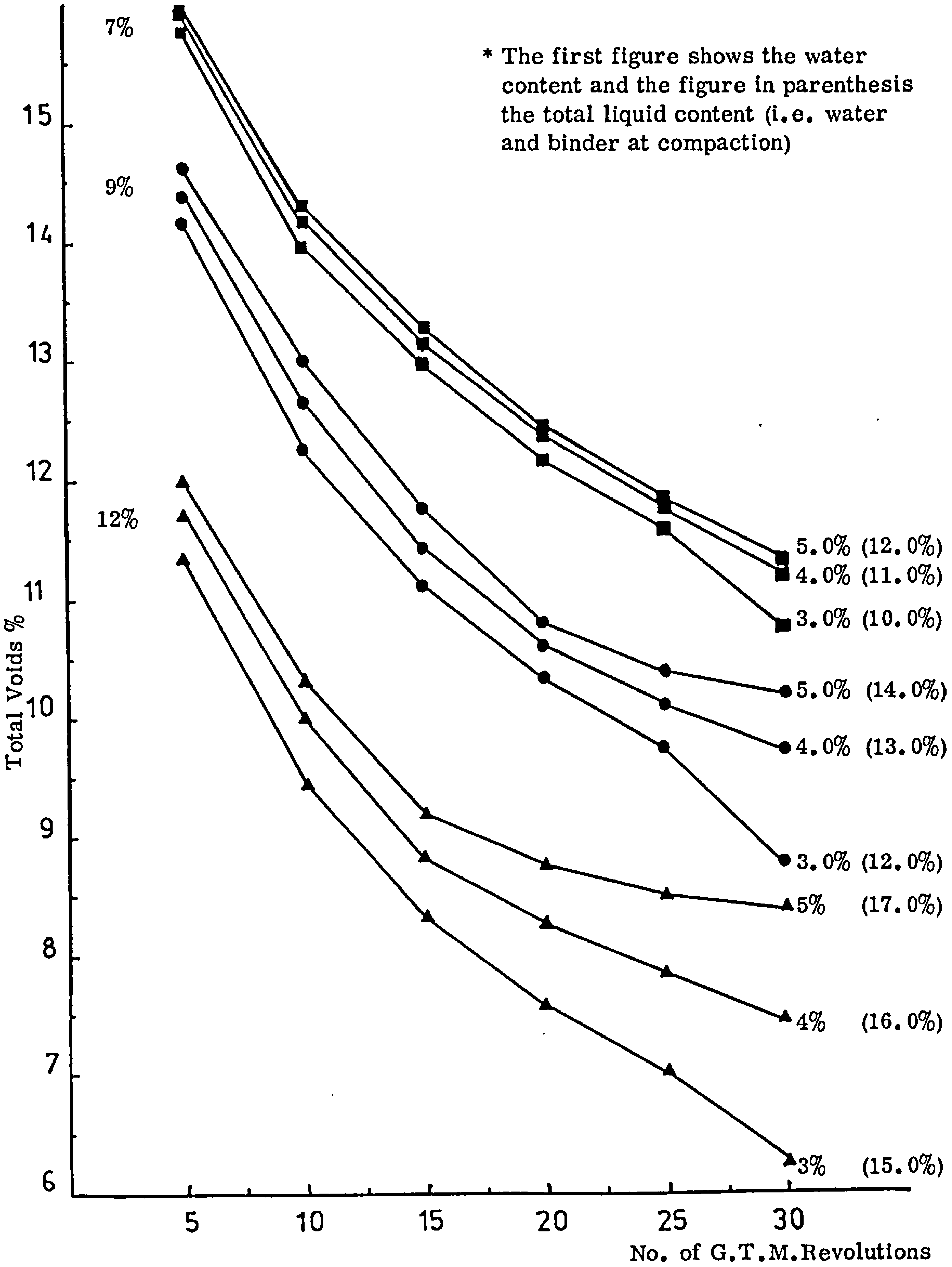


Fig. 5.2 C.R.A. COMPACTION CURVES - THE EFFECT OF LIQUID CONTENT AT COMPACTION, ON THE TOTAL VOIDS

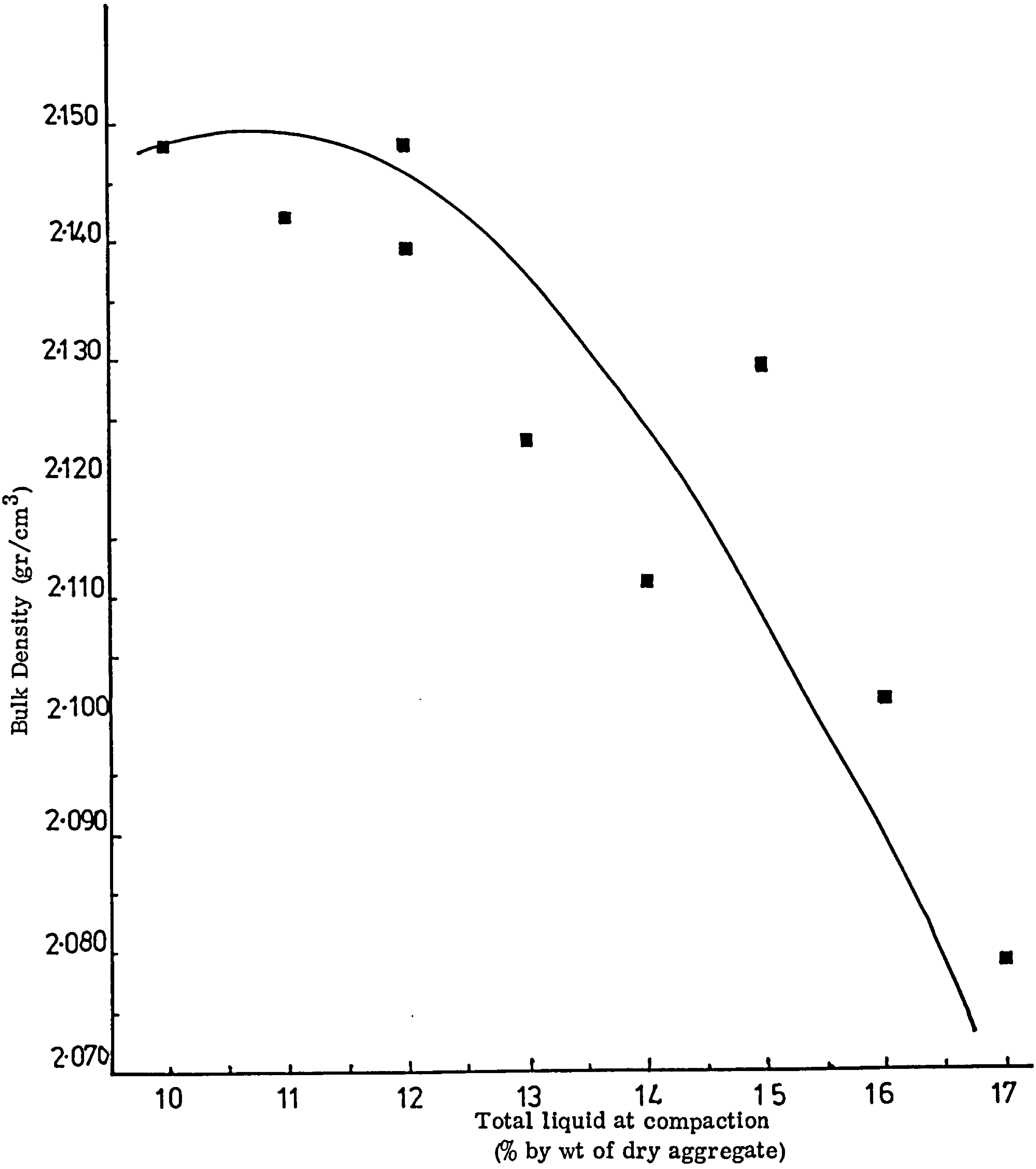


Fig. 5.3 BULK DENSITY v TOTAL LIQUID AT COMPACTION - C.R.A.

(Compaction by G.T.M. at 30 revs and 1° angle of gyration) liquid contents it was discovered that good compaction could be obtained and that there was no free water running out of the specimen during compaction. The compaction curves, shown in Fig. 5.4, revealed that for a given binder content, an increase in total water content results in mixtures with lower total voids. This effect was more pronounced at mixtures with low binder contents. In fact, mixtures with a high binder content (6.5%) showed the opposite effect.

The above behaviour of DEMc had an effect on their bulk densities. It can be seen, Fig. 5.5, that the bulk density was increased as the total liquid content increased, until a maximum value was reached. This maximum was obtained at approximately 10.5% of total liquid content.

It was, therefore, apparent that if compaction was going to be carried out at the optimum or near optimum liquid content for maximum bulk density a certain amount of water had to be evaporated. Kari (63) after an extensive field study, recommended that the total moisture content of the emulsion-treated base course mixtures should be less than three percent prior to the construction of the surfacing layers. Darter et al (60) have shown that for continuously graded mixtures the total liquid at compaction for maximum bulk density did not coincide with that of maximum stability. The total liquid content at compaction for maximum stability was always less than for maximum bulk density.

In view of the above and in order to examine the effect of binder content and added water on the properties of emulsion-treated mixtures, irrespective of the water content at compaction, it was decided to cure all the mixtures until they reached a total water content of 3.0 percent.

The required level of total water content was obtained by placing the pre-weighed mixture immediately after mixing in a 60°C ventilated oven. The three percent water content was determined by recording the weight loss at regular intervals of time.

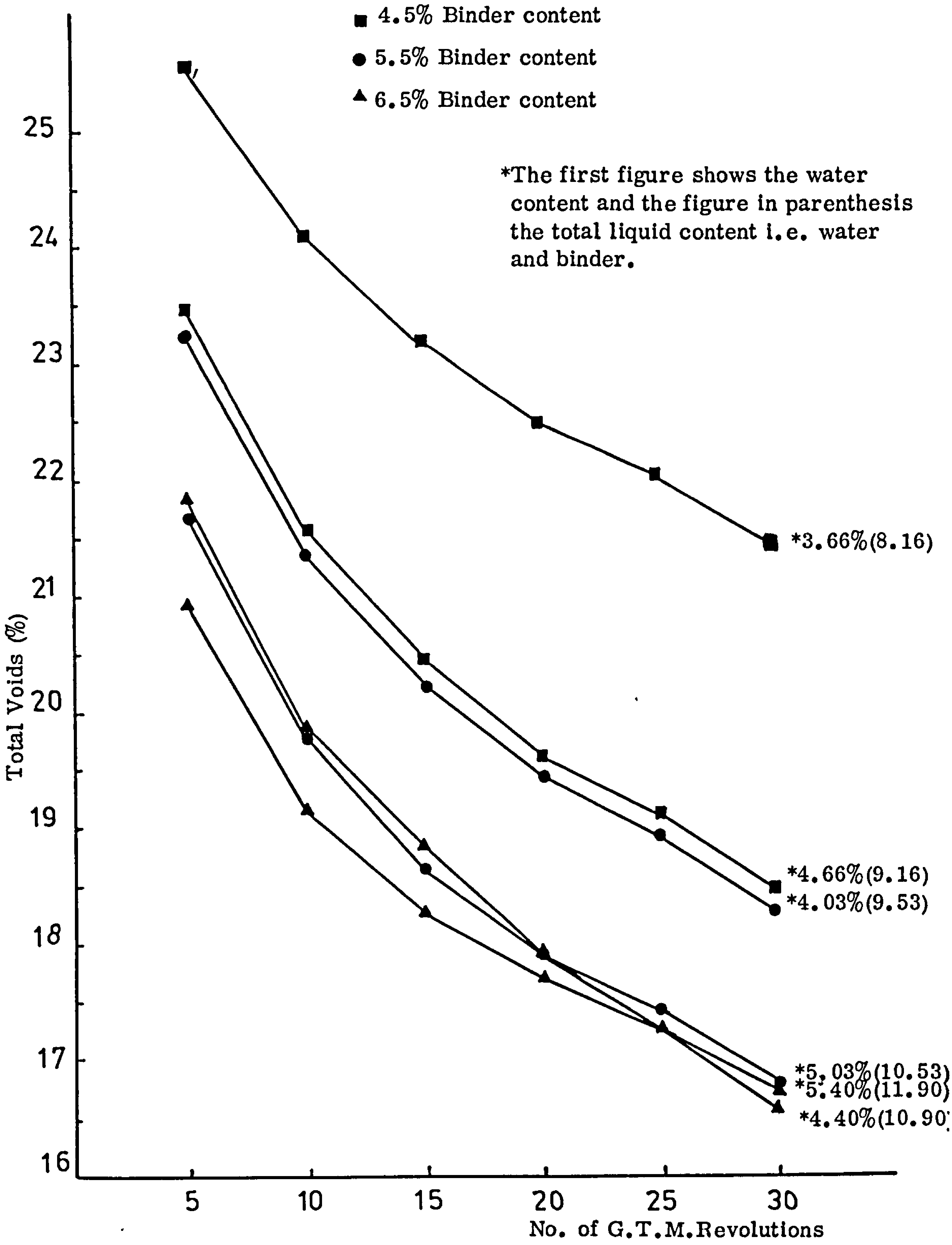


Fig. 5.4 D.E.M_C COMPACTION CURVES - THE EFFECT OF LIQUID CONTENT AT COMPACTION ON THE TOTAL VOIDS

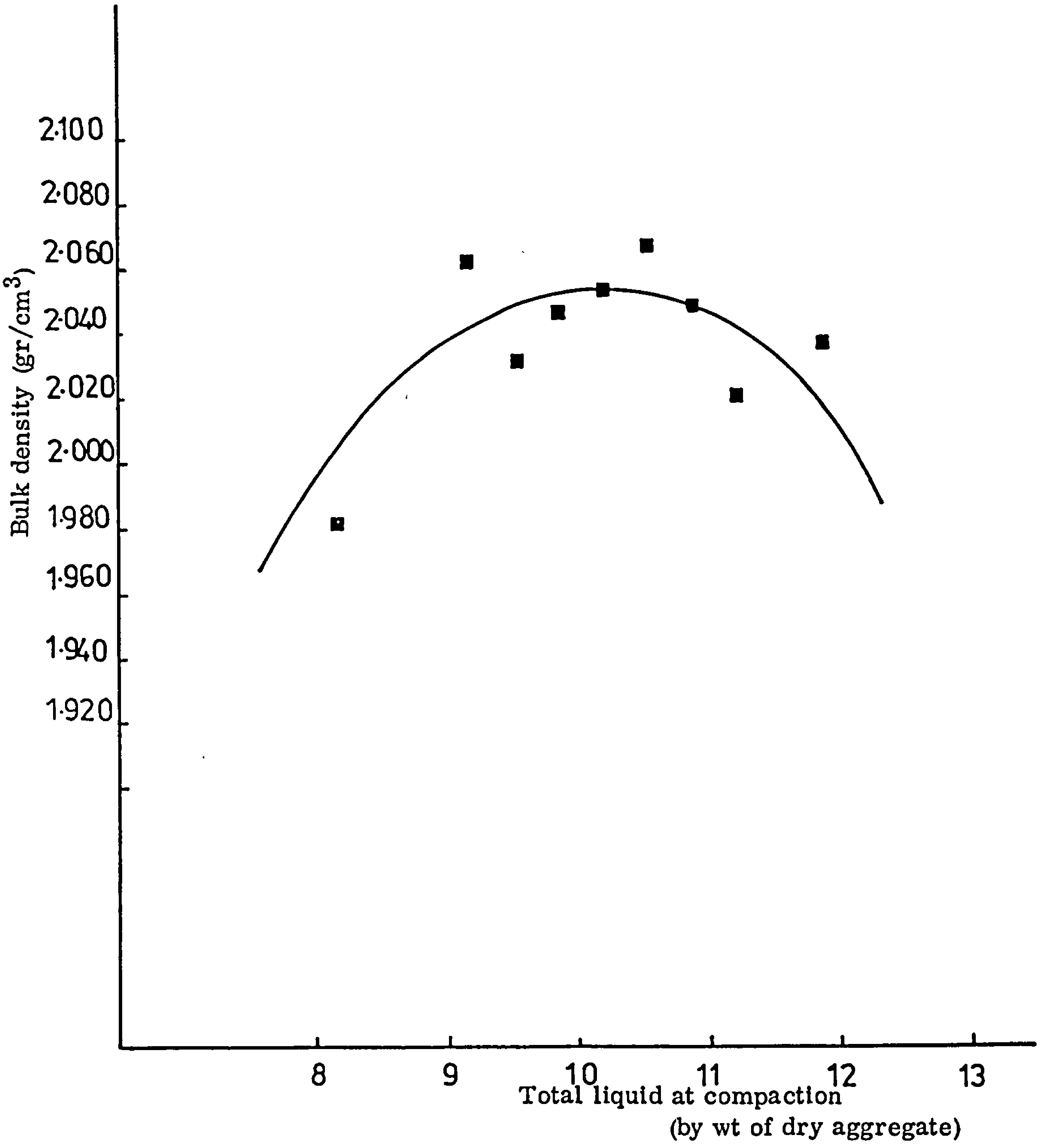


Fig. 5.5. BULK DENSITY vs TOTAL LIQUID CONTENT (D.E.Mc)

The mixture was then allowed to cool down to room temperature prior to compaction, with allowances being made for a further weight loss during this stage.

5.3.2.3. Compaction

All specimens were compacted at room temperatures, 21°C ± 1°C, using a fixed roller Gyratory Testing Machine (G.T.M.), Plate 5.3. The G.T.M. was developed by the Corps of Engineers, U.S. Army (181) for the purpose of simulating field compaction under laboratory conditions and for the selection of an optimum binder content (182). The G.T.M. shown in Plate 5.3 is a combination of kneading compaction and dynamic compaction machine. It has been reported (182) that G.T.M. produced specimens, which had stress-strain characteristics, much closer to the actual pavement samples than the impact-compaction method (Marshall compaction). Busching and Goetz (183) added that G.T.M. produced specimens with a greater uniformity than other laboratory compaction methods.

The use of G.T.M. for the selection of the optimum binder content was examined by Kallas (184). He concluded that the optimum binder content selected by G.T.M. is essentially the same as the ones determined by the Marshall and Heem methods. The determination of optimum binder by G.T.M. was based on the sudden increase of the angle of gyration during compaction, shown on the gyrograph, called "flushing". Ruth and Schaub (185) however, expressed their doubts about the sensitivity of the gyrograph, and showed that flushing was also proportional to material type and gradation.

The latest work by Kumar and Goetz (186) confirmed the suggestions made by Kallas (184) and as a result it is now considered as standard method of compaction and pavement evaluation (187).

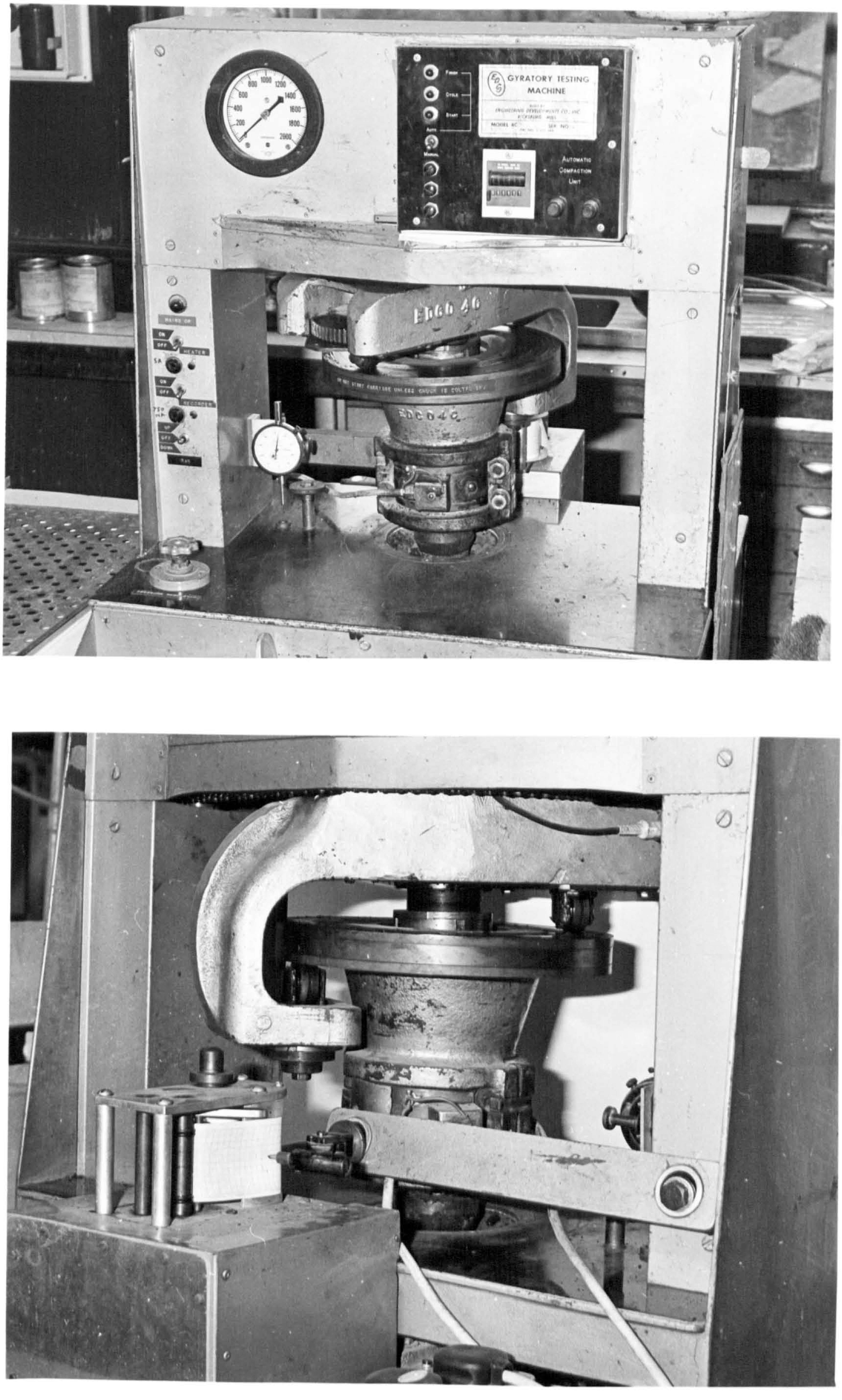


Plate 5.3 The Gyratory Testing Machine (G.T.M.)
the front and the back view (top and bottom picture)

The emulsion-treated mixture, after reaching the 3 percent water content, was placed in three equal layers into a 101.6mm diameter mould. Each layer recieved 15 blows by hand using a 12.5mm diameter steel rod. The top and bottom surface of the specimen was covered with filter paper to prevent any aggregate sticking to the upper and lower plate of the machine during compaction.

Compaction was then carried out using 1.38MPa(200 psi) ram pressure, 30 revolutions (plus three at the end for leveling off) and 1° angle of gyration. This compaction , as suggested by McRae and McDaniel (182) and confirmed by Ruth and Schaub (185) corresponds to 75 Marshall blows, and is normally classified as heavy compaction.

During compaction the reduction in height of the specimen was recorded at every five revolutions for subsequent use in calculations of total voids changes during compaction. An example of how to calculate the void content at every five revolutions is given in Appendix C.

The compacted specimens were extracted almost immediately from the mould by means of a hydraulic extrusion jack. It should be noted that at no time, during the series of tests, did any of the compacted specimens collapse. On the contrary, if specimens were left in the mould for more than two hours after compaction, then higher extrusion forces were required which caused a noticable doming effect on the specimens. This was due to high frictional forces between the specimens and the walls of the mould. Doming of the specimens could affect the results of subsequent tests such as permeability and creep test.

After extracting the specimens from the mould, the filter paper was removed from either side of the specimens, the specimens were weighed in the air and were then placed sideways in perforated trays to be cured before testing.

An examination of all gyrographs obtained from the compaction of specimens used in this study revealed that flushing could be seen only on some of the gap-graded mixtures and in none of the continuously graded mixes. This reinforces the findings of Ruth and Schaub (185) that flushing was proportional to aggregate gradation. A typical set of gyrographs is shown on Figure 5.6 for gap-graded mixtures and on Figure 5.7 for continuously graded mixtures. Whether or not the flushing which occured at 10 percent binder content on the gap-graded mixtures coincides with the optimum binder content will be examined later in Chapter 8.

5.3.2.4. Curing (of the specimens) prior to testing

Two levels of post-compaction curing were used throughout the research programme representing the early and final stage of curing.

The early stage of curing was obtained after one-day air-curing at controlled air temperature and humidity levels. The room temperature was $21^oC \pm 1^oC$ and the humidity 65 degrees.

The final stage of curing was obtained after five days air-curing at room temperatures, followed by two days air curing in an air ventilated oven at 60^oC.

It was found that under the above laboratory conditions water loss principally took place at the very early stage of curing (during the first week) see Figures 5,8 and 5.9. It can be seen that even after twenty-eight days of air curing followed by two days in the oven at 60^oC there was still some water remaining in the system. This water was absorbed by the aggregate or/and trapped under the binder film and disconnected air voids. The amount of water remaining in the system was found to be dependent on the type of aggregate gradation and binder content. Gap-graded mixtures were found to retain more water content than dense graded mixtures and

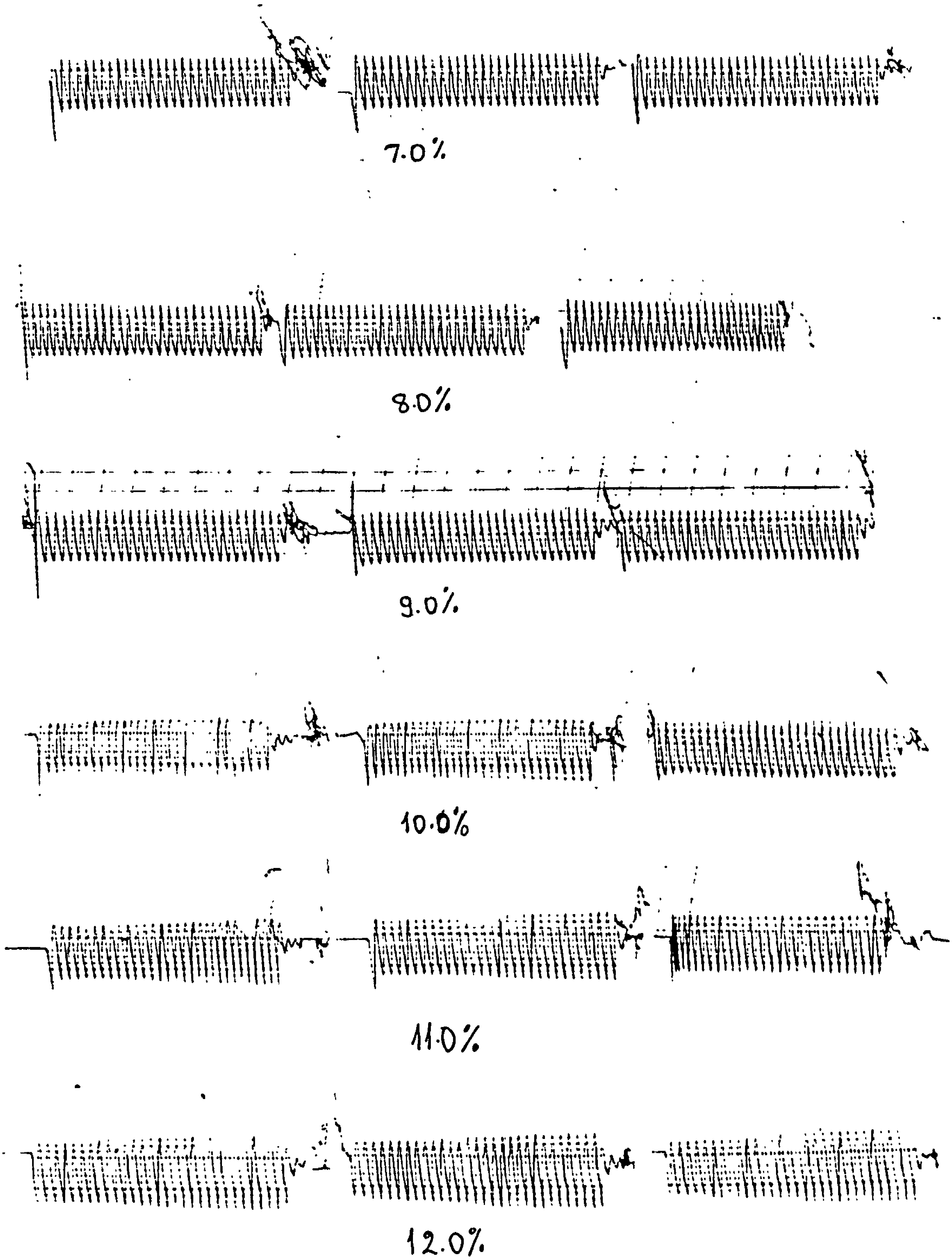
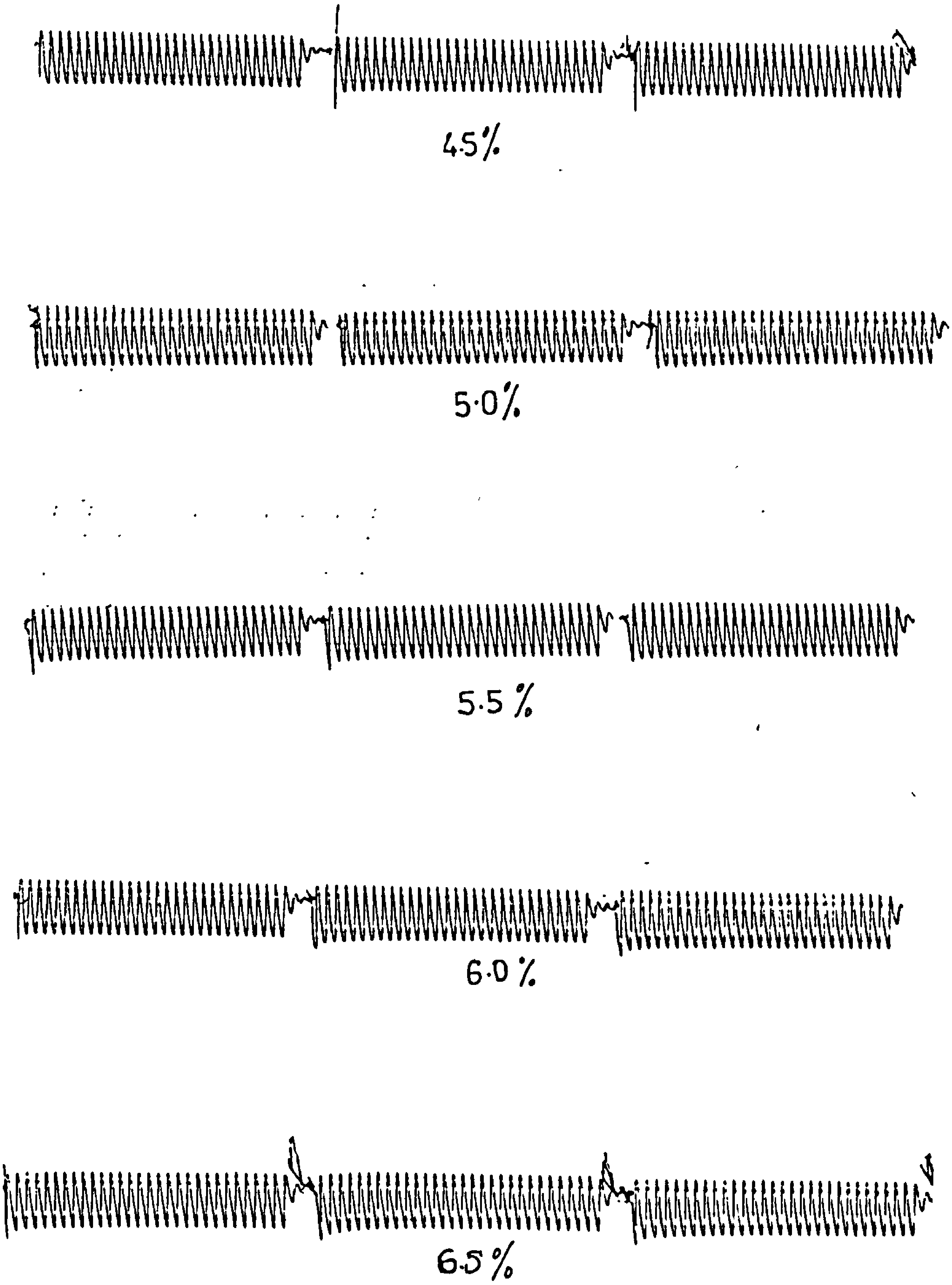


Fig. 5.6 G.T.M. GRAPHS (6 levels of Binder Content) C·R·A



4.5%

5.0%

5.5%

6.0%

6.5%

Fig. 5.7 G.T.M. GRAPHS FOR D.E.Mc AT 5 BINDER CONTENTS

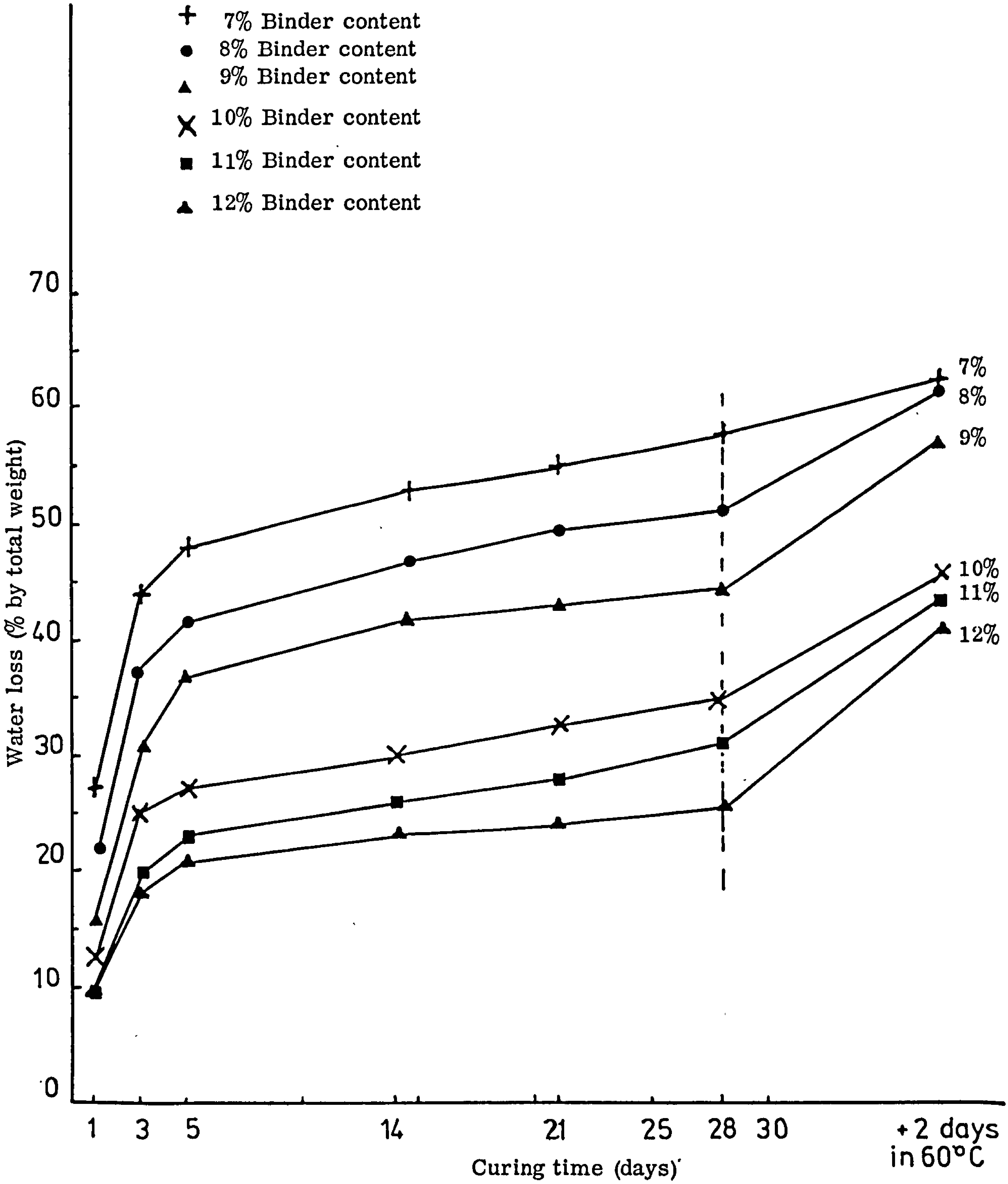


Fig. 5.8 PERCENTAGE OF WATER LOSS DURING CURING - C.R.A
(Curing at room temperature 21^{o}C and 65 degrees humidity)

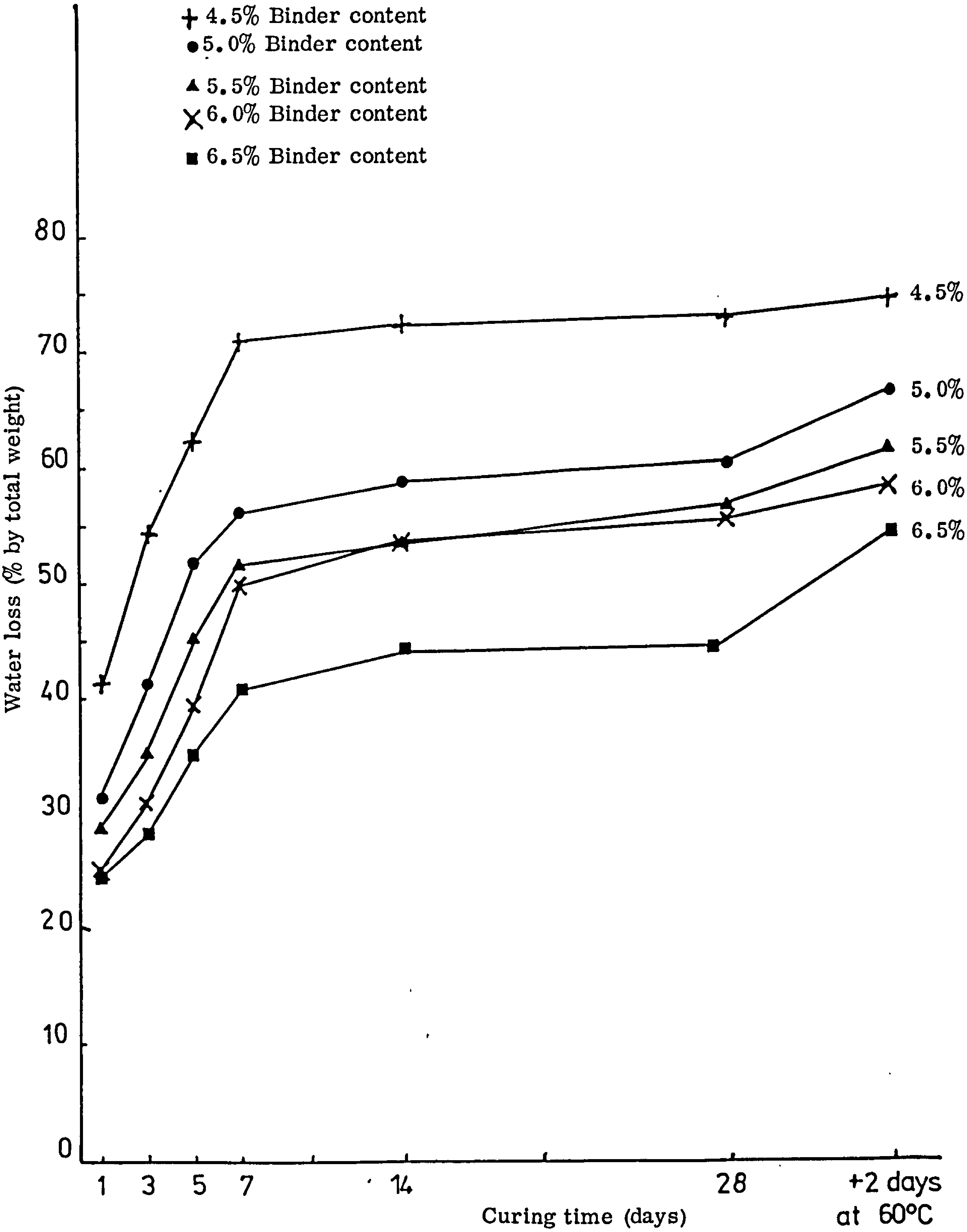


Fig. 5.9 PERCENTAGE OF WATER LOSS DURING CURING - D.E.Mc

Environmental conditions: Room temp: 21°C ± 1°C

Humidity: 65 degrees

in both cases the higher the binder content the greater the amount of water retained.

5.3.3. Determination of the properties of the mixtures

This is the final stage of the preparation and testing procedure outlined in Fig. 5.1. The determination of the properties of the emulsion-treated mixtures was obtained by carrying out three tests: The modified Marshall test, the Permeability test and the Static creep test.

5.3.3.1 The modified Marshall test on dry specimens

The apparatus used for carrying out the modified Marshall test was the conventional one, used for hot bituminous mixtures. A detailed description of the apparatus is given in reference (69). The test was called the modified Marshall test because the compaction and testing conditions were different. The compaction, as it was mentioned earlier on, was carried out by using the Gyratory Testing Machine (G.T.M.) and the temperature at testing was $21^oC \pm 1^oC$.

The stability values of the dry specimens were corrected for difference in sizes by using the correction factors given in reference (49), a copy of which is shown in Appendix D.

The formulae used for calculations of compacted bulk density, compacted aggregate density, theoretical maximum density, percentage of voids in the mixture and percentage of voids in the mineral aggregate, are all given in Appendix B.

5.3.3.2 Modified Marshall test on soaked specimens

A modified Marshall test was also carried out on specimens which had been exposed to water (capillary soaking). The procedure of testing was the same as before but the resulting stability and flow was called wet stability and wet flow. The ratio between wet stability over dry stability was called retained stability and it was used as an indication of water damage to the specimen.

5.3.3.2.1. The soaking test

Soaking due to capillary suction took place under normal atmospheric pressures at a room temperature of $21^{0}C \pm 1^{0}C$. (Plate 5.4)

The cured specimens were placed in a bath filled with water, to a depth of 25mm and to facilitate the one way movement of water, the specimens were sited on a layer of coarse clean sand (free of clay). To avoid evaporation the containers used for the soaking test were kept covered throughout the period of the test.

The specimens were left to soak for a total of 96 hours, (48 hours each side). They were then removed, surface dried and weighed before testing, in order to determine the amount of water absorbed during soaking.

It must be noted that the specimens were soaked without the confinement of moulds. This was done to ensure that there was no disturbance of the matrix of the specimens, and also no water loss or damage during extraction from the moulds.

Gadallah (61) carried out a comparative study between capillary soaking and two types of vacuum soaking tests. He concluded that, for the type of gradation used in his study (continuously graded mixture) the capillary soaking test, as proposed by the Asphalt Institute (49) was more severe than the two vacuum soaking tests, proposed by the Chevron Asphalt company (95) and the Asphalt Institute (93). Later studies by

Plate 5.4 Capillary soaking test - specimen arrangement

Darter et al (66) showed that statistically there was no significant difference between capillary soaking and vacuum soaking for the stability or the resilient moduli. They also pointed out the advantage of the capillary soaking over vacuum soaking, which was based on the simplicity of the method and the use of inexpensive equipment.

It must be noted that the difference between the test recommended by the Asphalt Institute (49) (capillary soaking test) and the capillary soaking test used in this study was that the specimens were not confined by their moulds. This, although might have resulted in a more severe test, due to the absence of confinement, it had the advantages, as mentioned earlier on, of avoiding possible damage and water loss during extraction of the specimens form their moulds.

5.3.3.3. Permeability measurements

The significance of the permeability of bituminous pavements on their properties, as explained in Chapter 3, led to the development of a number of permeameters. A survey carried out by Gilbert and Keyser (188) indicated that 15 types of permeameters were actually in use in North America and Europe. They can be classified in terms of the liquid used (air or water) to permeate through the bituminous mixture.

The first air permeameter was developed by Ekse and Zia (97). It was a very simple device, measuring permeability by recording the time required for the air to escape through the specimen or the pavement, until the air pressure in the champer was dropped from 4 psi to 0.5 psi. A more sophisticated apparatus was proposed by McLaughlin and Goetz (102), in which a volume of air was passing through the specimen under the influence of a positive pressure difference. The apparatus, although reliable, was very complex and could not be used on site. Ellis and Schmidt (110) a few years later, developed a new air permeameter, which was much easier to operate than the McLaughlin and Goetz type and it could be used either in the laboratory or on site. The permeameter measured the air flow passing through the specimen, or pavement area, covered by a glass dome under a low negative constant pressure. The negative pressure (vacuum) was created by a falling head of water. This apparatus was found to be very popular and was used by various investigators in its original form (103, 106) or slightly modified (101, 190).

Water permeameters with a constant or variable head were also used successfully by various investigators (111, 189) and although these were the only ones measuring the true coefficient of permeability, their use was limited to very impervious material (188). If they were to be used with emulsion treated mixtures, the water would cause some structural damage, which might affect the results. Gilbert and Keyser (188) carried out a compartive study between air and water permeameters and found that water permeameters generally give significantly less permeability values than the air permeameters. It was reported that in some cases when the test was performed on core specimens the difference was as high as 14 times (the variability was better when laboratory specimens were used i.e. only 8 times).

In this study, the permeability of emulsion treated mixtures was measured using an air permeameter. The apparatus used was built at Leeds University (190) and it is the same, in principal, as the apparatus developed by Ellis and Schmidt (110). A brief description and the procedure used is given below.

5.3.3.3.1. Description of air permeameter and test procedure

The apparatus shown on Plate 5.5 consists of a water manometer, a cylindrical mould open at both ends (102.0mm) in diameter, a glass dome of 101.6mm diameter and 150mm in length, a 1 litre capacity water container, a measuring cylindrical flask and a stop watch. The flow of water from the water container is controlled by sensitive tap which allows

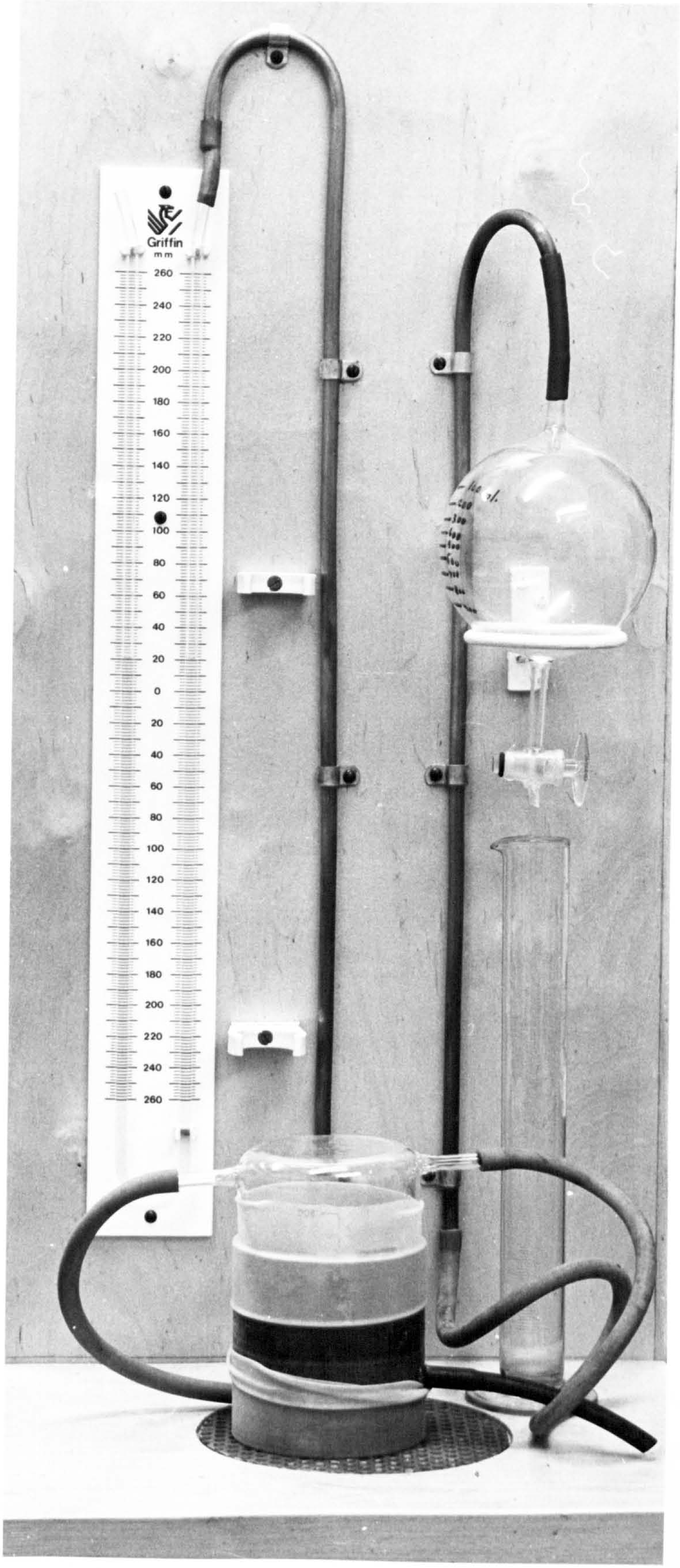


Plate 5.5 Constant Head Air Permeameter

close control of a predetermined pressure differential.

The sealing between the specimens, the mould and the glass dome was secured by two thin rubber membranes. They were placed inside the steel cylinder and folded over the top and bottom edges of the mould. The air trapped between the membranes and the mould was removed by suction through a pipe fixed to the middle of the mould.

The specimen was placed into the mould and the glass dome was placed at the top, seated firmly on the inside groove of the mould. A very thin layer of silicon grease was spread around the glass dome, and the two membranes were folded over the dome and the mould to provide the sealing (see Plate 5.5).

The mould containing the almost self supporting specimen (the specimen support was assisted by a small tripod) was placed over a wire mesh to allow a free flow of air. A vacuum was then applied at the top of the specimen, by opening the water tap. Various negative pressures could be obtained but for simplicity only three were used throughout the tests, 5.08 or 3.81 or 2.54 cm of water, depending on the permeability of the specimens. If possible, only one pressure differential of 50.8mm of water was used, in order to eliminate possible error due to pressure differential.

When the pressure differential had been stabilised at the required level, the time required by 50cc of water to flow through the tap was recorded. It was assumed that the volume of water flowing through the tap at any given moment, after stabilising the pressure differential, was equivalent to an equal volume of air flowing through the specimen. It was, therefore, possible to determine the rate of air flow through the specimen and hence the air permeability of the specimen by using the following formula, as defined by Wyckoff et al (191).

$$K = \mu \times V \times L/(A + \delta P + \delta t) \qquad \ldots\ 5.1$$

where K = permeability (cm^2)

μ = viscosity of fluid (air), (poise)

V = volume of fluid passing, (cm^3)

L = length of porous medium, (cm)

A = area of porous medium, (cm^2)

δP = differential pressure, (dynes per cm^2)

δt = time taken for fluid with volume V to pass through the porous medium, (secs)

For specimens with 10.16cm in diameter, air viscosity equal to 1.853×10^{-4} poise at 20°C, and volume of fluid equal to $50 cm^3$ the equation 5.1 becomes:

$$K = 1.143 \times 10^{-4} \times L/(\delta P \times \delta t) \qquad \ldots\ 5.2$$

Since δP was measured in (cm) equation 5.2 becomes:

$$K = 1.143 \times 10^{-4} \times L/(980.7 \times \delta P \times \delta t)$$

or

$$K = 1.165 \times 10^{-7} \times L/(\delta P \times \delta t) \qquad \ldots\ 5.3$$

where $K = cm^2$

$L = cm$

$P = cm$

$\delta t = sec$

The permeability values measured in cm^2 can be converted to a coefficient of water permeability (cm/sec) at normal temperatures, by multiplying them by the factor of 10^5 (102).

5.3.3.4. Creep deformation

The creep deformation of the mixtures examined in this study was measured by employing the static uni-axial constant load test, known as the Creep test.

The test was carried out using a new apparatus, called CANIK UL, designed and built in the Department of Civil Engineering, University of Leeds.

The CANIK UL apparatus, shown on Plate 5.6, differed from the four other apparatuses reviewed by Hilster and Van de Loo (151), with respect to load application. The full load was applied directly to the specimens with a hydraulic jack using compressed air, instead of using yoke or lever arm system.

The type of loading arrangement and the relatively small temperature controlled chamber made the apparatus portable and easy to operate under any environmental conditions in a laboratory or on site. The only requirement was the supply of compressed air and electricity.

5.3.3.4.1. Description of the apparatus

The CANIK apparatus, shown on Plate 5.6, consists of two hydraulic jacks (2-12 psi pressure range), six dial guages (0.002mm per division), two load platens, a temperature control chamber with a built-in heating element and fan, a thermostat with an order of accuracy of 0.2°C, a thermometer with the same degree of accuracy as the thermostat and a stop watch. A 135mm single reflex lense (SRL) camera mounted on a tripod is also essential for recording the early deformation of the specimens.

The hydraulic jacks were fixed on a tubular portal frame, see Fig.5.10. A stiffener bar was placed in the middle span to avoid excessive deflections on the frame. The maximum deflection of the frame using twice the required pressure was measured and was found to be in the order of less than 0.002mm. It was therefore safe to assume that deflection from the frame did not affect the deformation readings.

Plate 5.6 The CANIK U.L. creep testing apparatus

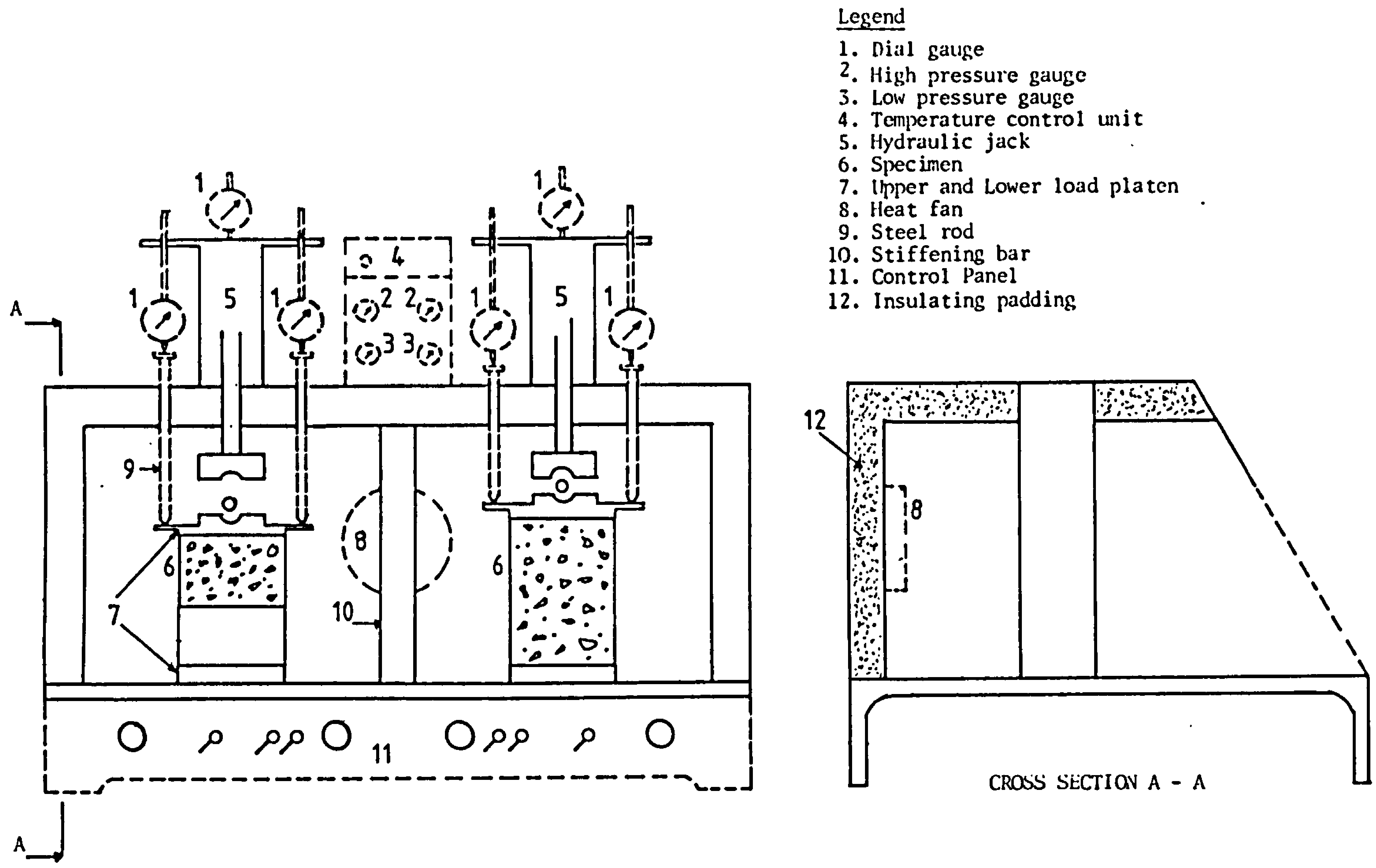


Fig. 5.10 SCHEMATIC REPRESENTATION OF THE CANIK U.L. CREEP TESTING APPARATUS

5.3.3.4.1a. The loading system

The load was applied by hydraulic jacks which were connected to the compressed air supply and to the control panel. The connections of the jacks to the air supply was made with reinforced plastic tubing to ensure flexibility while the connections to the control panel were made with copper tubing, a detailed drawing is shown in Fig. 5.11.

Two sets of pre-set pressures (load) could be selected; a high pressure under which the test was run and a low pressure for the pre-testing loading condition. The change over from low to high was done almost instantaneously and without losing contact with the specimens. After the test the hydraulic jacks were returned to their original position by operating a switch. The control panel of the CANIK UL machine is shown in detail on Plate 5.7.

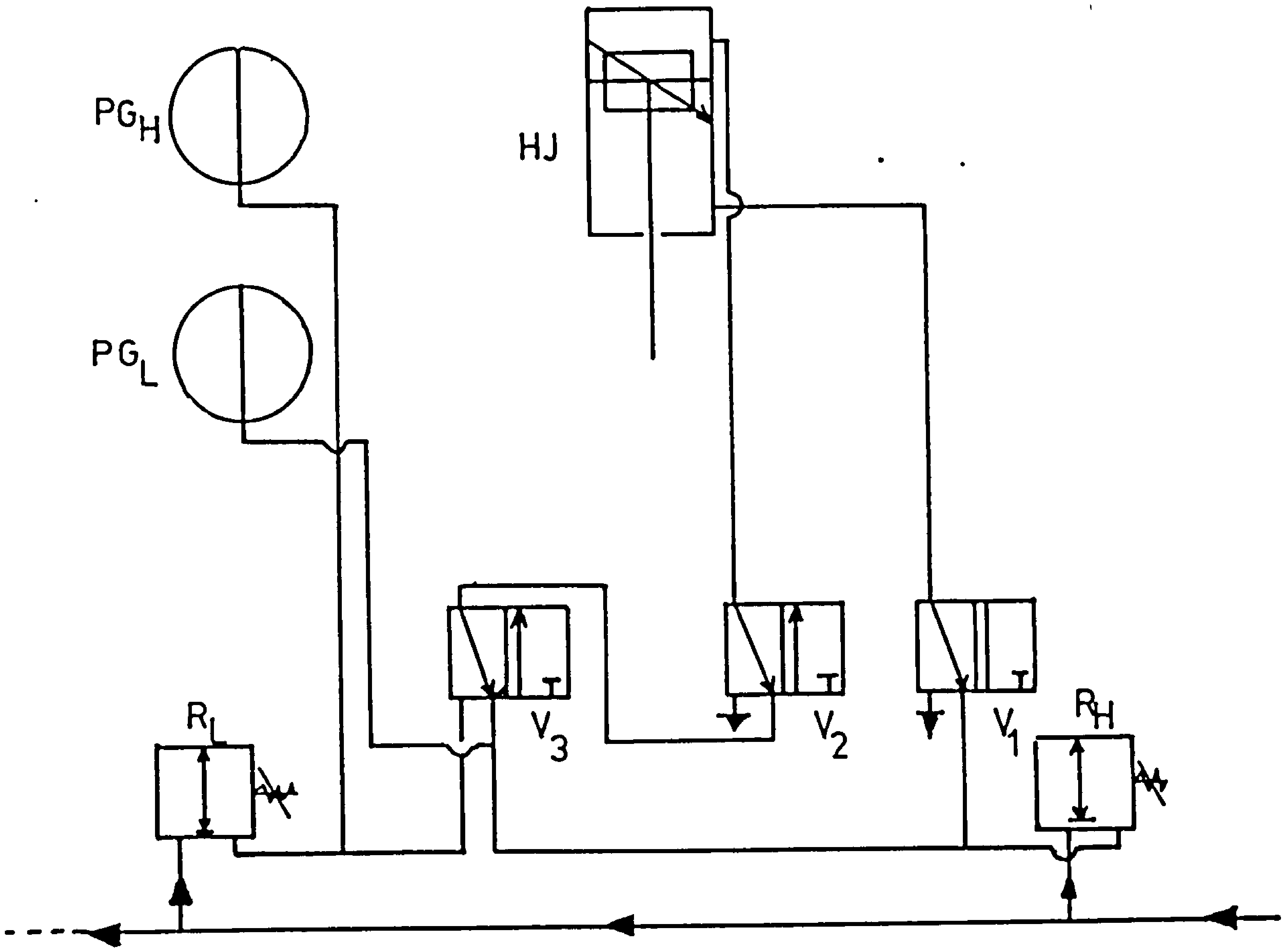
The fluctuation of the applied load was monitored at different periods, for a maximum duration of 6 hours, using a load cell connected to an amplifier. It was found to be zero, within the working pressure range, for a 101.6mm diameter specimen.

The overall system is capable of applying maximum load of 2000N to an accuracy of 3%.

5.3.3.4.1b. The load platens

The apparatus consisted of two horizontal platens; one was fixed to the base of the apparatus and the other was placed on top of the specimen.

The upper load platen had a centered hardened steel ball joint, enabling it to adjust to non-parallel specimen surfaces. It was also acting as a hinge and therefore there was no moment acting at the upper surface of the specimen. Both platens were made of hardened stainless steel, and the surfaces were highly polished in order to eliminate frictional forces



R_H - Regulator for High pressure

R_L - Regulator for Low pressure

V_1 - Switch for high load (testing) or low load (pre-testing condition)

V_2, V_3 - Switches controlling the upwards or downwards movement of the hydraulic jack

HJ - Hydraulic Jack

PG_H - Pressure guage for high pressure

PG_L - Pressure guage for low pressure

Fig. 5.11 PRESSURE PIPES NETWORK FOR THE CANIK U.L. CREEP TESTING APPARATUS (right hand side only)

Plate 5.7 Temperature chamber and control panel of CANIK U.L. apparatus

between the platens and the specimen. The platen's diameter, on the model shown onPlate 5.7, was 101.6mm, though with little effort they could be changed to any other size. The top platen was welded to a triangular shape plate, at the corners of which three steel rods were positioned in order to measure the deformation of the specimen.

5.3.3.4.1c. The deformation measuring system

The deformation was measured with three dial guages, placed in a triangular formation, and attached to three steel rods, see Plate 5.6 and 5.7. The height of the dial guages could be adjusted depending on the height of the specimen (specimens up to 150mm height could be tested).

The three readings of the deformation served the purpose of giving a clear picture of how the specimen deformed. Thus, any excessive deformation due to local weaknesses or non-parallel surfaces of the specimen, could be easily detected, and in this case the test had to be re-run. In any other case, the average of the three readings was used for further calculation.

5.3.3.4.1d. Data recording

The deformation readings were recorded by a single lens reflection camera, at fixed intervals of time. This was due to the difficulty of recording six dial guages simultaneously, especially when a great deal of deformation occurs at the beginning of the test, and accurate recording time is essential.

The camera was mounted on a tripod and placed approximately 1.5m away from the apparatus. In order to eliminate the shaking of the camera during exposure and ensure quick reload, a motor drive with a remote control button was attached to the camera.

After the test the film was processed and the recorded readings could be read either from the negative with the aid of a projector or from the prints.

5.3.3.4.1e. The temperature chamber

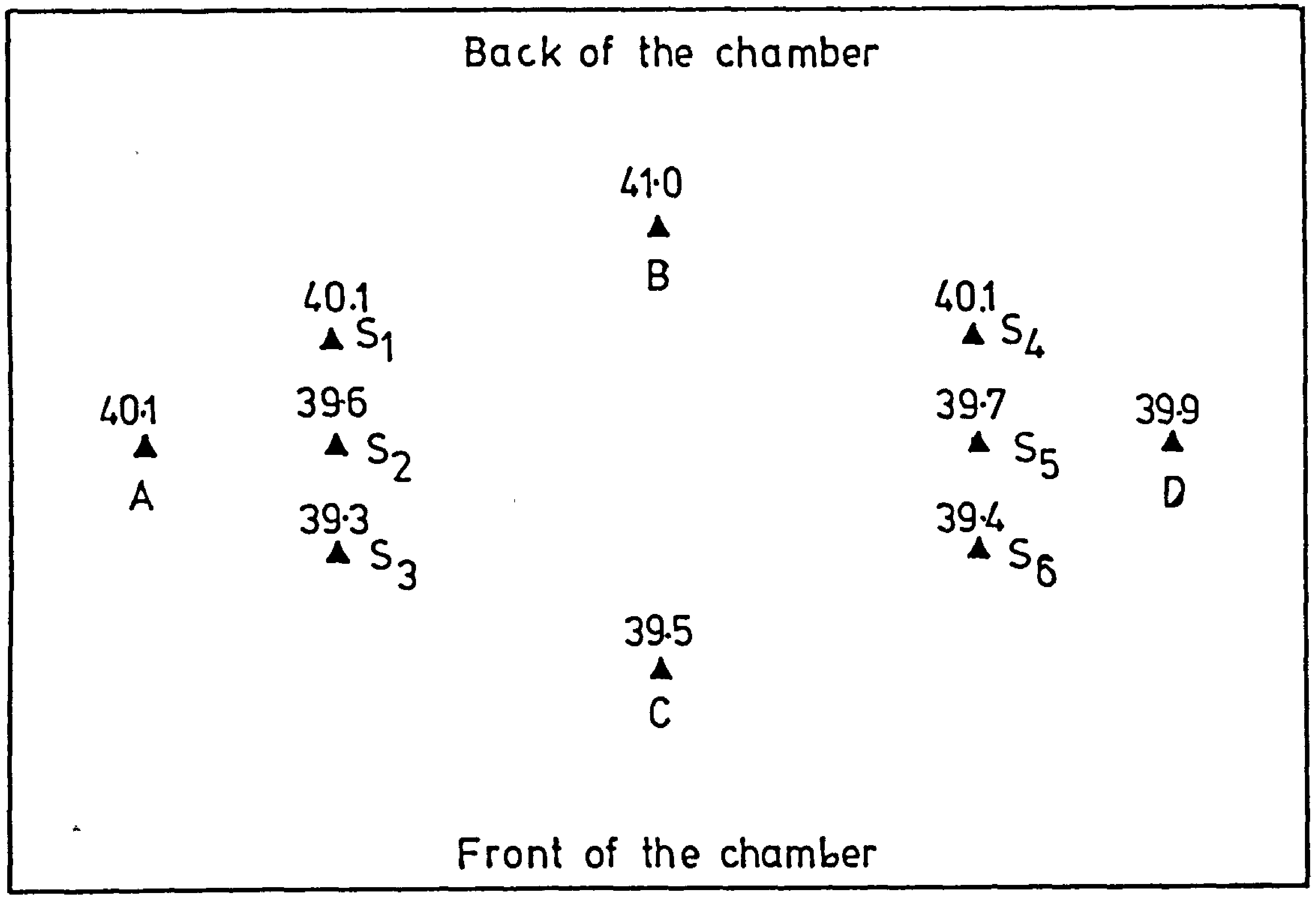
The two specimens with the top and bottom load platens were enclosed in a chamber, as shown in Plate 5.7. The walls of the chamber were double skinned, filled with a heat insulating material, in order to eliminate heat losses.

The heating element was connected to an integrated temperature control unit, capable of controlling the temperature with an order of accuracy of 0.2^{o}C. An electric fan was also attached to the back of the chamber to facilitate the even distribution of temperature. The temperature distribution was measured by thermocouples as shown in Fig. 5.12. It must be noted that points S_1 to S_6 were points on the specimens and as it can be seen the temperature difference within the specimens was less than $\pm 1^{o}$C.

5.3.3.4.2. Testing procedure

The specimens were inspected for parallel surfaces and each surface was treated with a thin layer of silicon grease and graphite flakes in order to minimise frictional forces. They were then placed into the pre-heated chamber and left for at least one hour to reach a uniform temperature of 40^{o}C. To eliminate water evaporation from the specimens during pre-heating period, they were sealed into plastic bags before being placed in the chamber.

After a uniform temperature was achieved, the plastic bags were removed from the specimens and the specimens were positioned between the load platens. The steel rods and the dial guages were then adjusted



$*S_{1,6}$ = points on the specimens

The numbers correspond to temperature in°C

Fig. 5.12 TEMPERATURE DISTRIBUTION GRID OF THE CHAMBER and the piston of the jack was lowered using the low pressure. The low pressure of $0.01\mathrm{MN/M}^2$ was sustained for exactly 2 minutes, during which a good contact between the load platens and the specimens was ensured.

After the pre-testing period of 2 minutes the high pressure load of $0.1\mathrm{MN/M}^2$ was applied instantaneously and readings of deformation were taken at 10, 20, 40, 60, 90, 120, 300, 600, 1200, 2400 and 3600 seconds. Immediately after the total loading time of 1 hour the load was removed and deformation recovery was measured at 10, 600 and 3600 seconds.

It must be emphasised that the testing conditions were in compliance with the recommended testing conditions of the European Conference held in Zurich in 1977 (151) for any bituminous mixture under the static creep test.

5.3.3.4.3. Calculations

The ranking of the ETMs was obtained by calculating the stiffness modulus Screep of the mixture as a function of loading time.

The stiffness modulus S creep was obtained by using the formula 5.4 below:

$$(\mathrm{S\ creep})_t = \sigma / (\varepsilon \mathrm{mix})_t \ , \ (\mathrm{N/m}^2) \qquad \ldots 5.4$$

where σ = the applied stress $(0.1\mathrm{MN/m}^2)$

and $(\varepsilon\mathrm{mix})_t$ = the compressive strain at loading time t

The compression strain was calculated using equation 5.5

$$(\varepsilon \mathrm{mix})_t = \Delta H/Ho \quad (\mathrm{mm/mm}) \qquad \ldots 5.5$$

where ΔH = the total measured deformation at a certain loading time t

and Ho = the original thickness of the specimen

The results of the stiffness of the mixtures S creep were plotted against loading time in a double logarithmic graph, and the average of Screep at t = 3600 sec, from two specimens, was reported to two significant digits.

The stiffness of the mixture Screep was also plotted against the stiffness of the bitumen Sbit in a double logarithmic graph. The stiffness of the bitumen Sbit as a function of loading time and temperature was calculated by using Van der Poel's nomograph (127). It has been shown in the literature review that this graph is very useful for the estimation of permanent deformation of the pavement.

5.3.3.4.4. Precision of creep testing using CANIK UL apparatus

The precision of the test was determined in terms of relative experimental error, otherwise known as coefficient of variation. The experimental error was calculated on stiffness values corresponding to a loading time equal to 3600 sec. This loading time was used because it eliminates the additional variation of results observed at the early stage of testing (151). Hilster and Van de Poel (151) have shown that relative experimental error is greater at the beginning of the test but that this stabilizes after the first 3 minutes.

The precision of the test depends among other things on the homogeneity of the mixture. For this reason sand bitumen mortars were used, which are more homogeneous than any other bituminous mixtures, and hence the lowest possible experimental error can be determined. Sixteen specimens were prepared in batches of three in the laboratory, according to specifications BS594/73 (69). The compaction was carried out at $150^{o}C \pm 5^{o}C$ by G.T.M. using 0.69MPa(100psi) pressure, 30 revolutions and 1^{o} angle of gyration. The specimens were tested for creep under the conditions described in Section 5.3.3.4.2. The result of the creep curves and the stiffness at 3600 sec are shown in Table 5.1.

SAND-BITUMEN MORTAR MIXTURES			
Coefficient[1] "a" (x10^6)	Slope[1] "b"	Correlation Coefficient	Stiffness at 3600sec N/mm^2 (x10^6)
28.82 x10^6	-0.1876	-0.993	6.202
24.82	-0.1694	-0.991	6.200
18.92	-0.1700	-0.994	4.700
19.78	-0.1812	-0.995	4.487
10.92	-0.0839	-0.972	5.491
17.861	-0.1479	-0.973	5.319
39.26	-0.9950	-0.991	6.223
21.76	-0.1502	-0.999	6.360
27.70	-0.1940	-0.991	5.651
27.20	-0.1990	-0.991	5.332
41.11	-0.2450	-0.982	5.529
25.31	-0.1764	-0.993	5.970
42.31	-0.2540	-0.997	5.290
30.77	-0.203	-0.989	5.814
28.91	-0.186	-0.992	6.300
30.83	-0.199	-0.997	6.064

Average = 5.683 x10^6

Standard Deviation

= 0.565 x10^6

[1] The equation is of the form

$$Y = a \times X^b$$

where Y = Stiffness of mix (N/mm^2)

X = Loading time (secs)

TABLE 5.1 CREEP RESULTS OF SAND-BITUMEN MORTAR MIXTURES (TEST CONDITIONS: TEMP = 40°C, STRESS = 0.1MN/m^2, DURATION = 1 HOUR)

The relative experimental error was calculated using the following equation:

$$\text{Relative experimental error} = Sd\,/\bar{S}mix \times 100\,,(\%) \qquad \ldots\ 5.6$$

where Sd = Standard deviation of results

$\bar{S}mix$ = average value of results

The experimental error was 9.94%. This value is lower than the experimental error reported by Hilster and Van der Poel (151) when using other apparatuses.

The repeatability of the test results, also associated with the precision of the test method, was determined from data shown in Table 5.1. The repeatability is a quantitative measure of the variability of results associated with the same operator, in a given laboratory using the same apparatus testing conditions and identical material. It is the value equal to or below which the absolute difference between two single test results, under the above conditions, may be expected to vary with a specified probability, normally 95% level. The repeatability, when expressed as a factor of the two results i.e. X1/X2 where X1 $>$ X2, can be determined by the equation 5.7 (151).

$$\text{Repeatability} = 1 + 2.77 \times \sqrt{(Sd/\bar{X})^2/K} \qquad \ldots\ 5.7$$

where Sd = standard deviation of the results

$\bar{X}$ = average value of the results

K = the number of specimens to be tested

The accuracy of the above formula depends upon how representative the standard deviation and average value of the results is, which implies that the larger the number of observations, the closer to the true value of population. Assuming that the standard deviation, and value of stiffness calculated in Table 5.1 is representative for all sand-bitumen mortar specimens and that two specimens are going to be tested at the time, the repeatability was found to be equal to 1.19. This implies that two results, expressed as a factor, obtained under the repeatability conditions differing by more than the above value, should be considered as suspect.

Hilster and Van de Poel found that repeatability deteriorates as the mixtures become less homogeneous. The lowest repeatability factor they reported was 1.23 from sand-sheet mixtures and the highest was 1.35 from gap graded mixtures when the Wykeham Farrance apparatus was used. Consequently, the repeatability for the emulsion dense mixture may deteriorate. Repeatability values using these mixtures will be given in Chapter 10.

It must be emphasised however, that although the newly designed apparatus for the creep test compares favourably in terms of precision with all the other apparatuses available (151), it is necessary to examine the precision with other types of mixtures. It is also necessary to determine the reproducibility between laboratories and different operators, before it can be used with confidence by other laboratories.

CHAPTER SIX

DEVELOPMENT OF A SLOW SETTING EMULSION FOR DENSE GAP GRADED AND CONTINUOUSLY GRADED BITUMINOUS MIXTURES

6.1 Introduction

The scope of the first part of this research study was to develop a slow setting emulsion so as to obtain a good coating of the aggregate mixtures containing a high percentage of fine aggregate (passing 2.36mm B.S. sieve). This would overcome the restrictions encountered in using mainly coarse aggregate in emulsion treated mixtures and hence to blend aggregates of any desired gradation.

Testing potentially useful commercial emulsions showed very rapidly that they were unsuitable for use in dense bituminous mixtures. It was therefore decided at this early stage to develop a suitable emulsion which could be used for the production of dense mixtures. This development was carried out with the aid of Naylor Chemicals Ltd. (212).

Out of a large number of cationic emulsifiers, three types were chosen, namely the Redicote E-11, the NH-10 and the KS4, all of which produce a stable slow setting cationic emulsion. The adhesive agent used was Imidazoline and the water shading agent was PN-39. All the emulsion formulations and chemicals used were manufactured and developed in the laboratories of Nayler Chemicals Ltd. under the expert advice of Mr.J.Hill from Kelbit Ltd. (213).

6.2 The manufacturing procedure for the bituminous emulsions

All the cationic emulsions used in this study were prepared by using a Hurrell type emulsification machine, capable of producing approximately one ton of bituminous emulsion per hour. The settings on the emulsification unit were such as to provide dispersion of bitumen in water, in droplets of approximately 1 to 5 microns in diameter.

The water was always added to the emulsifier and the solution was heated gently to 60°C, and stirred continuously until the emulsifier completely dissolved in the water. The amount of emulsifier used was, on average, about one percent by total weight of binder and water.

The binder was preheated until it reached a uniform temperature of approximately 130°C and then transferred to one of the containers of the emulsification unit; the other container was filled with water and emulsifier solution. Emulsification was started immediately by allowing the water/emulsifier solution to go through the system. Collection of the bituminous emulsion started after a homogeneous mixture was obtained (normally within a few seconds). The hot bituminous emulsion was allowed to cool down to room temperature and it was then sieved through a 710 micron sieve before being stored away.

In order to facilitate the emulsification of the relatively hard bitumens used,the bitumen was cut back with kerosene to approximately 200 pen equivalent.

6.3 Stability, coating and chemical composition of the emulsions used

The chemical stability of an emulsion depends on the concentration of the emulsifier. A minimum concentration of emulsifier is needed for the formation of micelles, known as Critical Micelle Concentration (CMC), which provides minimum chemical stability. The stability increases as the concentration of emulsifier increases until a maximum level is obtained, at which the electrophoretic mobility of the particles expressed in terms of zeta potential reaches its maximum. Further increase in the concentration of the emulsifier will reduce the zeta potential of the solution. The amount of emulsifier at which maximum stability and zeta potential occurs depends on the type of emulsifier (22).

Emulsions with low CMC values will possess lower zeta potential value at which maximum stability occurs. The higher the zeta potential value of an emulsion the faster the breaking of the emulsion is expected to be.

The coating ability of an emulsion depends not only on the zeta potential of the emulsion but also on the ion exchange capacity of the aggregate surface. High ion exchange capacity and high zeta potential levels will result in fast breaking of the emulsion and poor coating. In order to reduce the ion exchange or to completely neutralise the surface of the aggregate, water is normally added to the aggregate prior to mixing. The addition of water to the aggregate although neutralising the surface ions, retards the final breaking of the emulsion, and if excessive amounts are used it may also affect the ease of compaction. It is therefore clear that in order to obtain good coating of the aggregate and good properties of the final mixture, the amount of added water to the aggregate should be kept as low as possible which requires emulsion with low zeta potential levels at maximum stability.

It must be noted that the coating of the aggregate may also be affected by the temperature of the aggregate at mixing, the type of mixing and the size of binder droplets. For the purpose of this investigation the size of droplets was kept constant in all emulsion mixtures and the type of mixing was the same throughout the tests.

Three different types of emulsifiers were selected to be tested, Redicote E-11, NH-10 and KS4. Redicote E-11 is commercially available and is mainly used in slurry seal mixtures. The other two types NH-10 and KS4 were specially designed to produce emulsions suitable for coating aggregate mixtures high in fine aggregate content.

The exact chemical composition of Redicote E-11 could not be found, since the product is patented, but its properties as an emulsion are well documented in references (22, 53, 54).

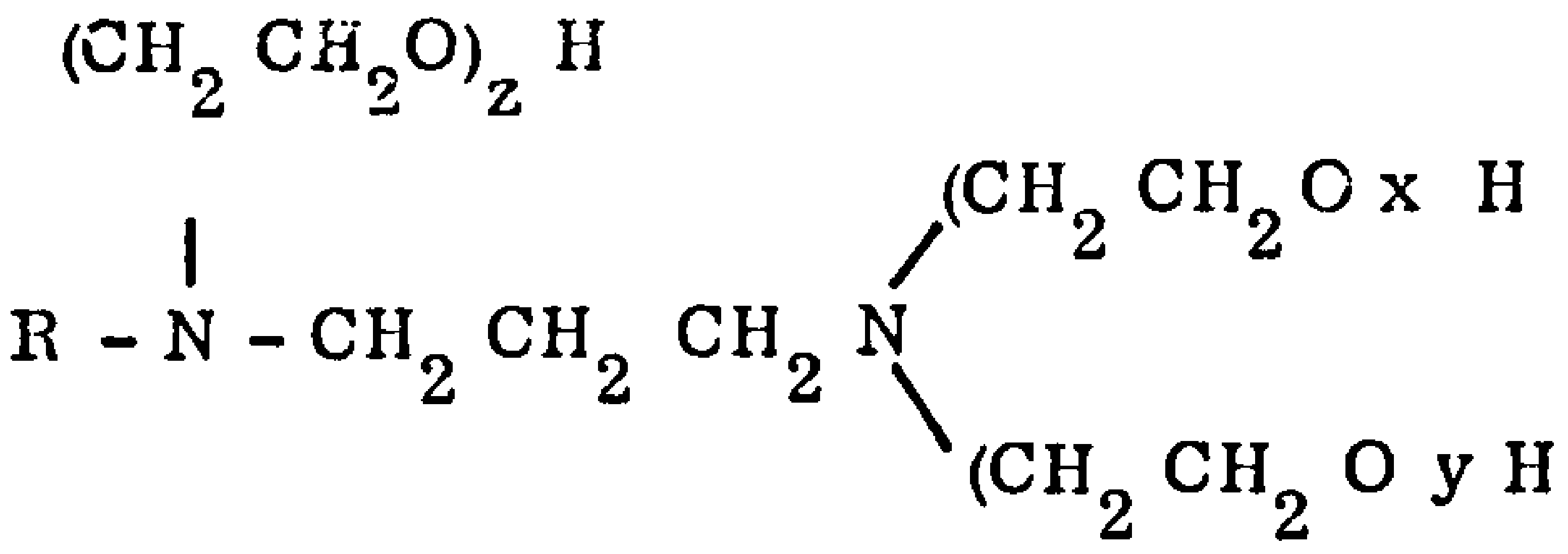
In the chemical composition of NH-10, the major constituent is an aqueous solution of an ethylene oxide-nonyl phenol adduct, containing 50 moles of ethylene oxide per mole of nonyl phenol as represented by the following formula:

$$R\ (CH_2\ CH_2\ O)_n\ H$$

where R = nonyl phenol

$n = 50.$

Also included in the NH-10 formulation were aluminium chloride and 15 mole ethoxylated tallow diamine (212, 213):



where $x + y + z = 15$

The KS4 type of emulsion was based on an emulsifier commercially known as Polyram S. Polyram S is a poly-amine with tallow ends (i.e. $R - (NH - (CH_2)_3)_n - NH_2$)(212).

Out of the two additives used to improve the adhesive between aggregate and binder film, one was an amido-amine adhesive agent, commercially known as Imidazoline. The other was a newly developed (212) water shading agent called PN - 39. PN - 39 agent was a modified tallow di-amine, di-oleate which is a long chain fatty acid with tallow ends. Both the above agents were incorporated within the bitumen prior to emulsification.

6.4 Coating results and discussion

The coating ability of the emulsions was determined by the coating test as described in detail in Chapter 5 Section 5.3.1.1. The results obtained are shown in Table 6.1.

MINIMUM REQUIREMENTS FOR 75% COATING				
Type of Emulsion	Type of Mixture	AMOUNT REQUIRED		Final Breaking Time
		Binder	Added Water	
NH-10	C.R.A.	6.0%	1.5% (5.1%)	< 6 hours
	D.E.Mc	4.0%	1.0% (2.7%)	< 6 hours
KS4	C.R.A.	9.0%	1.5% (5.4%)	< 6 hours
	D.E.Mc	5.5%	1.5% (3.9%)	< 6 hours
Redicote E-11	C.R.A.	15.0%	3.5% (9.9%)	> 6 hours
	D.E.Mc	10.0%	1.5% (5.8%)	> 6 hours
NH-10 + Imidaz.	C.R.A.	-	-	-
	D.E.Mc	6.0	1.5% (4.1%)	< 6 hours
NH-10 + PN39	C.R.A.	-	-	-
	D.E.Mc	6.0	1.5% (4.1%)	< 6 hours

(   ) Total amount of water in the system, calculated on 70/30 ratio of binder to water emulsion.

TABLE 6.1 AMOUNT OF BINDER AND ADDED WATER REQUIRED FOR 75% AGGREGATE COATING (all percentages are by weight of dry aggregate).

From the three different cationic emulsions used, only one, the NH-10 type, could coat the aggregate satisfactory, using reasonable amounts of added water and binder. The required 75% minimum coating was easily obtained by NH-10, even at the low 1.5% added water content and 6% binder content for C.R.A. mixtures (65.7% passing 2.36mm B.S. sieve).

The Redicote E-11 produced a similar degree of coating (75%) to NH-10 but only when very high binder content was used (15% by weight of dry aggregate) for the same type of mixture i.e. C.R.A. Even with Dense Emulsified Macadam (DEMc) Redicote E-11 gave a minimum coating only when 10% binder content was used, which is very high compared to the 4.0% binder content required when NH-10 was used. The high percentage of binder content and water added resulted in a very high total water content in the mixtures and as a result, final breaking of the emulsion did not occur within 6 hours after mixing (mixtures left at room temperature).

An attempt was made to improve the coating ability of both emulsions, Redicote E-11 and NH-10, by changing their pH values. Normally, Redicote E-11 emulsion has a pH value of approximately 2.2 and NH-11 of 4.1, see Table 4.3, Chapter 4, but by adding a base (Na OH) or an acid (HCl) the pH values were varied from 1.8 to 4.9 pH. It was found that changing the pH values had no apparent effect on the coating of the aggregates, with either of the emulsions used. This was in agreement with Scott (21) who suggested that a change in pH alone does not have as great effect on the breaking of the emulsion as a combination of change in pH and type of emulsifier.

The KS4 type of emulsion gave better results than Redicote E-11 but not as good as NH-10. The minimum coating of 75% was obtained for C.R.A. mixtures with 9% binder content which was relatively high compared to NH-10 (6%).

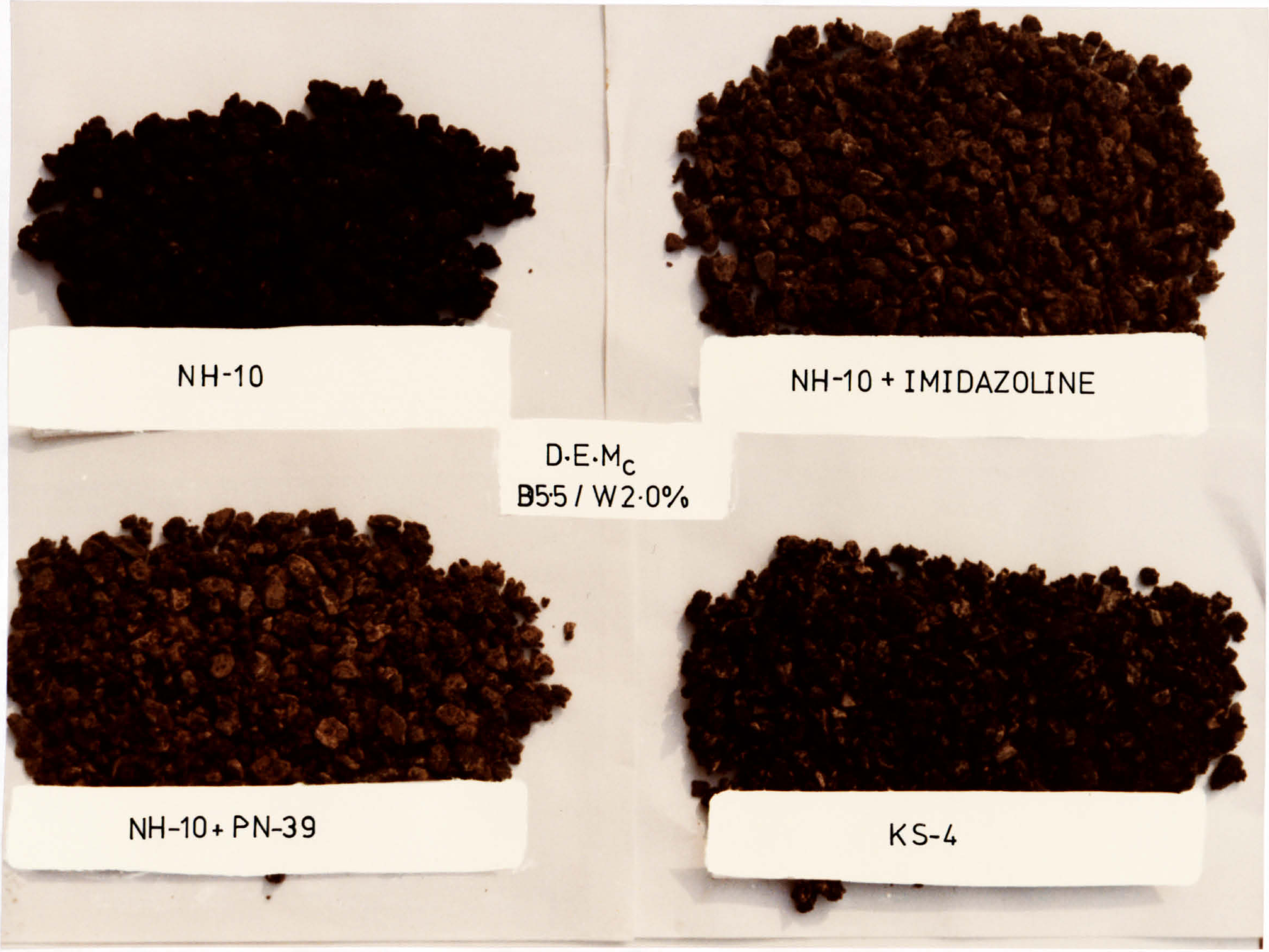
It was apparent that only the NH-10 type of emulsion could be used with both C.R.A. or D.E.Mc mixtures, without using uneconomically high binder contents. This was the only type of emulsion used for the manufacturing of the mixtures and the determination of their properties.

The excellent coating ability of NH-10 was undoubtably due to the very slow breaking of the emulsion resulting from the relatively weak charges (hence low electrophoretic mobility) of the bitumen particles. This arose i) from the ionization of the nitrogen atoms in the ethoxylated tallow diamine under acidic conditions, created by the aluminium chloride and ii) from the formation of a complex structure, between aluminium ions and ethylene oxide groupings. The storage stability was not affected by the weak positive charges, because stability was due to the physical protection of the long chain ethylene oxide groupings which surround each bitumen particle, rather than to charge repulsion.

The weak positive charge of the particles, necessary to obtain good coating, may have influenced the rate of second stage breaking of the emulsion after coating and hence the development of the adhesive properties of the bitumen. For this reason an attempt was made to improve, artificially, the adhesion of the binder by adding an adhesive (Imidazoline) or a water shading agent (PN-39). Unfortunately in both cases the degree of coating deteriorated and higher amounts of binder were needed for the same degree of coating see Table 6.1. The reason for this is believed to be due to the increase in overall electrophoretic mobility of the bitumen particles when the two chemicals were introduced to the binder phase. Plate 6.1 shows the degree of coating of a D.E.Mc mixture with 5.5% binder and 2.0% added water.

Finally, the effect of temperature on the coating ability of NH-10 was examined. It was assumed that most probably the aggregate will be at higher temperature and to simulate this condition the aggregate was heated to 30°C, 40°C and 50°C. The added water was also heated to the same

Plate 6.1
Degree of coating of
D. E. Mc using four
different formulations



temperature in order to avoid a temperature drop in the aggregate. Mixing of the aggregate with the water and the emulsion took place at the same temperatures of 30°C, 40°C or 50°C. The results have shown that coating deteriorates particularly above 30°C and that this was more distinct in the C.R.A. than D.E.Mc mixtures, see Plates 6.2 and 6.3. The reason is believed to be two fold: the increase in the speed of chemical breaking of the emulsion due to heat and the evaporation of a certain amount of water during mixing. It can therefore be said that mixing at higher temperatures than 30°C should be avoided.

6.5 Conclusion

1. From the three different types of cationic emulsions used, Redicote E-11, NH-10 and KS4, it has been found that the newly developed NH-10 type is the only one capable of coating satisfactorily aggregate mixtures high in fine aggregate content (passing 2.36mm sieve). The success of the NH-10 is believed to be due to the reduction of the electrophoretic mobility of the bitumen particles.

2. The degree of coating is not affected by the change in the pH value of the emulsion alone, but by the combination of the change of pH and the type of emulsifier together. Redicote E-11 with pH = 2.2 gives bad coating, NH-10 with pH = 4.1 gives excellent degree of coating for both C.R.A. and D.E.Mc mixtures.

3. The degree of coating deteriorates when additives, Imidazoline and PN-39, are incorporated into the NH-10 emulsion to improve adhesion between the binder and the aggregate. Coating also deteriorated when mixing took place at temperatures greater than 30°C.

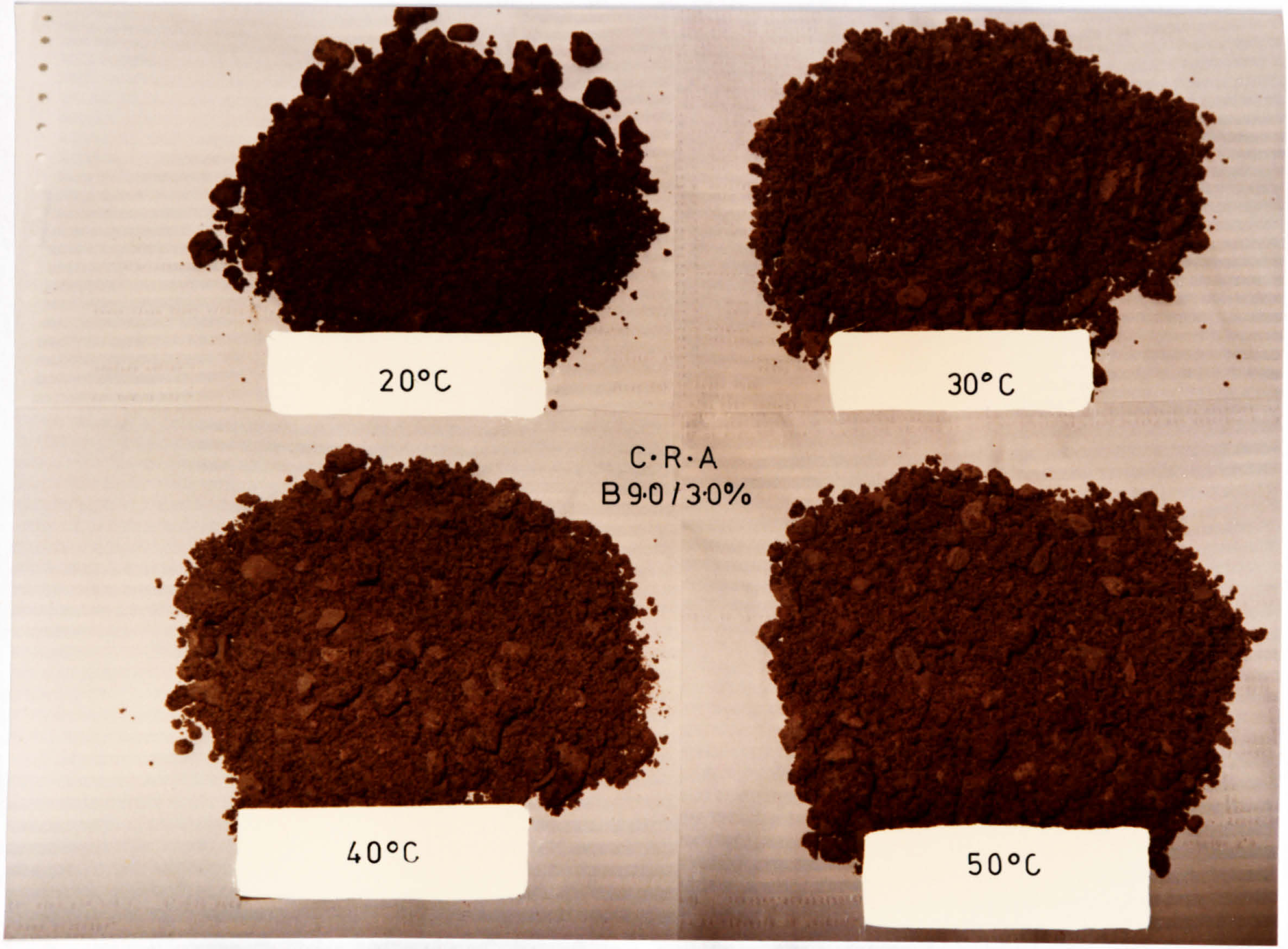


Plate 6.2
The effect of temperature
on the coating of C.R.A.
mixtures

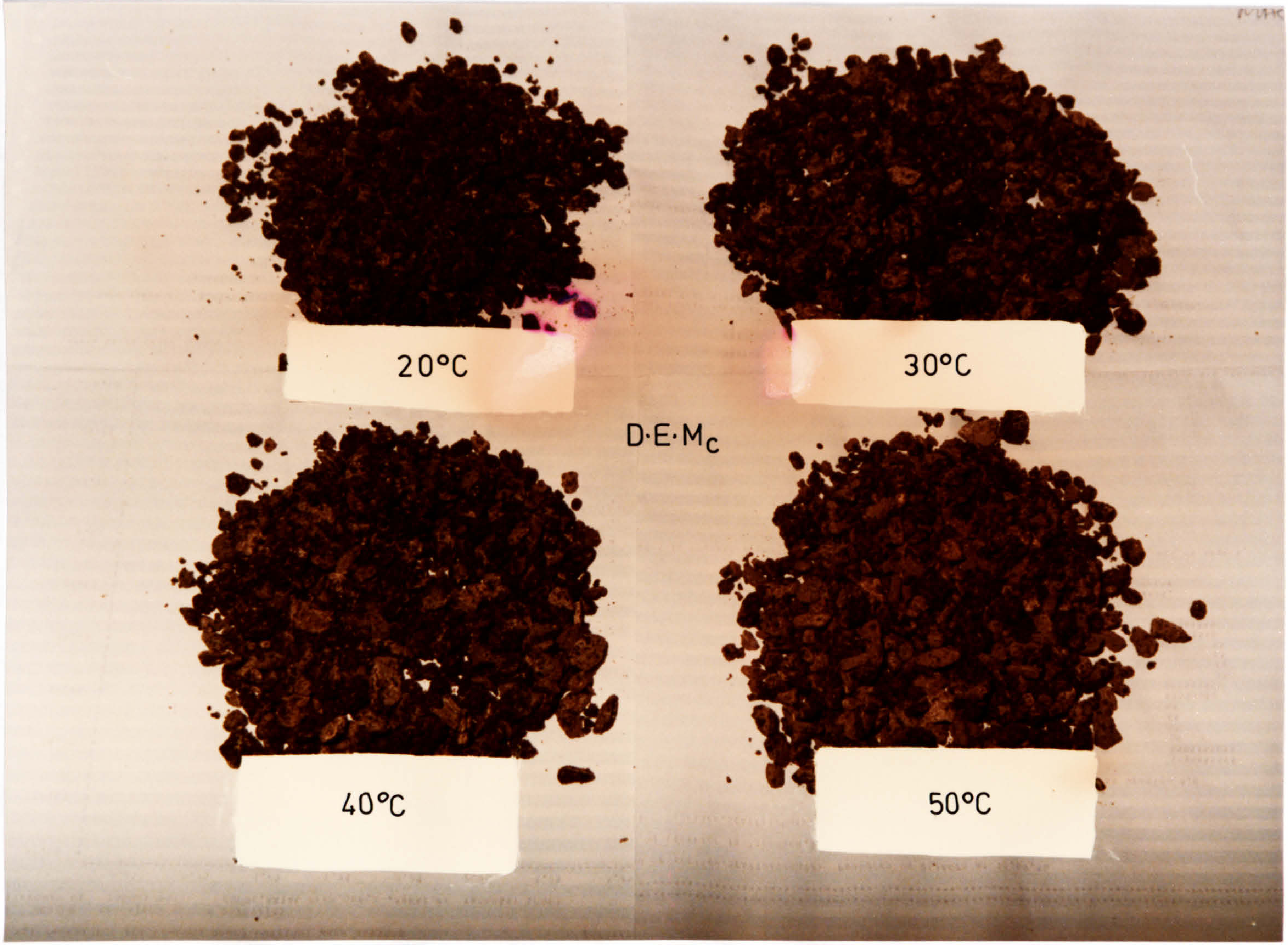


Plate 6.3
The effect of temperature
on the coating of D.E.Mc
mixtures

CHAPTER 7

RHEOLOGICAL MEASUREMENTS OF THE CATIONIC EMULSIONS - TYPE OF FLOW AND FACTORS AFFECTING THE FLOW

7.1 Introduction

One of the factors affecting the uniformity and thickness of the binder film on the surface of the aggregate in a BEM and its workability, is the rheological behaviour of the emulsion. Rheological behaviour is affected, among other factors, by the percentage of binder in the colloidal solution, penetration grade of binder, type of emulsifier and temperature.

This chapter presents the results of a limited investigation of the flow behaviour of the cationic emulsions used in this study, and an examination of the factors affecting their viscosity. The study was carried out using mainly a uniaxial rotational viscometer (Epprecht Rheomat 15). An Engler viscometer and a glass capillary viscometer were also used in order to examine the correlation between the fundamental and empirical measurements of viscosity.

7.2 Type of flow of bituminous emulsions

Bituminous emulsions are colloidal dispersions. Early studies (171) on the flow of a colloidal dispersion revealed some striking characteristics when flow was studied under different conditions. Some dispersions possessed higher viscosities when stirred slowly (low shear rate) and lower viscosity when stirred rapidly (high shear rate), and some of them recovered their original viscosity after some period of rest. This behaviour, where the viscosity is dependent on the shear rate, is typical of a non-Newtonian or Complex liquid, and together with a partial or complete recovery of consistency after stress is removed, represents a property called thixotropy. Williamson (171) also noticed that there were some colloidal dispersions in which the viscosity was lower at low shear rates and higher at high shear rates. This, being opposite phenomenon to thixotropy, was called Rheopexy.

Lyttleton and Traxler (27) examined a large number of bituminous anionic emulsions and found that almost all of them possessed non-Newtonian flow, with the majority of them showing thixotropic behaviour. Few emulsions possessed rheopexic behaviour, and this was attributed to the presence of alkaline inorganic salts (27, 171). Cationic emulsions behave in exactly the same way, and over all, they possess lower viscosities than anionic emulsions (29).

7.3 Characterisation of the rheological behaviour of bituminous emulsions

The measurement of the consistency of an emulsion is, principally, obtained by using the Engler viscometer (45) and the Saybolt Furol viscometer (34). Both tests measure viscosity in arbitrary units, i.e. Engler degrees and Saybolt seconds respectively, and because of the manner in which the measurement is carried out they cannot reveal the actual type of an emulsion. Nevertheless, they are used widely in the road industry, mainly because of their simplicity as a classification test.

The curve shown on Figure 7.1 is a typical curve of a thixotropic liquid. It can be seen that as the shear rate increases, the viscosity (shearing stress over shear rate) decreases (part OA of the curve), and as the shear rate decreases the shearing stress decreases but it does not follow the same path due to thixotropic breaking down, (AA_1). Path BB_1 is obtained when the liquid is left undisturbed for a certain period of time during which partial or total recovery of the structure takes place. When the liquid is sheared for a certain period of time at a certain shear rate (CB), thixotropic breaking down due to time takes place and a completely different downwards curve is formed, BCC_1.

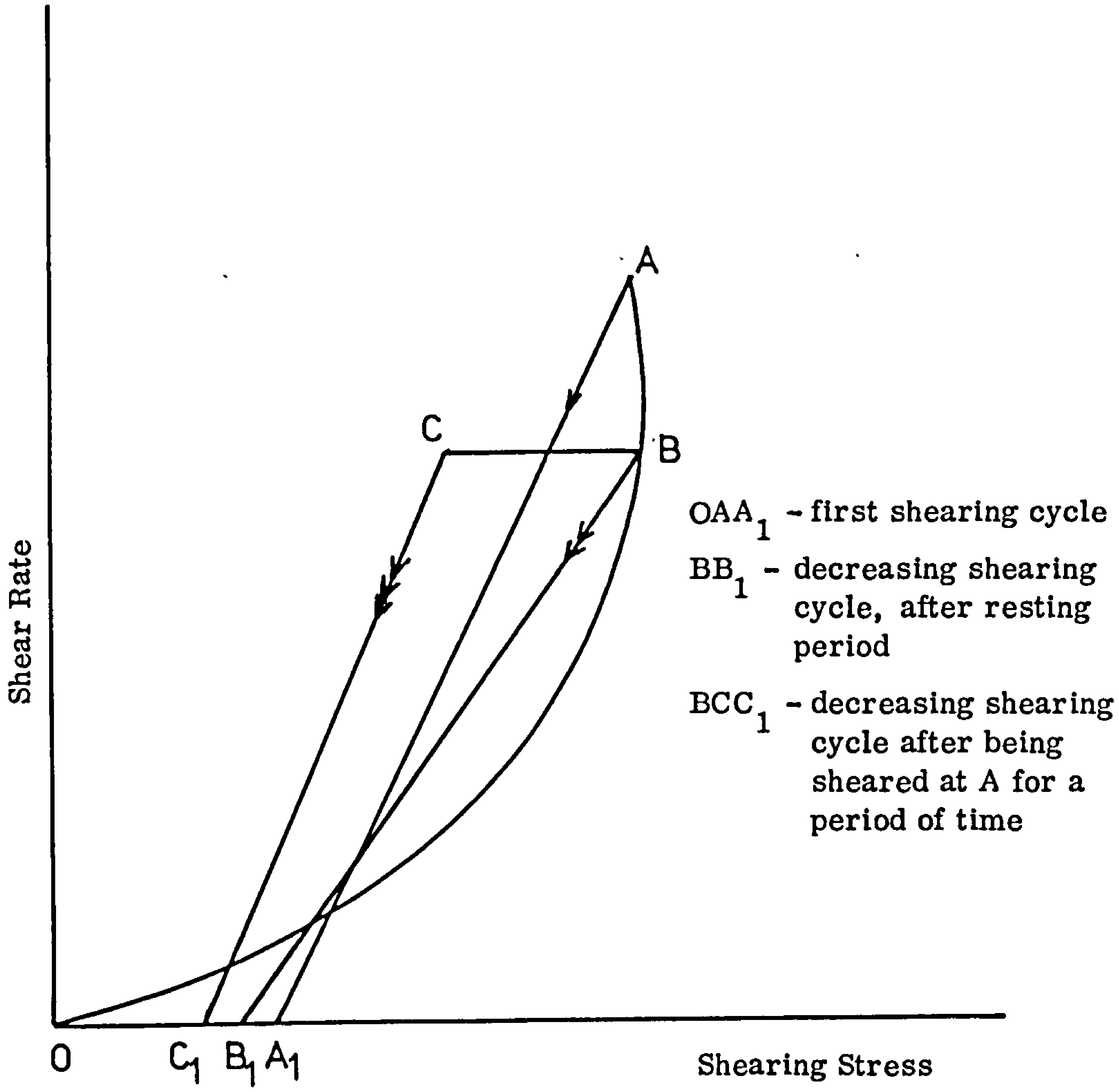


Fig. 7.1 HYSTERESIS LOOP OF A NON-NEWTONIAN LIQUID WITH THIXOTROPIC BEHAVIOUR

Analytical studies of the thixotropic behaviour of a liquid have been carried out by Weltmann (172) and Green and Weltmann (173). They derived two thixotropic coefficients which are sufficient to characterise the thixotropic behaviour. One is the coefficient of thixotropic breaking down due to time B_T , and the other is the coefficient of thixotropic breaking down due to shear rate M_S. They showed that these two coefficients can be calculated by equation 7.1 and 7.2 respectively.

$$B_T = \frac{U_B - U_C}{\log t_C - \log t_B} \qquad \ldots \text{ eq. } 7.1$$

$$M_S = \frac{U_B - U_A}{\log f_A - \log f_B} \qquad \ldots \text{ eq. } 7.2$$

Where U_A, U_B and U_C are plastic viscosities at A, B, C Fig7.1)
t_B and t_C - shearing times corresponding to B and C
and f_A and f_B - the shear rate at A and B.

The plastic viscosity at A, B and C may be calculated by using the following equation:

$$U_N = \frac{F_N - F_{N-1}}{S_N} \qquad \ldots \text{ eq. } 7.3$$

Where N = any point
F_N shearing stress at any point N
S_N shear rate at N

Although the above two coefficients are extremely useful to a rheologist to characterise fully the liquid, most engineers would prefer a slightly less complicated classification system. Traxler et al (174) and Romberg and Traxler (175) have proposed two simplified ways of presenting viscosity measurements of bituminous materials, which may equally be applied to bituminous emulsions.

In both methods the shearing stress was plotted against shear rate in a log-log scale and the slope of the straight line revealed the type of flow. Slopes other than 1.00 correspond to non-Newtonian fluids. This slope was called the coefficient of complex flow (C) and the more this constant varied from 1.0 the greater was the deviation from the Newtonian viscous flow. Obviously the evaluation of this constant alone was not sufficient to evaluate the consistency of the liquid. Traxler et al (174) proposed to calculate the viscosity at an arbitrary shear rate of 5×10^{-2} sec $^{-1}$, while Romberg and Traxler (175) proposed to calculate viscosity at a certain power input of 1000 erg/sec/ml (i.e. shearing stress x shear rate equal to 1000 ergs/sec/ml). Both viscosity measurements when compared with other viscometers showed that the "power input" method gave in most cases better correlation (29).

Both of the above methods were used in this study, with readings of shear rate and shearing stress being taken using the Epprecht Rheomat 15 (ER15) rotational viscometer described in Chapter 5.

7.4 Results and discussion

The study of the flow on the emulsions used carried out by the Epprecht Rheomat 15 (ER15) and the glass capillary viscometer.

The ER15 enables to vary the shear rate causing a certain shearing stress and by plotting the shear rates against the shearing stresses, the type of flow can clearly be seen. Newtonian fluids give a straight line and non-Newtonian a curve. Depending on the type of non-Newtonian behaviour the curve can be concave or convex.

The glass capillary viscometer is normally used with liquids exhibiting Newtonian flow (180). Nevertheless, an attempt has been made in this study to find whether it can be used with emulsions possessing a certain degree of non-Newtonian behaviour. The procedure was carried out according the BS188 (180) and is outlined in Chapter 5.

The results of the laboratory study are presented in three parts:

In the first part, an investigation was carried out into the effect of the type of emulsifier and penetration grade of the binder, on the viscosity of a cationic emulsion. Two types of cationic emulsifiers were used, "Redicote E-11" type and "NH-10" type, both of them producing slow setting emulsions. The former is commercially available but the latter was specially developed for this study.

The binders used were 74, 100 and 200 penetration grade representing hard, medium and soft types of binder respectively. Details regarding the properties of the binders and the emulsions used are given in Chapter 4. The testing temperature and binder content of the emulsions at this stage was kept at 20°C and 65 percent respectively.

In the second part, a further investigation was carried out on the effect of temperature and binder content on the viscosity of a cationic emulsion. The temperature range chosen covered the normal mixing temperatures i.e. between 12°C to 30°C. The binder content was 60, 65 and 70 percent corresponding to low, medium and high percentage of binder. The type of emulsifier used at this stage was the NH-10 and the binder was of 74 penetration grade.

Finally, in the third part, further viscosity tests were carried out using the Engler viscometer in order to find a relationship between the fundamental and empirical measurement of viscosity. The emulsion used in these tests was the NH-10 with 70 percent binder of 74 penetration grade, which is in fact the type of emulsion that has been used in the rest of the study in this research programme.

7.4.1. Type of flow and the effect of emulsifier and penetration grade of binder on the viscosity of a cationic emulsion

The experimental values of shear rate and shearing stress obtained by using the rotational viscometer ER15, were plotted on a linear scale and a sample of the resulting curves is given in Figure 7.2.

From this figure, and in particular curve I and II, it can be seen that there is definitely a non-linear relationship between shear rate and shearing stress, at high binder contents (65 and 70 percent). This relationship is more noticeable at 70 percent binder than 65 percent, curve I, and parts OA and AO of this curve shows the changes in shearing stress with shear rate. The part BO in the same curve was obtained by decreasing the shear rate after a period of 15 minutes rest. It is obvious that the resting period of 15 minutes was not enough for the thixotropy to build up. For this reason the emulsion was left for a further half hour and then sheared at the highest shear rate at A, but again failed to produce shearing stress equal to those at A during the first shearing cycle. Longer resting periods were not attempted because of the risk of obtaining unrepresentative results due to excessive settlement and "creaming" of the emulsion. Creaming may be caused due to bitumen particles moving to the surface and its effect together with settlement on the viscosity of an emulsion has been investigated by Lyttleton and Traxler (27). They showed that the effect of settlement is more severe than "creaming" and can cause an increase of viscosity up to 1300 times, when viscosity was measured in poise.

Since complete recovery of the structure of the NH-10 emulsion was not obtained, it may be safely concluded that the emulsion did not possess a measurable degree of thixotropy. It is necessary to point out that during prolonged resting periods settlement may take place causing a reduction in the number of particles in suspension and as a consequence, a reduction in the consistency of the liquid. Excessive settlement can be caused by the relatively large size of the particles of the binder in

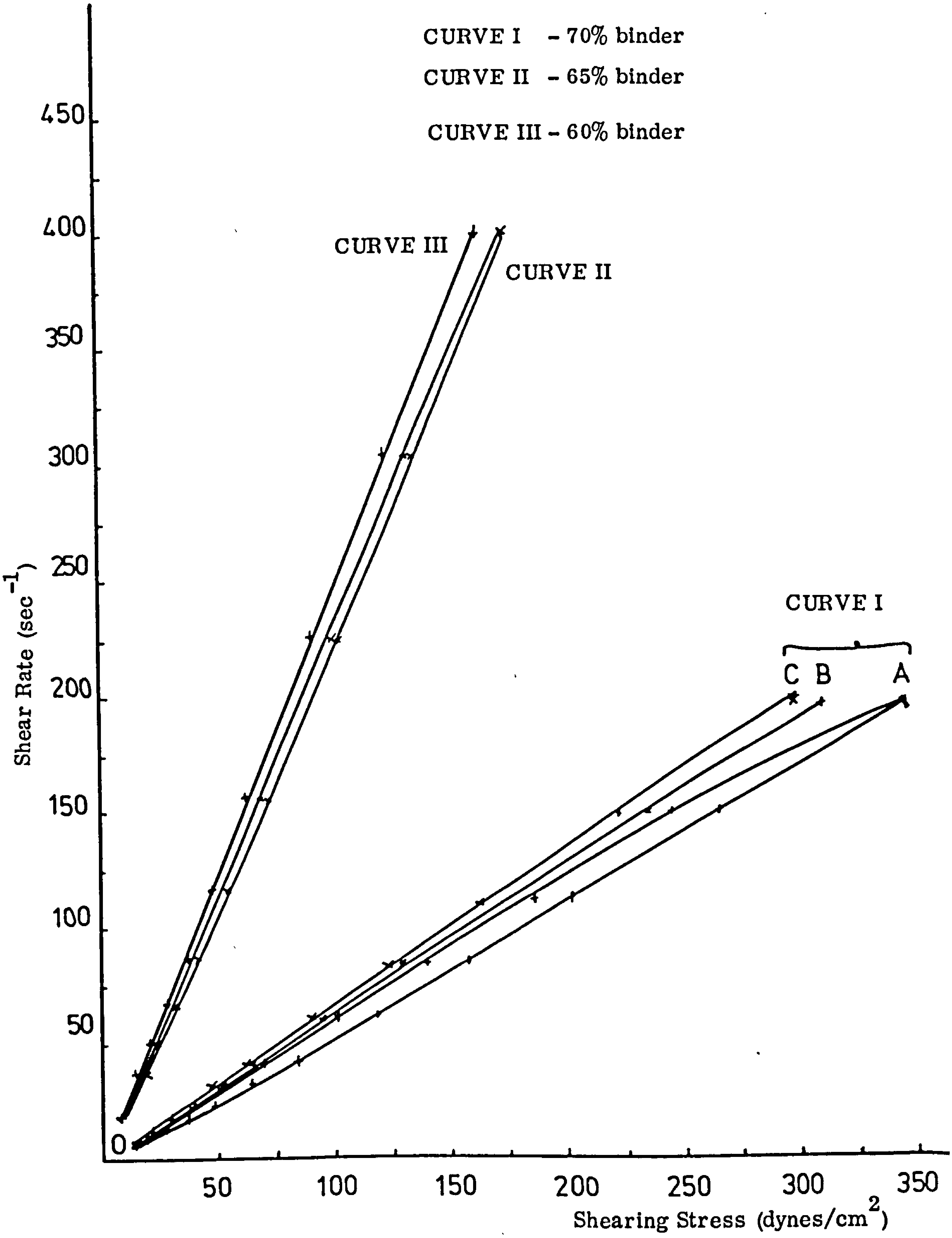


Fig. 7.2 RHEOLOGICAL BEHAVIOUR OF NH-10 CATIONIC EMULSION UNDER VARIED SHEAR RATE, TEMPERATURE 20°C, 50 PEN BINDER, BINDER CONTENT VARIED

suspension and/or by possible fluculation or coagulation after the application of a certain shearing stress.

From the results it was clear that it was impossible to calculate the two thixotropic coefficients, B_T and M_S. Hence, the study of flow and the NH-10 emulsion was carried out by using the complex flow coefficient "C", calculated from the log-log graph of shearing stress against shear rate. Similarly the Redicote E-11 emulsion did not produce a particularly well defined shear rate-shearing stress loop, and, therefore, all the evaluation of results for both types of emulsion was carried out in terms of coefficient of complex flow.

The viscosity values were calculated at an arbitrary shear rate of 50 sec^{-1}. For comparison purposes, viscosity was also calculated at power input of 1000 ergs/sec/ml as suggested by Romberg and Traxler (175).

Figures 7.3 and 7.4 show the rheological behaviour of NH-10 and Redicote E-11 cationic emulsions, using different penetration grade binder. From these two figures the viscosity at 50 sec^{-1} and 1000 erg/sec/ml was calculated together with the coefficient of complex flow "C" (slope of the line), see Table 7.1. It can be seen that although there is an increase in viscosity of the emulsion as the binder gets harder, this increase is very small, approximately 14 percent for NH-10 and none for Redicote E-11.

The complex coefficients of the NH-10 emulsions were all less than one (1.00) but there was an indication that as the binder gets softer this coefficient gets closer to one. This suggests that NH-10 emulsions with softer than 200 pen binder may possess Newtonian flow. However, despite the fact that NH-10 emulsion with 65 percent binder had shown coefficients of complex flow less than one, which indicates non-Newtonian flow with thixotropic behaviour, all values of this coefficient were above 0.95.

TYPE OF EMULSION "CATIONIC"		Complex Flow Coefficient	Viscosity at 50 sec^{-1}	Viscosity at 1000 erg/sec/ml
Emulsifier	Binder Grade, Pen.	(C)	(cP)	(cP)
NH-10	74 pen	0.971	47.1	46.7
	100 pen	0.956	44.8	43.2
	200 pen	0.985	40.2	40.0
REDICOTE E-11	74 pen	1.040	35.2	35.1
	100 pen	1.055	48.8*	46.2
	200 pen	1.006	36.4	36.5

*Binder content was 66.1%

TABLE 7.1 COMPLEX FLOW COEFFICIENTS AND VISCOSITIES OF CATIONIC EMULSIONS USING DIFFERENT BINDER GRADE; TEST TEMPERATURE 20°C AND BINDER CONTENT 65 PERCENT

In contrast to NH-10, the complex coefficients of Redicote E-11 were slightly higher than one unit, which indicated that this emulsion possessed a certain degree of rheopexy, i.e. application of shear rate for a period of time (agitation) will cause an increase in viscosity. The effect of the type of binder on the type of flow produced similar results to NH-10, the emulsion with the softer binder (200 pen) possessed a coefficient of complex flow very close to one unit (1.006). This reinforces the suggestion, made earlier on for the NH-10 emulsion, that it is likely that emulsions with softer than 200 pen binder possess a Newtonian flow at 20°C temperature when the binder content is 65 percent.

The fact that the Redicote E-11 emulsion possesses a certain degree of rheopexy is very important, because the viscosity of the emulsion is expected to increase when mixed with aggregates. This will certainly result in a reduction of workability of the mixture and in a non-uniform and thick film of binder deposited on the surface of the aggregates. As a consequence, in order to obtain a good coating, more emulsion and hence binder will be needed, which will certainly increase the cost of the mixture and this excess amount of binder might result in excessive permanent deformation.

The reason for the rheopexic behaviour of Redicote E-11 could be attributed to the presence of anhydrous calcium chloride ($CaCl_2$). The presence of alkaline inorganic salts, as suggested by Lyttleton and Traxler (27), will destroy or markedly decrease the thixotropy found in most bituminous emulsions, and in some cases will carry the system to rheopexic type of flow. It must be stated that the results of Redicote E-11 can only be used as an indication of the type of flow that exists at a particular temperature (20°C) and binder content (65 percent), and in order to draw more conclusive results, further viscosity tests must be carried at various binder contents and temperatures.

7.4.2. The effect of temperature and binder content on the rheological behaviour of NH-10 cationic emulsion

For the study of the effect of temperature and binder content on the viscosity of NH-10 cationic emulsion, the temperature range chosen was between 12° to 30°C, which represents the range of normal mixing temperatures. The binder content was 60, 65 and 70 percent by weight of total liquid, corresponding to low, medium and high percentage of binder, respectively. The grade of binder was fixed at 74 penetration grade. Redicote E-11 emulsion was eliminated from this study, on the basis that it possessed non-Newtonian rheopexic behaviour and also because of the unsatisfactory coating test results, which run in parallel to viscosity tests (see Chapters 5 and 6).

The results of shear rate and shearing stress were plotted in a log log scale, and are shown in Figures 7.5, 7.6 and 7.7. From these figures the coefficients of complex flow and the viscosities at 50 sec^{-1} and 1000 erg/sec/ml have been calculated and are as shown in Table 7.2.

TYPE OF EMULSION NH-10 Cationic		Complex flow coefficient (C)	Viscosity at 50 sec^{1} cP	Viscosity at 1000 erg/sec/ml cP
Binder content %	Test temperature ^{o}C			
60%	12	0.976	49.8	52.2
	14	0.979	47.1	47.3
	20	0.992	41.2	41.0
	25	0.977	38.2	38.0
	30	1.000	31.7	31.7
65%	12	0.960	62.5	63.8
	16	0.968	52.0	52.8
	20	0.971	47.1	46.7
	25	0.980	41.5	41.0
	30	0.992	33.3	33.0
70%	12	0.942	256.4	266.7
	16	0.944	217.9	226.4
	20	0.965	188.9	192.6
	25	0.969	169.5	172.0
	30	0.950	162.4	158.8

TABLE 7.2 COMPLEX FLOW COEFFICIENTS AND VISCOSITIES OF NH-10 CATIONIC EMULSION AT DIFFERENT TEMPERATURES AND BINDER CONTENT

(BINDER GRADE:74 PEN)

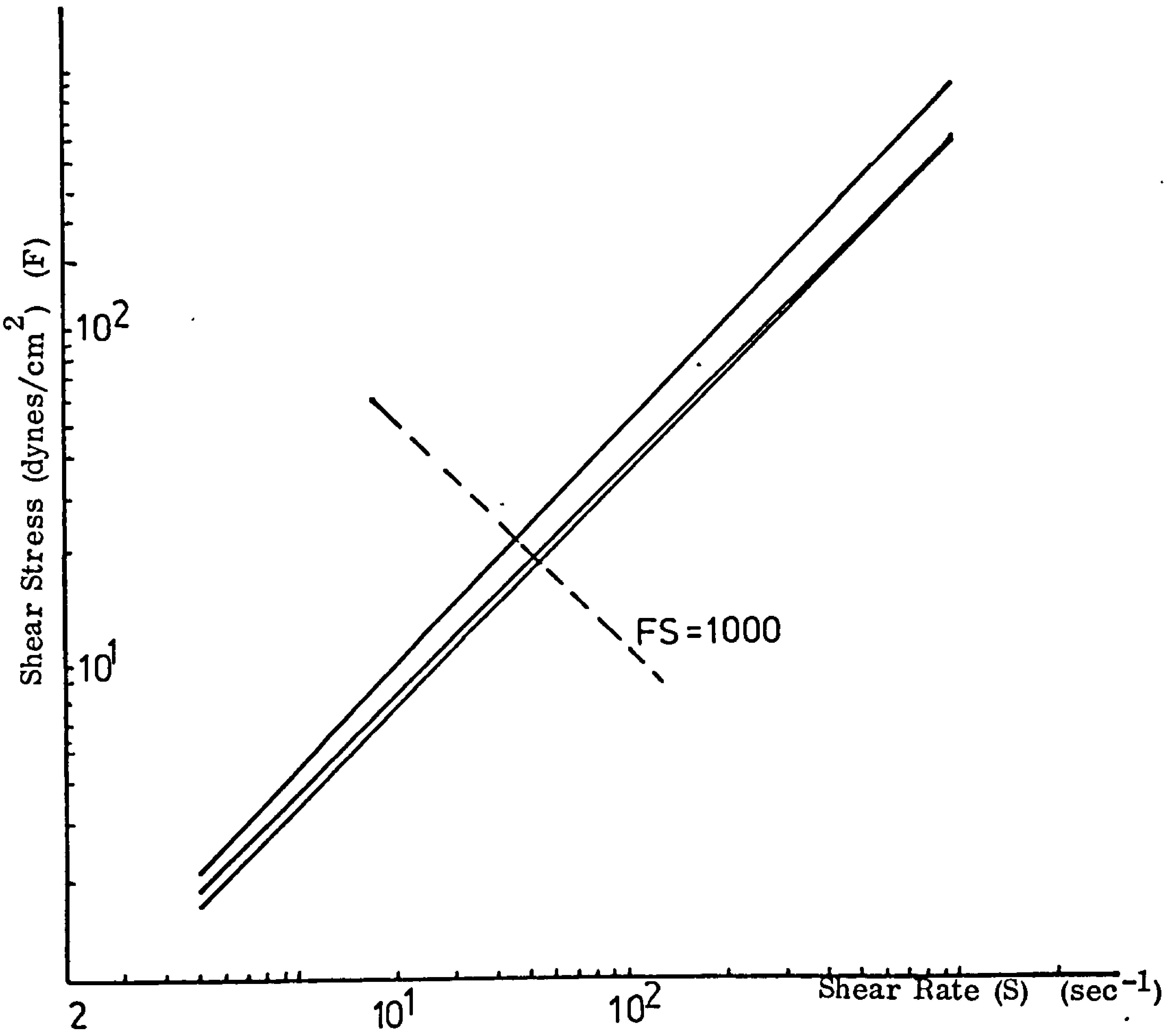


Fig. 7.4 RHEOLOGICAL BEHAVIOUR OF REDICOTE E-11 USING THREE GRADES OF BINDER TEMP 20^{o}C, BINDER CONT. 65%

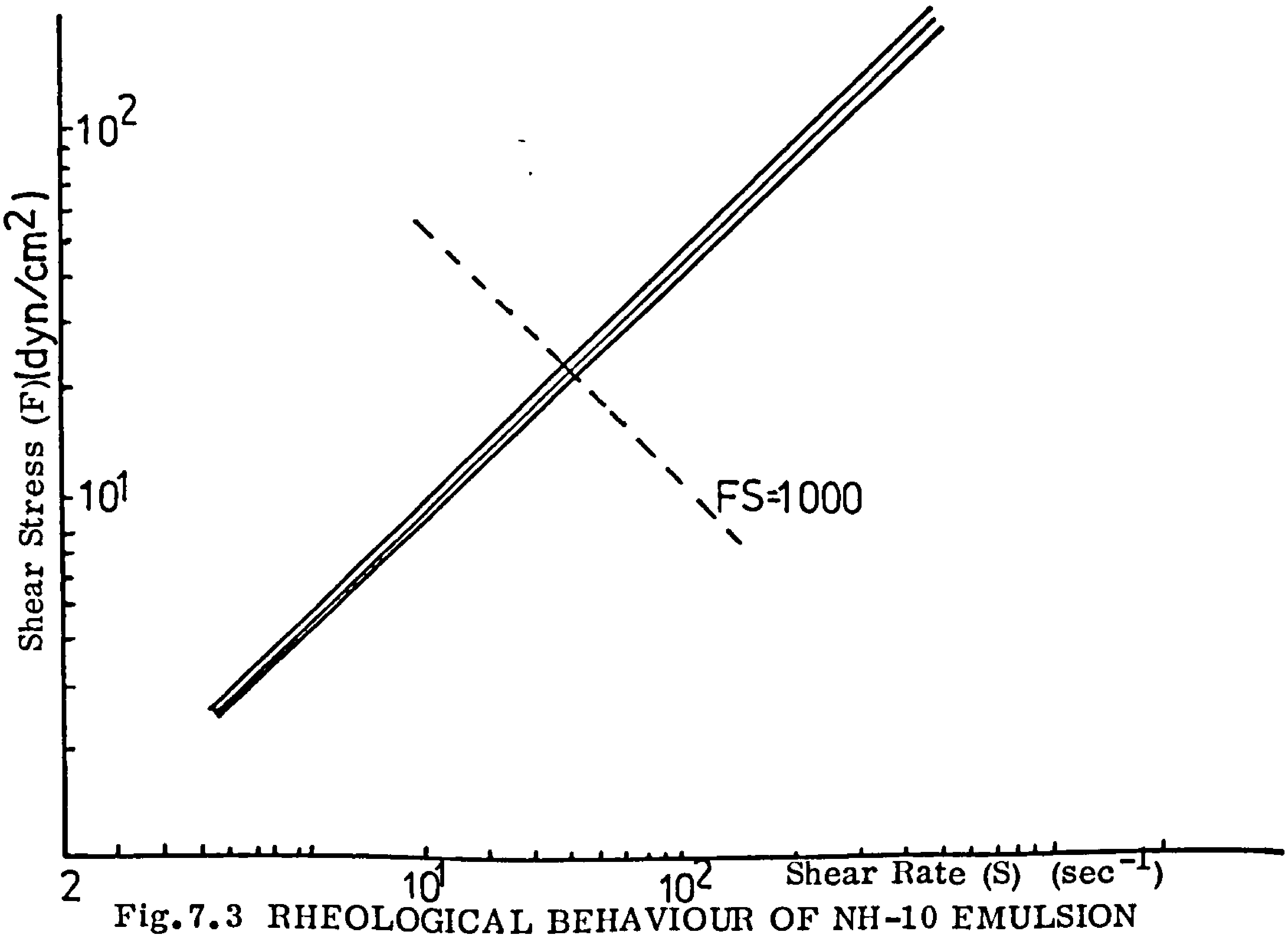


Fig.7.3 RHEOLOGICAL BEHAVIOUR OF NH-10 EMULSION USING THREE DIFFERENT GRADES OF BINDER TEMP 20^{o}C, BINDER CONTENT 65%

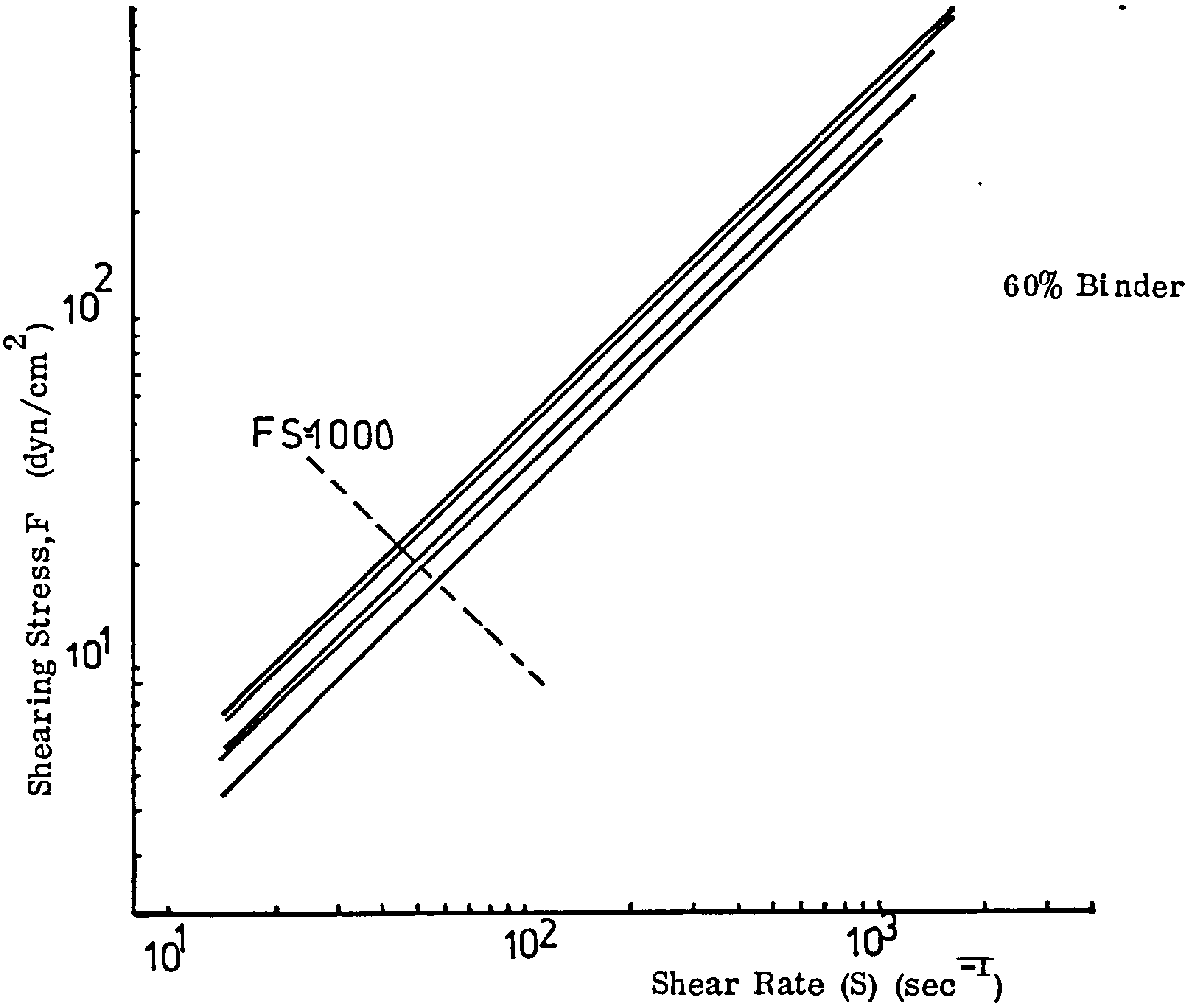


Fig. 7.5 RHEOLOGICAL BEHAVIOUR OF NH-10 WITH 60 PERC. BINDER CONTENT AT DIFFERENT TEMPERATURES (Binder grade 74 pen)

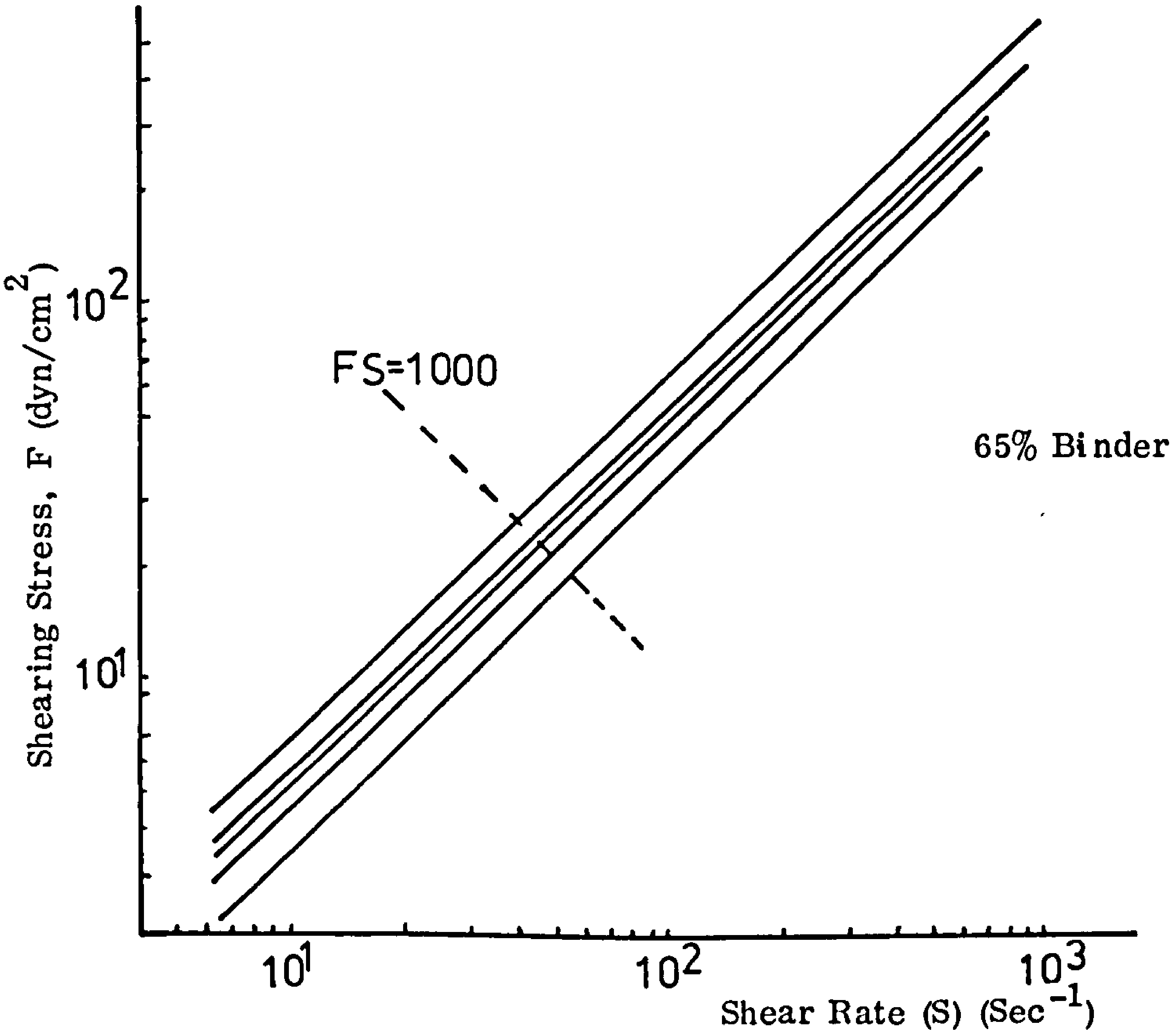


Fig. 7.6 RHEOLOGICAL BEHAVIOUR OF NH-10 WITH 65 PERCENT BINDER AT DIFFERENT TEMPERATURES (Binder grade 74pen)

It can be seen, Fig.7.5, 7.6, 7.7 and Table 7.2 that as the temperature increases and/or the binder content decreases, the coefficient of complex flow increases and tends to reach the value of 1.00. This means that at low binder contents and at temperatures above 20°C, the behaviour of the cationic NH-10 emulsion tends to a Newtonian flow. Similarly, as the binder content decreases and/or the temperature increases, the viscosity also decreases.

It is interesting to note the drastic change in flow and viscosity, when the binder content increases from 65 to 70 percent Fig.7.6 and 7.7 and Table 7.2). There is an increase in viscosity by a factor of the order of approximately 4.5 times, and the complex flow coefficient drops to a minimum of 0.94. The increase in viscosity due to binder content can be seen more clearly in Fig. 7.8.

The effect of temperature on the viscosity of the NH-10 emulsion is also shown on Fig. 7.9. It is apparent that the viscosity decreases as the temperature increases but also that there is a tendency for the viscosity to reach a limiting value above a certain temperature. The effect of temperature on the viscosity is more prounounced at high binder contents. It was found that for emulsions with 70 and 65 percent binder content, a decrease in temperature from 20°C to 12°C, caused in increase in viscosity of 36 and 33 percent respectively. The same temperature decrease caused only 20 percent increase in viscosity, when the emulsion had a binder content of 60 percent. This statement is of great importance because it shows the necessity to keep a strict temperature control during mixing particularly when emulsions with high binder content are used.

Comparing overall the effect of binder content and the effect of temperature on the viscosity of the NH-10 emulsion, it can be said that the effect of binder content is more important than temperature, at high binder contents, and the reverse is true at low binder contents. It was

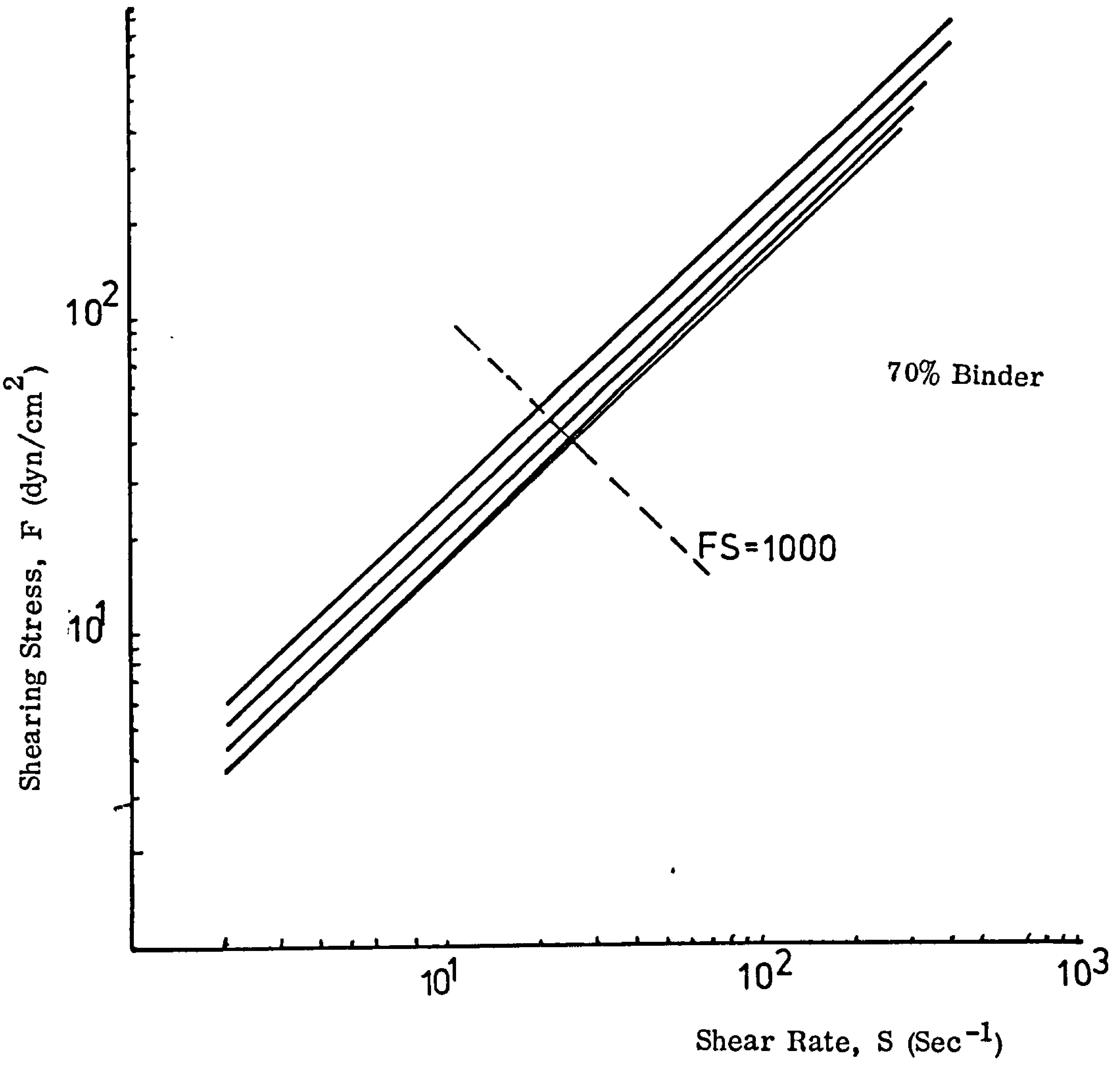


Fig. 7.7. RHEOLOGICAL BEHAVIOUR OF NH-10 WITH 70 PERCENT BINDER, AT DIFFERENT TEMPERATURES

(Binder grade: 74pen)

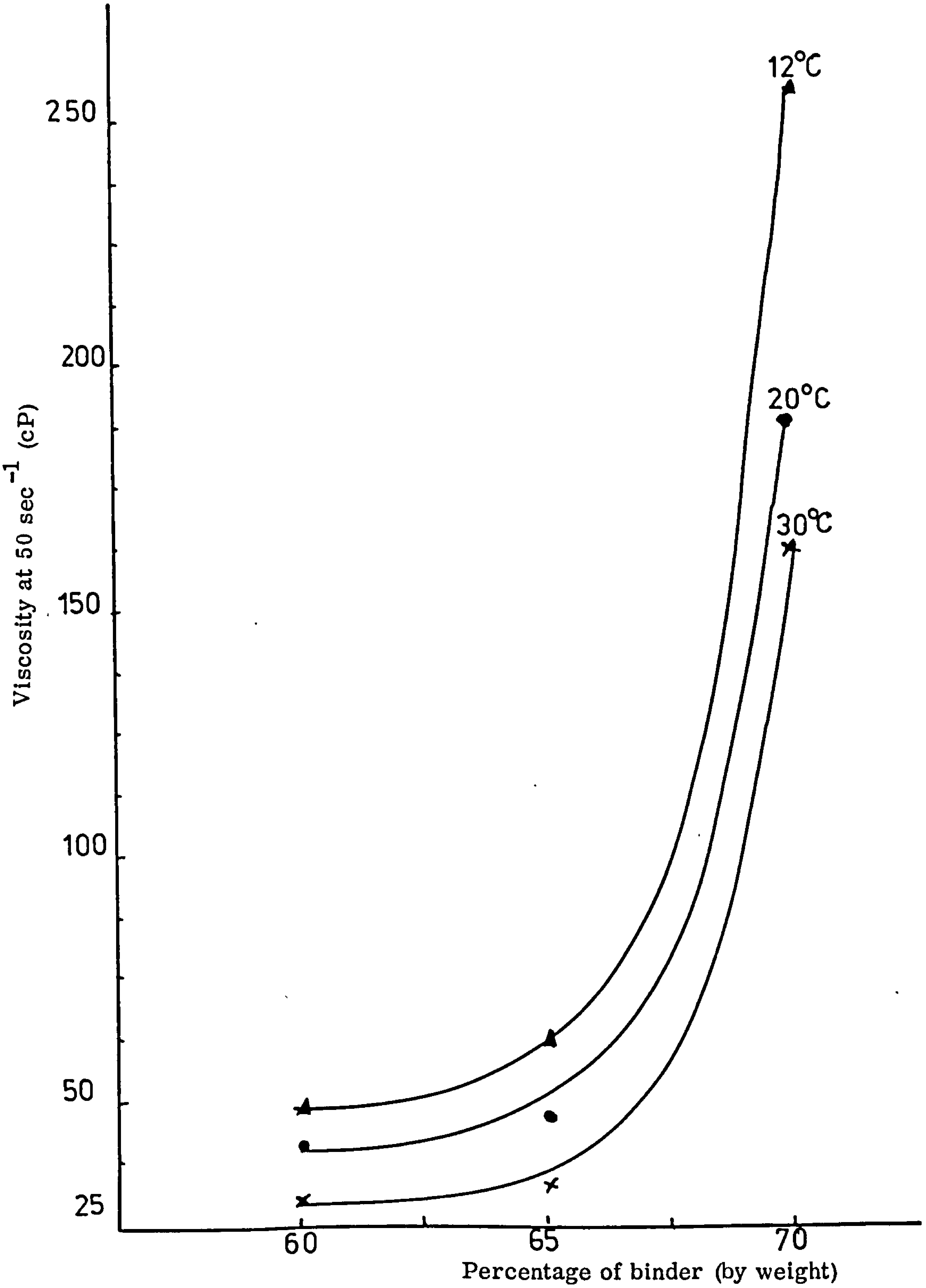


Fig. 7.8 EFFECT OF BINDER CONTENT ON THE VISCOSITY OF NH-10 EMULSION (Temperature varied)

found that viscosity increased by a maximum of 385% (at 30°C) when the binder content increased from 65 percent to 70 percent and only 58 percent when the temperature dropped from 30° to 12° (at 70% binder content level). Conversely, there was only 25% maximum viscosity increase as the binder content increased from 60 to 65 percent (at 12°C) but 57 percent for the temperature decrease from 30° to 12°C (at 60% binder content level).

7.4.3. Correlation between Rotational Glass capillary and Engler viscometers

As was shown in the previous section, the flow of the NH-10 cationic emulsion was non-Newtonian. To examine whether the non-linear behaviour creates any difficulty in obtaining reproducable results when apparatus for Newtonian fluids is used, further tests were carried out using the Glass capillary viscometer. The emulsion used was the one with the highest coefficient of complex flow i.e. the emulsion with 70 percent binder content and with a binder of 74 penetration grade.

Similarly, investigation was also carried out to find whether or not an Engler viscometer produces reproducable results with emulsions possessing relatively high viscosities. British Standard, BS434 (45) suggests that at low temperatures and at high viscosities, exceeding 25 Engler degrees, the non-Newtonian behaviour is more likely to cause difficulties in obtaining reproducable results.

7.4.3.1 Correlation between Rotational and Glass capillary viscometers

The Glass capillary viscosity tests were carried out according to British Standard BS 188:1977 (180) at five different temperatures. The preparation and procedure of the test is also outlined in Chapter 5.

The results obtained have been tabulated in Table 7.3. Column 4 gives the repeatability of measured time as a percentage of their mean. British Standard BS188 requires a percentage repeatability of 0.35 or less. Column 5 gives the calculated kinematic viscosity in mm^2/sec while column 6 gives the equivalent dynamic viscosity in centipoise, assuming that the density of the emulsion does not vary appreciably between the temperature range of 12°C to 30°C and is equal to 1.020 gr/am^3.

U-TUBE REVERSE FLOW VISCOMETER, BS/IP/RF NO.5/146
U-TUBE COEFFICIENT C = 0.292

Temperature °C	Time (sec)	Average Time (sec)	Repeatability (% of the mean viscosity)	Kinematic Viscosity mm^2/sec	Dynamic from Kinematic (cP)
1	2	3	4	5	6
	858.3		(-0.94)		
12	850.3	850.3	±0.94	248.3	253.3*
	842.3		(+0.94)		
	717.2		(-0.75)		215.2
16	723.8	722.6	±0.75	211.00	
	726.8		(+0.58)		
	641.6		(-0.09)		
20	640.4	641.0	±0.09	187.17	190.9
	641.1		(-0.09)		
	562.4		(-0.27)		
25	561.4	562.9	±0.27	164.37	167.7
	565.0		(+0.09)		
	509.1		(-0.36)		
30	504.4	506.6	±0.57	147.81	150.8
	506.2		(+0.57)		

*Density, ρ, assumed to be 1.020 gr/cm^3 at all temperatures.

TABLE 7.3 KINEMATIC VISCOSITY MEASUREMENTS

From the repeatability values obtained, it is apparent that at temperatures lower than 20°C the non-Newtonian behaviour, corresponding to a complex flow coefficient of less than 0.95, causes difficulty in obtaining reproducable results, while at higher temperatures seems to cause no great problem.

In order to find the relationship between dynamic and kinematic viscosity, the two viscosities together with a 45° degrees line were plotted and are shown in Figure 7.10. It can be seen that there is a good agreement between the two viscosities, within 20 and 25°C but that this tends to deteriorate slightly at both ends of the temperature range. The reason for this is thought to be the distinct non-Newtonian behaviour of the emulsions at the lower end and the change of shear rate in the capillary tube due to temperature changes. Therefore, it may be said that, for practical purposes and within the temperature range of 20°C to 25°C the dynamic viscosity of NH-10 cationic emulsion can be measured with the Glass capillary viscometer.

Also, from the same Figure 7.10, it is apparent that dynamic viscosities measured at a shear rate of 50 $\sec^{-1}$, from the log log shearing stress/shear rate diagram, correlate better with the kinematic viscosities, than viscosities measured at 1000 erg/sec/ml energy input.

7.4.3.2. Correlation between Rotational and Engler viscometers

The Engler viscosity test is the standard method of measuring the viscosity of an emulsion. The results obtained can only be used for classification purposes. British Standard BS434:1973 recommends that any emulsion having a viscosity greater than 10°E (Engler degrees) is rejected as being not suitable for bituminous emulsion mixtures.

The tests were carried out according to BS434 at a temperature range similar to that used in the Glass capillary tests (i.e. 12°C - 30°C). The data obtained were tabulated on Table 7.4.

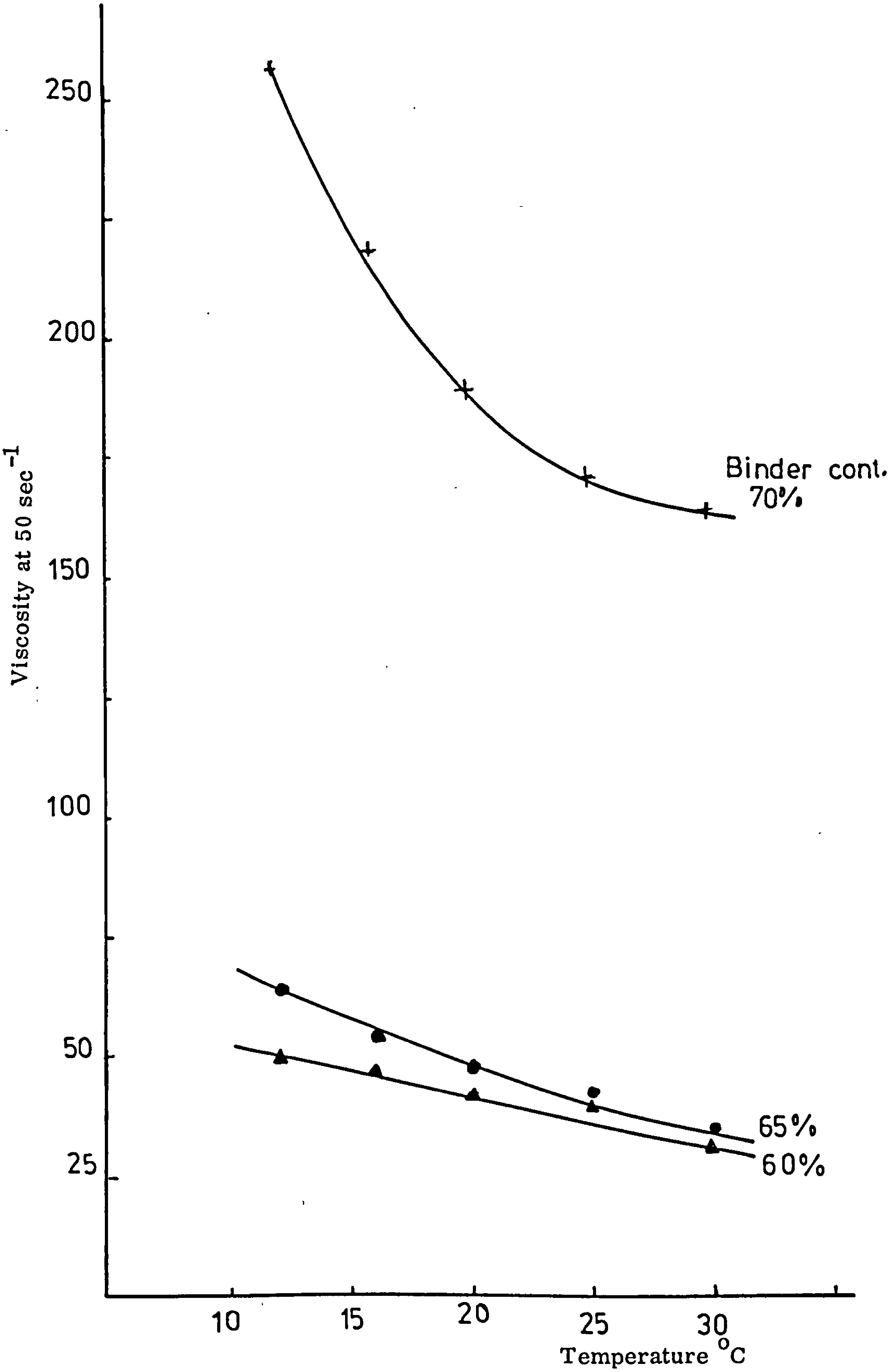


Fig. 7.9 EFFECT OF TEMPERATURE ON THE VISCOSITY OF NH-10 CATIONIC EMULSION

From Table 7.4, it can be seen that despite the fact that the emulsion possessed a viscosity much greater than 10°E and a certain degree of thixotropy, there was absolutely no difficulty in obtaining acceptable repeatability results. British Standard BS434 recommends repeatability values greater than 5% of their mean and all tests gave repeatability results between 0.1 to 1.7% of the mean.

NH-10 CATIONIC WITH 70 PERCENT BINDER OF 74 PEN. GRADE					
	TEMPERATURE (°C)				
	12°C	16°C	20°C	25°C	30°C
Viscosity (Engler degrees E°)	37.7	36.8	35.2	29.6	28.4
* Repeatability % of the mean	1.5	0.4	0.1	1.7	0.9

*Maximum permissible, by BS434:1973, 5% of the mean

TABLE 7.4 ENGLER VISCOSITY MEASUREMENTS

The relationship between dynamic viscosity and Engler viscosity is shown in Figure 7.11. It was found that within the temperature range of 12 - 30°C and using this type of emulsion, the best correlation ($r=0.909$) was obtained from the exponational relationship given in equation 7.4 below.

$$\text{Dynamic viscosity (cP)} = 1.96\ (\text{Engler})^{1.32} \quad \ldots \text{eq.7.4}$$

The above equation may be used to estimate dynamic viscosity within the temperature range of 12 - 30°C, and when the binder content is 70 percent. Comparing the value of viscosity at 20°C obtained by equation 7.4 with the value obtained by using the conversion factor

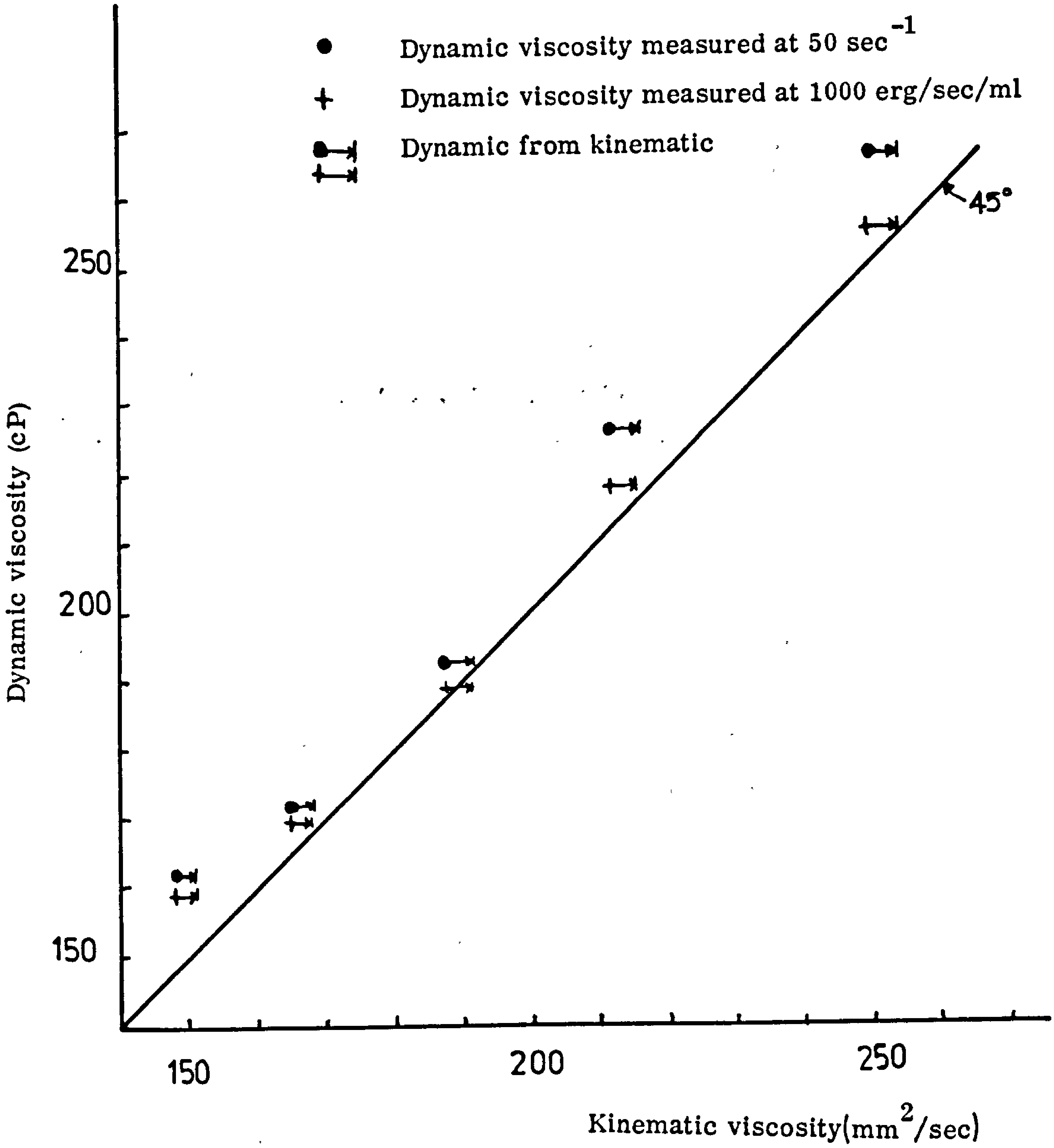


Fig.7.10 RELATIONSHIP BETWEEN DYNAMIC AND KINEMATIC VISCOSITY

proposed by Bates (177), it was found that equation 7.4 underestimates viscosity by approximately 15 percent. It is apparent that for better accuracy of the equation 7.4, more tests should be carried out at shorter temperature intervals.

The relationship between Engler viscosity and temperature is shown on Figure 7.12 and as expected, the viscosity decreased as the temperature increased. The relationship seemed to be linear since the linear correlation coefficient (r = 0.967) was fractionally better than the semi-log relationship (0.969), within the temperature range of 12°C to 30°C.

7.5 Compliance of NH-10 Cationic emulsion with proposed specifications

It is interesting to examine at this stage how NH-10 cationic emulsion with 70 percent binder content using 74 penetration grade binder, complies with British Standards and similar requirements proposed by other countries, in terms of viscosity.

British Standard BS434 recommends maximum viscosity of 10°E at 20°C for slow setting emulsions. It was found that NH-10 with 70 percent binder had a viscosity of 35.2°E and therefore this type of emulsion is not suitable for mixing the aggregates. Using equation 7.4 and assuming that it is valid for any binder content, the only emulsions that would satisfy BS434 would be the ones with 60 percent or less binder content.

American Standards, ASTM D977-77, measure the viscosity of an emulsion in Saybolt Furol units (seconds) and recommend a maximum of 100 seconds at 25°C for slow setting emulsion. Converting this to Engler degrees is equivalent to 30°E at 25°C. NH-10 emulsion at 25°C was found to have Engler viscosity of 29.6°E and therefore it just qualifies to be used for emulsified bituminous mixtures.

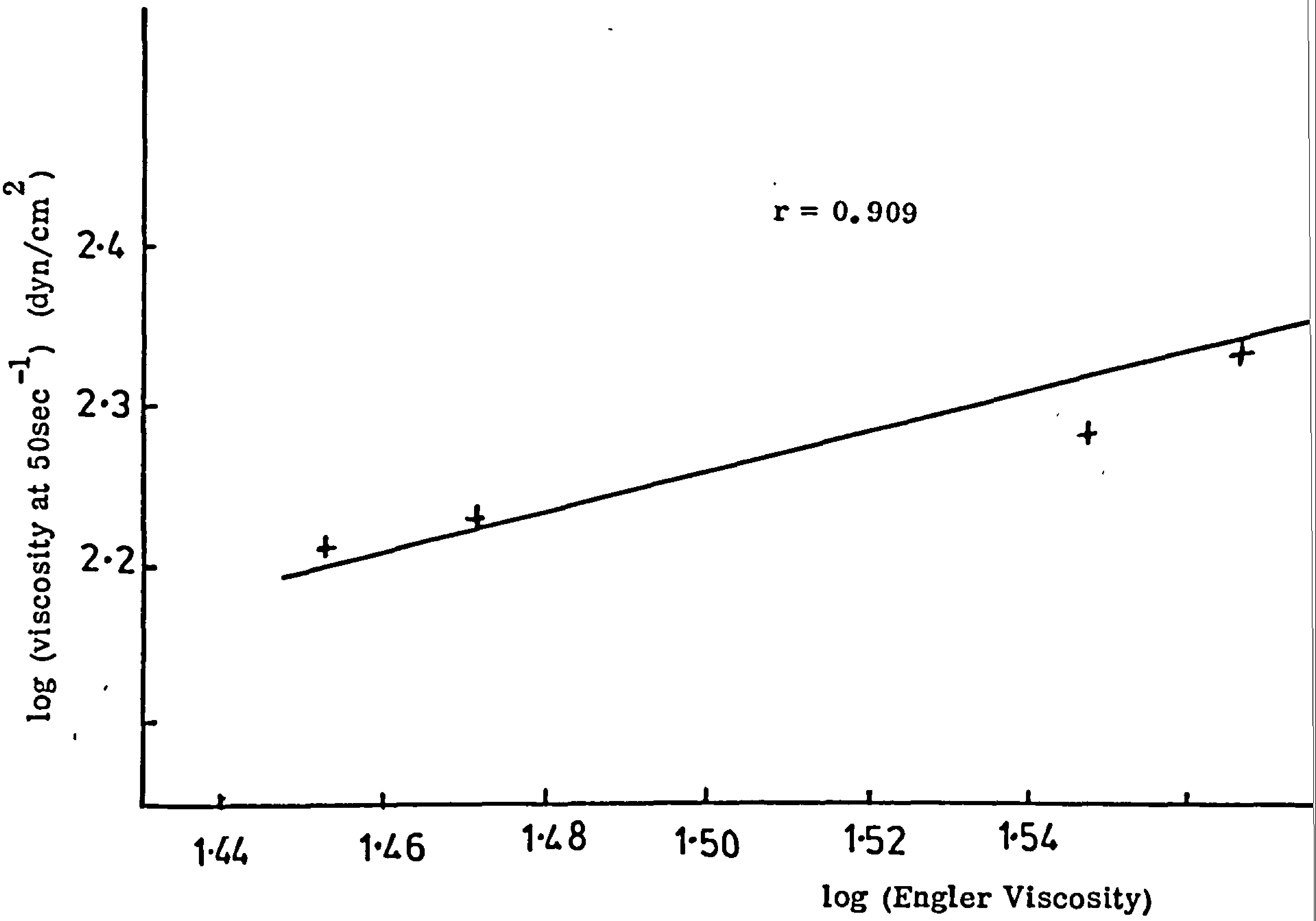


Fig. 7.11 RELATIONSHIP BETWEEN ROTATIONAL AND ENGLER VISCOMETER

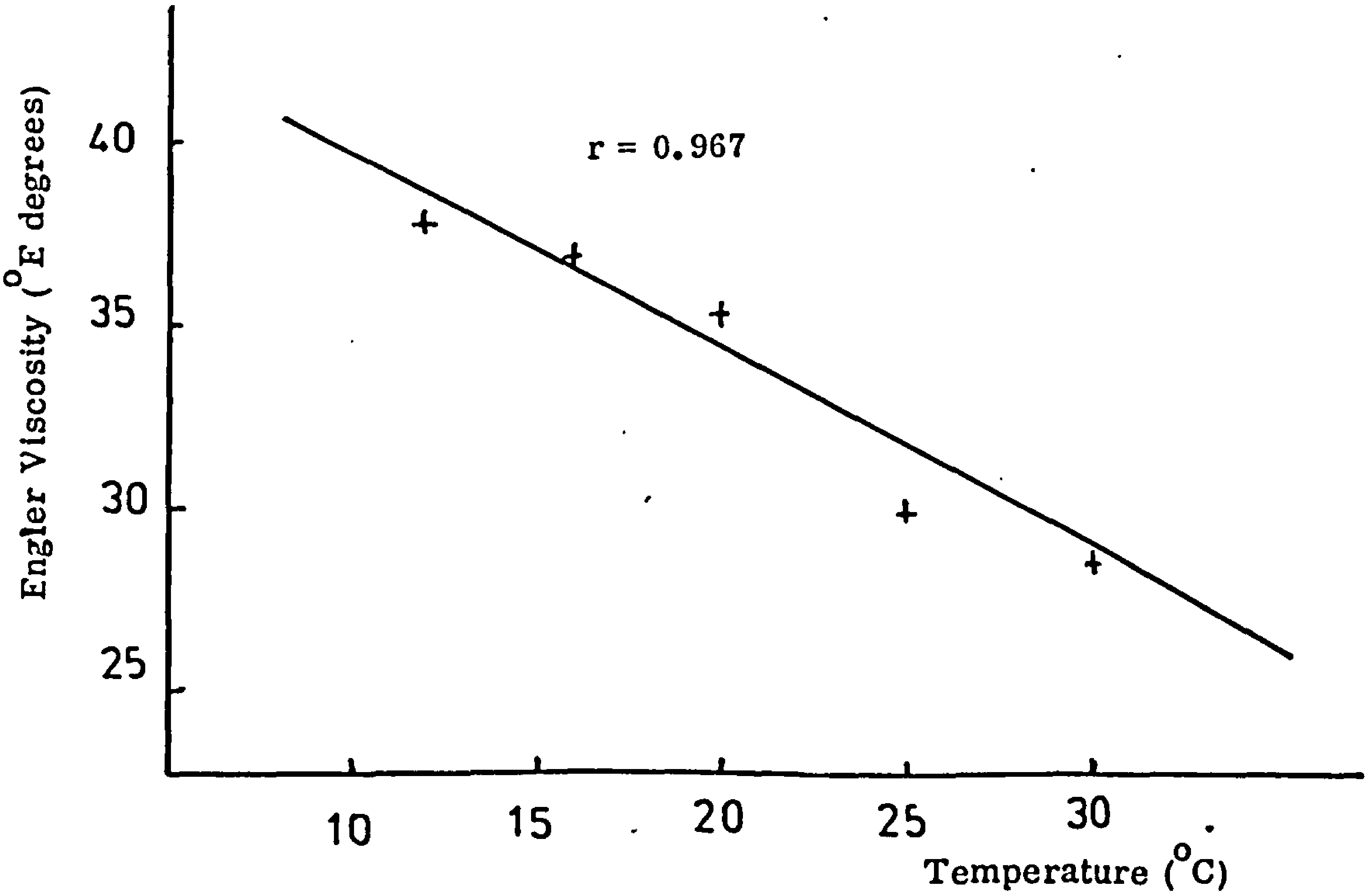


Fig. 7.12 ENGLER VISCOSITY WITH TEMPERATURE

French specifications (178) impose a viscosity susceptibility requirement and this does not seem to be restricted to maximum viscosity limit. It simply classifies any emulsion with Engler viscosity between 15 - 30°E as viscous and requires a susceptibility value of viscosity of less than 30%, if the temperature is decreased from 20°C to 10°C. The viscosity of NH-10 at 10°C found to be 39.5°E (Fig 7.12) which when compared to viscosity at 20°C, gives a susceptibility value of 12.2%. Therefore, according to the French specification the NH-10 cationic emulsion satisfies both requirements and thus it can be used for the production of emulsified bituminous mixture.

Finally, the German specifications, DIN 1995, a copy of which is given in Ref.(122) require a minimum Engler viscosity instead of a maximum, but with respect to slow setting emulsion no minimum value is given.

In the author's opinion British Standard BS434 does not cover a wide range of emulsions that could be used in emulsified bituminous mixtures. The requirement of maximum viscosity of 10°E is perhaps adequate for those emulsions which are going to be sprayed, but is very conservative for the emulsions which are going to be mixed with aggregates. Additionally, emulsions with viscosities lower than 10°E are associated with high water contents and if they are used for the production of emulsified bituminous mixtures they may result in extremely wet mixtures.

In view of the above, it is suggested that the British Standard BS434 should be amended. The amendments should include a susceptibility requirement for the viscosity of the emulsion as well as an increase in the maximum permissible viscosity limit. The susceptibility requirement of 30 percent imposed by French specifications is apparently too high. It can be suggested in view of all the above, that these amendments should be in the region of 35°E maximum at 20°C, and 20 percent viscosity susceptibility when the temperature decreases from 20°C to 10°C.

7.6 Summary and Conclusion

In this chapter the types of flow of two cationic emulsions were investigated and it was found that both possessed non-Newtonian flow. The specially formulated cationic slow setting emulsion, NH-10, for base course mixtures was found to have non-Newtonian rheological behaviour which was more distinct at binder contents above 65 percent. There was a strong indication that the commercially available Redicote E-11 slow setting emulsion, normally used in slurry sealing, possesses rheopexic behaviour and therefore its use in base course emulsified material is doubtful.

Further investigation of NH-10 emulsion revealed that the binder content causes greater changes in viscosity than temperature changes between the range of 12^{o} to 30^{o}C but nevertheless, the effect of temperature should not be underestimated.

The binder grade at a constant binder content does not seem to have any significant effect on the viscosity on the emulsion.

Despite the non-linear flow behaviour of the NH-10 emulsion, viscosity measurements between Rotational viscometer and Glass capillary viscometer have shown good agreement within the temperature range used (12^{o}C to 30^{o}C).

Out of the two proposed methods for measuring the dynamic viscosity, the one which uses a fixed shear rate of 50 sec^{-1} gives better results than the other method using a fixed power input of 1000 erg/sec/ml, when compared to viscosity obtained by the Glass capillary viscometer.

Finally, it is felt that British Standard BS434 does not cover a sufficiently wide range of emulsions and therefore rejects emulsions which might be suitable for emulsified mixtures. It has been pointed out that amendment is necessary and it has been suggested that this amendment should include a viscosity susceptibility requirement of 20 percent between 20^{o}C and 10^{o}C, together with an increase in viscosity from 10^{o}E to 35^{o}E at 20^{o}C.

CHAPTER 8

MODIFIED MARSHALL DESIGN AND PERMEABILITY MEASUREMENTS OF THE COLD ROLLED ASPHALT (C.R.A.) MIXTURES

8.1 Introduction

The evaluation of properties of the cationic emulsions, which led to the selection of a suitable emulsion for use in dense graded emulsified bituminous mixture, was carried out in Chapters 5 and 6. The subsequent two chapters evaluate the properties of the Cold Rolled Asphalt mixtures (C.R.A.), highlighting the effect of binder content, water added and curing time on the properties of these mixtures.

Cold Rolled Asphalt mixtures are mixtures with identical aggregate gradation as that required for Hot Rolled Ashpalts but with the difference that the binder is introduced to the system in a bituminous emulsion form and the mix preparation is carried out at ambient temperature. Rolled Asphalt mixtures, in general, are dense and impervious mixtures, they do not undergo any appreciable compaction by traffic after laying and when they contain a suitable stone content have great mechanical strength.

The determination of the properties of the C.R.A.s was carried out in terms of modified Marshall design parameters and permeability values, while the evaluation of the effect of the independent factors was supported by statistical analysis.

8.2 Design of the experiment

The effect of binder content*, added water** and curing time was examined as a factorial design; this is shown in Table 8.1. It can be seen that six levels of binder content and three levels of added water were

COMPACTION CONDITIONS	CURING TIME (days)	BINDER CONTENT (by wt. at dry aggr.) (percent)	ADDED WATER (Percentage by weight at dry aggregate)		
			1.5	3.0	4.5
Temp = 21°C Total w/c= 3%	1 day (early stage conditions)	7	x	x	x
		8	x	x	x
		9	x	x	x
		10	x	x	x
		11	x	x	x
		12	x	x	x
	5 days (final curing condition)	7	-	x	x
		8	-	x	x
		9	-	x	x
		10	-	x	x
		11	-	x	x
		12	-	x	x
Temp = 40°C w/c = 3%	1 day	7	-	x	-
		8	-	x	-
		9	-	x	-
		10	-	x	-
		11	-	x	-
		12	-	x	-
	5 days	7	-	x	-
		8	-	x	-
		9	-	x	-
		10	-	x	-
		11	-	x	-
		12	-	x	-

TABLE 8.1 FACTORIAL DESIGN FOR STUDYING THE EFFECT OF BINDER, ADDITION OF WATER AND TEMPERATURE AT COMPACTION ON THE PROPERTIES OF C.R.A. MIXTURES

used at the initial stage of the investigation. After careful examination of the results, the levels of added water were reduced to two. The levels of curing periods, however, were fixed to two throughout the investigation. These two levels corresponded, as explained in Chapter 5 to early curing and final curing of the specimens or pavement.

A limited study was also undertaken in order to examine the effect of warm compaction (40°C) on the properties of C.R.A. It was believed that the workability of the mixtures could be improved, as well as some of the properties of the mixture, and in particular the early curing stability. The added water level at this stage was reduced to only one level but all the other levels of the parameters remained the same.

Six specimens were prepared for each design cell, three to be tested under "dry" conditions and three under "wet" conditions. Dry conditions were defined as testing the specimens for modified Marshall stability after curing, while wet conditions as testing the specimens for modified Marshall stability after being subjected to capillary soaking for 48 hours.

The cationic emulsion used was the NH-10 type with 70 percent binder content of 74 penetration grade. The aggregates used were crushed limestone from Pateley Bridge, washed sand from Almingham and limestone filler. They all complied with BS594 specifications for Rolled Asphalt mixtures. The gradation used, shown in Chapter 4, complies with BS594 specifications as 10mm nominal dense wearing course mixture.

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*Binder content, throughout this work refers to binder content as a percentage of the weight of dry aggregate.

**Added water, refers to water added to the aggregate prior to mixing with emulsion, and is expressed as a percentage of the weight of dry aggregate.

The preparation and mixing procedures were as described in Chapter 5 and all specimens were compacted using the Gyratory Testing Machine (G.T.M.). Only one level of compaction was used for all mixtures, and that was 30 revolutions with the axial pressure at 1.38 MPa (200psi) at 1^{o} angle of gyration. The total water content at compaction was fixed at 3.0 percent by weight of dry aggregate, for reasons explained in Chapter 5.

Finally, all the data was processed by a computer programme especially written to do all the necessary calculations for the modified Marshall design. This is shown in detail in Appendix E.

8.3 Statistical analysis - Analysis of Variance (ANOVA)

The statistical analysis of the results of the factorial design was carried out by the ANalysis Of VAriance (ANOVA), which was incorporated in the statistical computer package SPSS (192). Analysis of variance in a factorial experiment provides information not only of the effect of independent factors over the response variable (dependent factor) but also of the interaction between the independent factors. If an interaction is present, the independent factors cease to have as much meaning by themselves, and the effect of one factor will depend on the level of the other factor (193, 194).

A two-factor analysis of variance was used, to evaluate the C.R.A.s dependent variables. The levels of the main factors (independent variables) were fixed and the mathematical model describing this situation was as follows:

$$X_{ijk} = \mu + A_i + B_j + (A \times B)_{ij} + E_{ijk} \quad \cdots \; 8.1$$

Where X = the dependent variable

μ = over all average

A_i = effect of binder content at ith level

B_j = effect of added water at jth level

E_{ijk} = random error due to k-time replicate of the experiment

i = levels of binder (6 levels, $i = 1, 2, 3, 4, 5, 6$)

j = levels of added water (originally 3 levels, $j = 1, 2, 3$, then two levels, $j = 2, 3$)

k = 3

The six levels of binder content were coded from 1 to 6 corresponding to 7, 8, 9, 10, 11 and 12 percent binder content. Similarly, the three levels of added water were coded 1, 2 and 3 corresponding to 1.5, 3.0 and 4.5 percent of added water.

The dependent factors used for the evaluation of the properties of C.R.A. were as follows:

i) Bulk Density (BD) at testing, (gr/cm^3)

ii) Air Voids (AV) in the compacted specimen (percentage)

iii) Total Voids (TV) in the compacted specimen, includes air voids and voids filled with water (percentage)

iv) Voids in the Mineral Aggregate (VMA), volume of total voids plus volume of binder, expressed as a percentage of the total volume (percentage)

v) Permeability (air), (cm^2)

vi) Dry Marshall Stability (MS_d),stability measured at room temperature without the specimens being subjected to capillary soaking (kN).

vii) Wet Marshall Stability (MS_w), stability measured at room temperature after specimens had been subjected to capillary soaking (kN).

viii) Dry and Wet Flow (F_d and F_w), Marshall flow corresponding to wet and dry stability (mm)

ix) Dry and Wet Marshall Quotient (MQ_d, MQ_w), Marshall Quotient (Stability/Flow) corresponding to dry and wet conditions (kN/mm)

x) Water Content at testing (WC), the percentage of water retained by the specimen at the time of stability testing. Expressed as a percentage by total weight of the specimen, (percentage)

The results produced by the analysis of variance are shown in Tables 8.2, 8.3, 8.4 and 8.5 and will be interpreted in conjunction with the physical trends of the measured parameters in the subsequent sections. A typical analysis of variance computer output is given in Appendix F.

8.4 Results and discussion

8.4.1. The effect of binder content and added water on the properties of C.R.A. during the early stage of curing

The early stage of curing was defined in Chapter 5 as one day air curing at controlled air temperature and humidity level ($21^o \pm 1^o$C, and 65 degrees humidity). During this time the specimens lost 9.5 to 27 percent of their total water content, Fig. 5.8 (Chp. 5), depending on the percentage of binder content. This laboratory curing may correspond approximately to three to four months of field curing since Darter et al (66) have shown that three days air curing followed by 48 hours of soaking give results equivalent to 3 to 4 months on site.

It must be emphasised that in order to examine the effect of added water on the physical properties of C.R.A. independently of water content at compaction, the water content at compaction was kept constant throughout the investigation. This water content was chosen to be 3.0 percent by total weight of the specimen for reasons explained in Chapter 5.

The results of the statistical analysis, shown in Table 8.2 have been drawn from six data per design cell, while those in Table 8.3 are from three per design cell.

8.4.1.1. The effect on bulk density(BD)and Compacted Aggregate Density (CAD)

The bulk density at testing obtained at various binder contents and at three levels of added water, has been plotted in Figure 8.1. It can be seen that as the binder content increases the bulk density also increases at all added water levels, until a maximum is reached. The maximum value is obtained at 9 percent binder content, for all added water levels. Mixtures with 1.5 and 3.0% appear to have, overall, higher bulk densities than mixtures with 4.5 percent added water, but statistical analysis has shown that this effect is not significant, Table 8.1. The effect of the binder content, though, together with the interaction of the independent factors was found to be highly significant. This means that although the binder content significantly affects the bulk density, its effect depends on the level of water added.

Figure 8.2 shows the changes in Compacted Aggregate Density with binder content, at three levels of added water. The curves show similar trends as for the bulk density vs binder content relation. As expected the statistical analysis shows the same results as for the bulk density analysis.

8.4.1.2. The effect on Air Voids (AV), Total Voids (TV) and Voids in the Mineral Aggregate (VMA)

Statistical analysis of the relations, shown in Figures 8.3, 8.4 and 8.5, has shown that all the above dependent variables are significantly affected by the binder content. Added water alone has no significant effect unless it is considered in conjunction with the binder content. This again, reveals that the effect of binder content on all the above physical properties depends on the level of added water.

ONE DAY CURING -C.R.A.					
Dependent Factors Independent	Bulk Density	Air Voids	Total Voids	V.M.A.	Permeability
Binder Content	S**	S**	S**	S**	S**
Added Water	NS	NS	NS	NS	S**
Binder Content and Added Water	S**	S**	S**	S**	S**

S** = Significant at 0.01 level of significance

NS = Not significant at 0.05 level of significance

TABLE 8.2 SUMMARY OF STATISTICAL ANALYSIS OF DENSITY, VOIDS, V.M.A. AND PERMEABILITY DATA, AFTER ONE DAY OF CURING

ONE DAY CURING -C.R.A.						
Dependent Factors Independent	Stability		Flow		Quotient	
	Dry	Wet	Dry	Wet	Dry	Wet
Binder Content	S**	S**	S**	S*	S**	S**
Added Water	S**	S**	S**	NS	S**	S**
Binder Content and Added Water	S**	S**	S**	S*	S**	S*

S** = Significant, at 1% level of significance

S* = Significant, at 5% level of significance

NS = Not significant, at 5% level of significance

TABLE 8.3 SUMMARY OF STATISTICAL ANALYSIS OF MARSHALL STABILITY FLOW AND QUOTIENT AT DRY AND WET CONDITION (ONE DAY CURING)

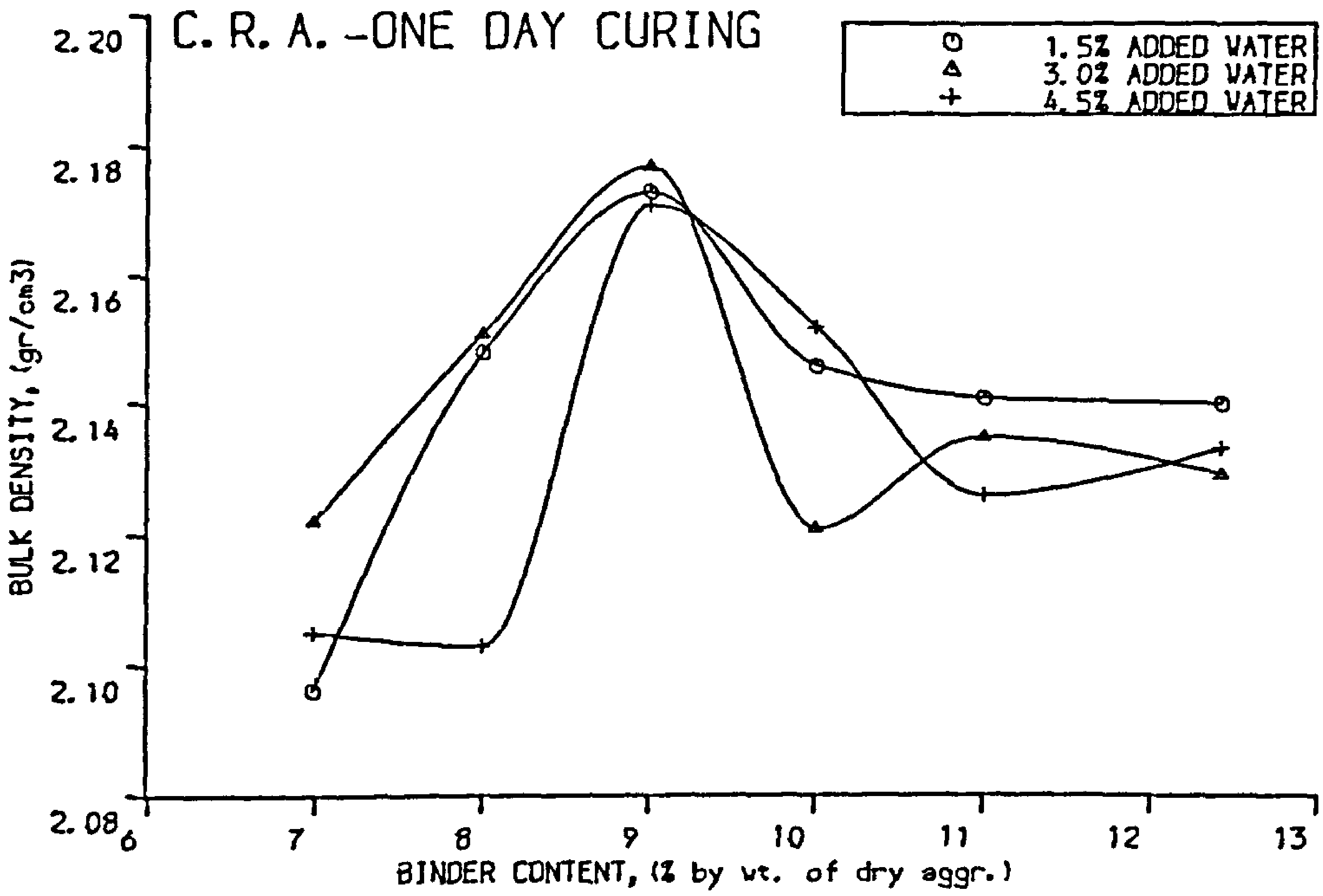


Fig. 8.1 BULK DENSITY v BINDER CONTENT

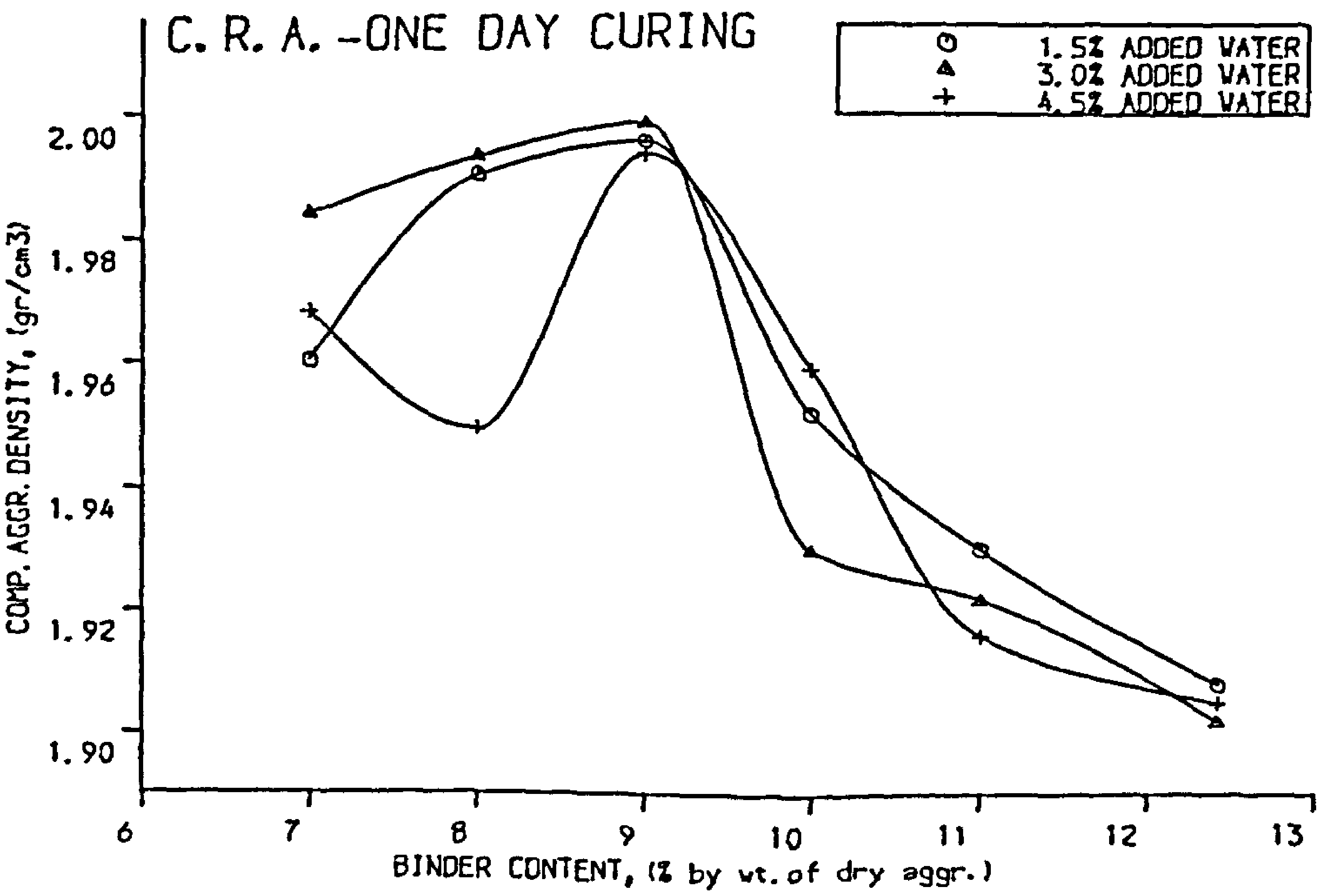


Fig. 8.2 COMP. AGGR. DENSITY v BINDER CONT.

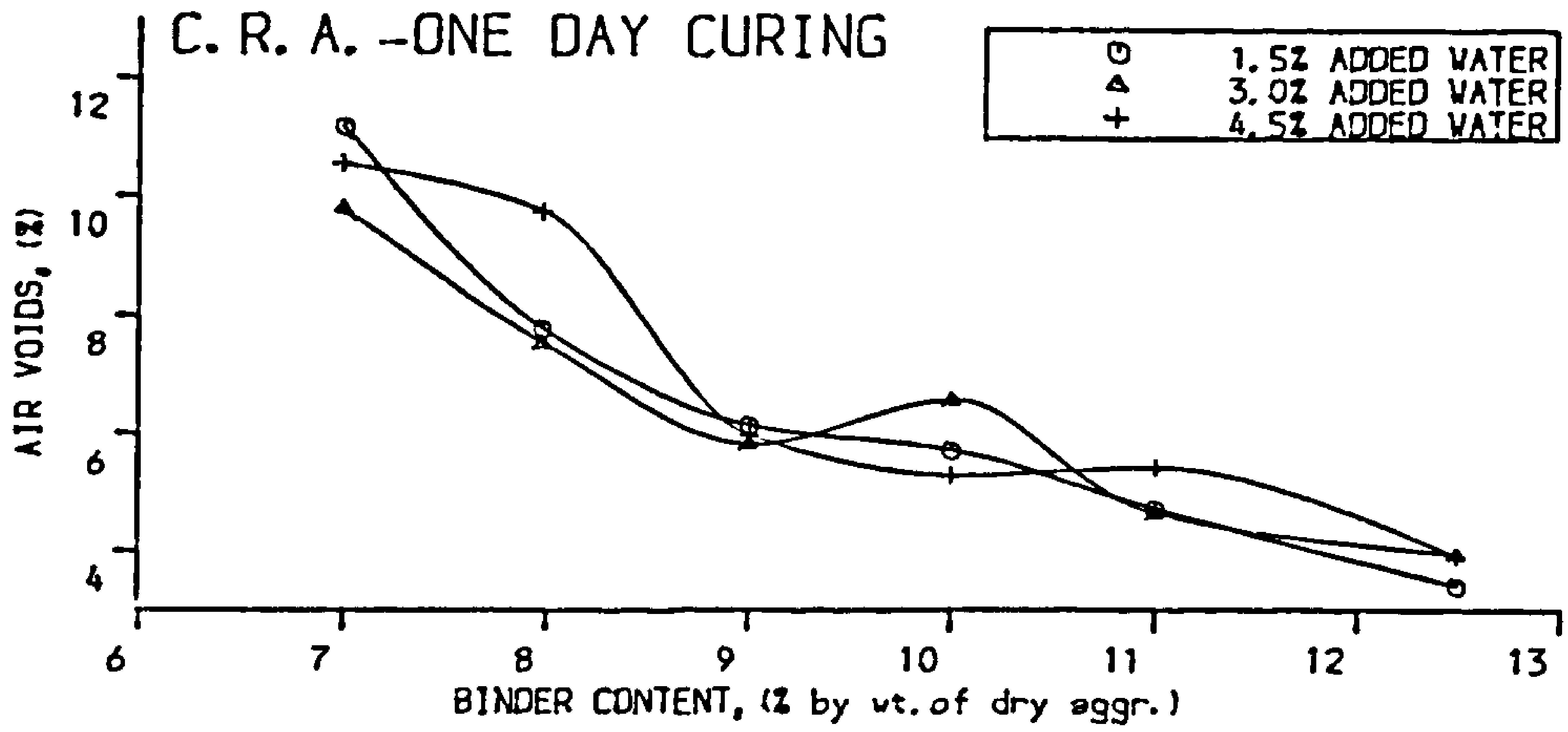


Fig. 8.3 AIR VOIDS v BINDER CONTENT

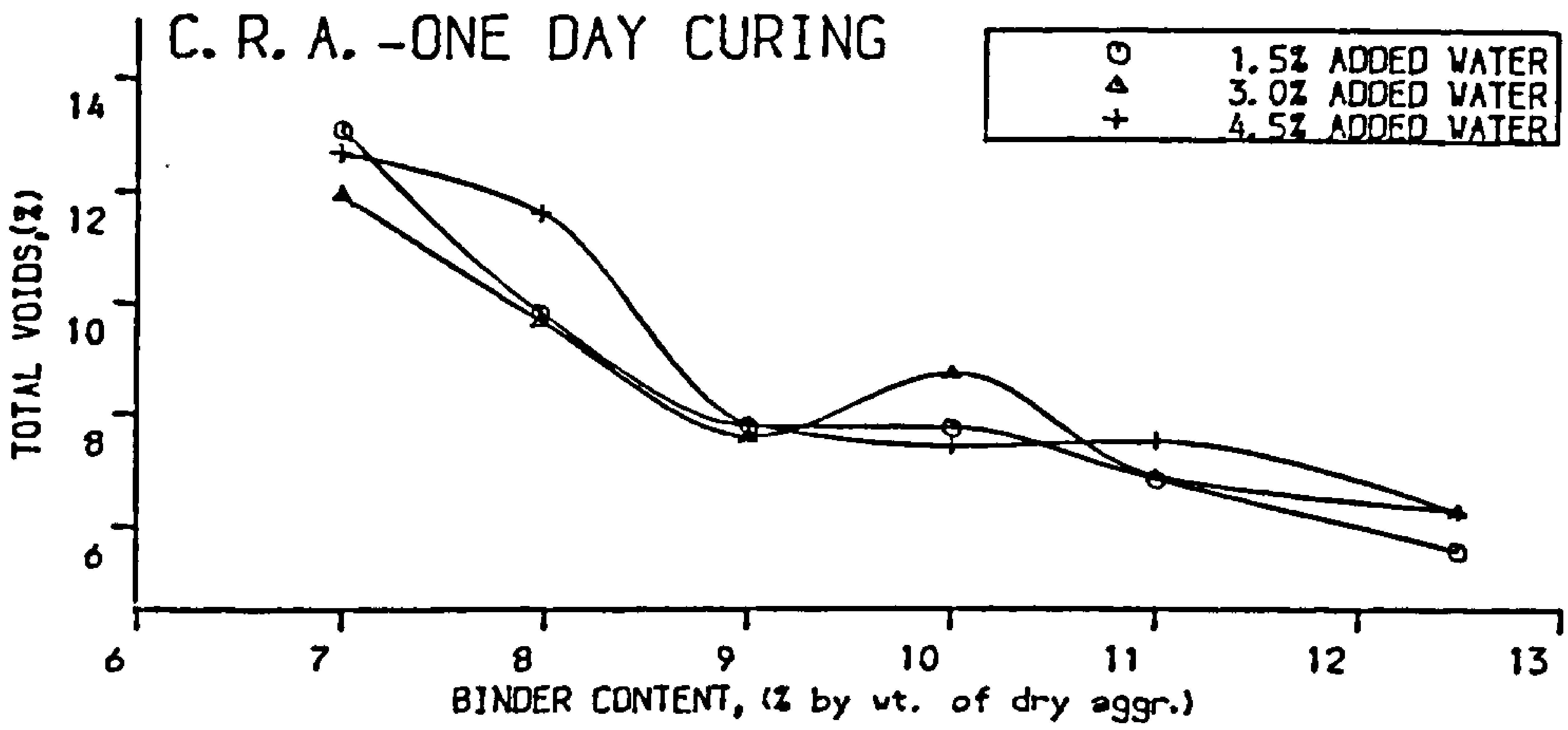


Fig. 8.4 TOTAL VOIDS v BINDER CONTENT

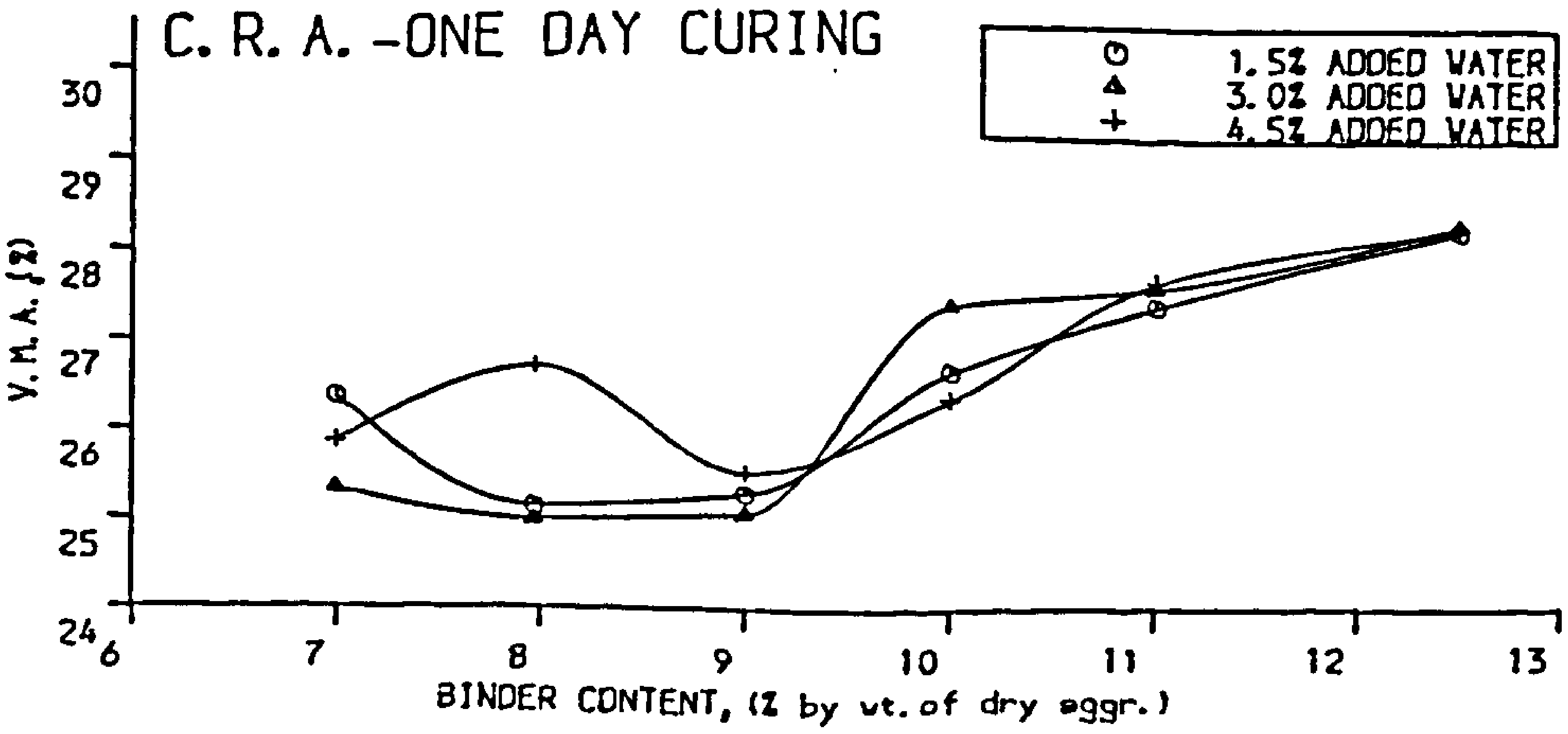


Fig. 8.5 V.M.A v BINDER CONTENT

Figure 8.3 shows that, initially, as the binder content increases, the air voids decrease rapidly, up to a certain percentage of binder content. The rate of decrease of voids then diminishes to almost zero. A closer examination of the results revealed that at around ten percent binder content, the percentage of air voids tend to increase slightly. The pattern of trend for total voids, Figure 8.4 was similar to air voids.

The change in VMA with respect to binder content was completely different to the air voids. In this case, the VMA slightly decreased as the binder content increased up to a certain level, above which it started to increase sharply.

The relations between air voids, total voids, VMA and binder content follows the same trends observed for hot rolled asphalt and other bituminous mixtures. It may be explained by the fact that as more binder is added into the matrix more voids are filled with binder and therefore the percentage of air voids and total voids decreases. The lubricating effect of the binder improves the packing of the aggregate matrix and therefore the VMA also decreases. After a certain percentage of binder further increase in binder overfills the system, destroys the maximum packing and the VMA increases.

Finally, the percentages of total voids vary between a minimum of 5.5% and a maximum of 13.0%, and the VMA between 25.0 to 28.3%.

8.4.1.3. The effect on Marshall properties

The one day cured specimens were tested at room temperature for Marshall stability and flow, and the resulting values were called "dry" Marshall stability and "dry" Marshall flow.

In order to examine the effect of water on Marshall stability, the specimens, having been cured for one day, were exposed for 96 hours in water (soaking test). They were then surface dried and tested for stability and flow. The resulting values were called "wet" Marshall stability and "wet" flow.

8.4.1.3.1. The effect on "dry" Marshall properties

The dry stability values were plotted against binder content, at all three levels of added water, and are shown in Figure 8.6. Statistical analysis of the results have shown, Table 8.3, that both factors, i.e. the binder content and added water together with their combined effect significantly affect the "dry" stability. The dry stability was increased as the binder content increased (Figure 8.6) without showing a clear maximum stability value apart from the mixture with 1.5% added water. The interesting point was that mixtures with different added water content possessed different dry stability. The difference in dry stability within mixtures with regard to added water content can be principally attributed to the degree of coating, since all the other factors which might influence the dry stability were kept constant, i.e. moisture content at compaction, compaction level, type of binder and aggregate gradation. The mixtures with 1.5 percent added water did not have enough water to facilitate good distribution of binder around the aggregate's surface, and the emulsion tended to break more easily leaving a number of aggregates partially and/or completely uncoated. It was observed that these mixtures had an excessive amount of uncoated fine aggregate (sand) especially when the binder content was at the lower end. As the percentage of added water was increased, the rate of "breaking" of the emulsion was reduced and hence the coating of the aggregates was improved. The slow rate of breaking results in a better distribution of binder and a reduction in the number of uncoated aggregates both of which contribute towards better stability.

Although an increase in the amount of added water improves the coating of the mixture and results in better dry stability, an excessive amount of water will produce a very wet mix which has two distinct

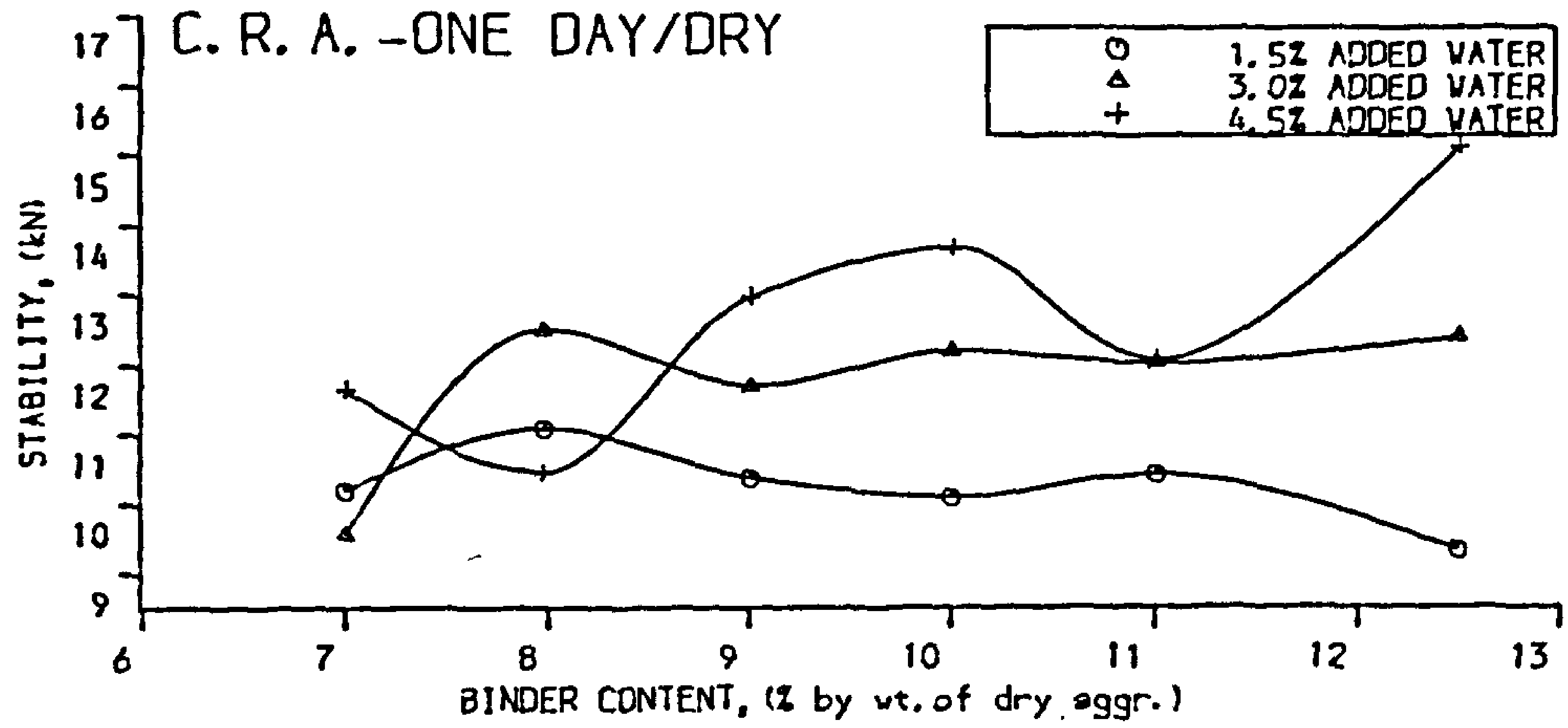


Fig. 8.6 MARSH. STABILITY v BINDER CONTENT

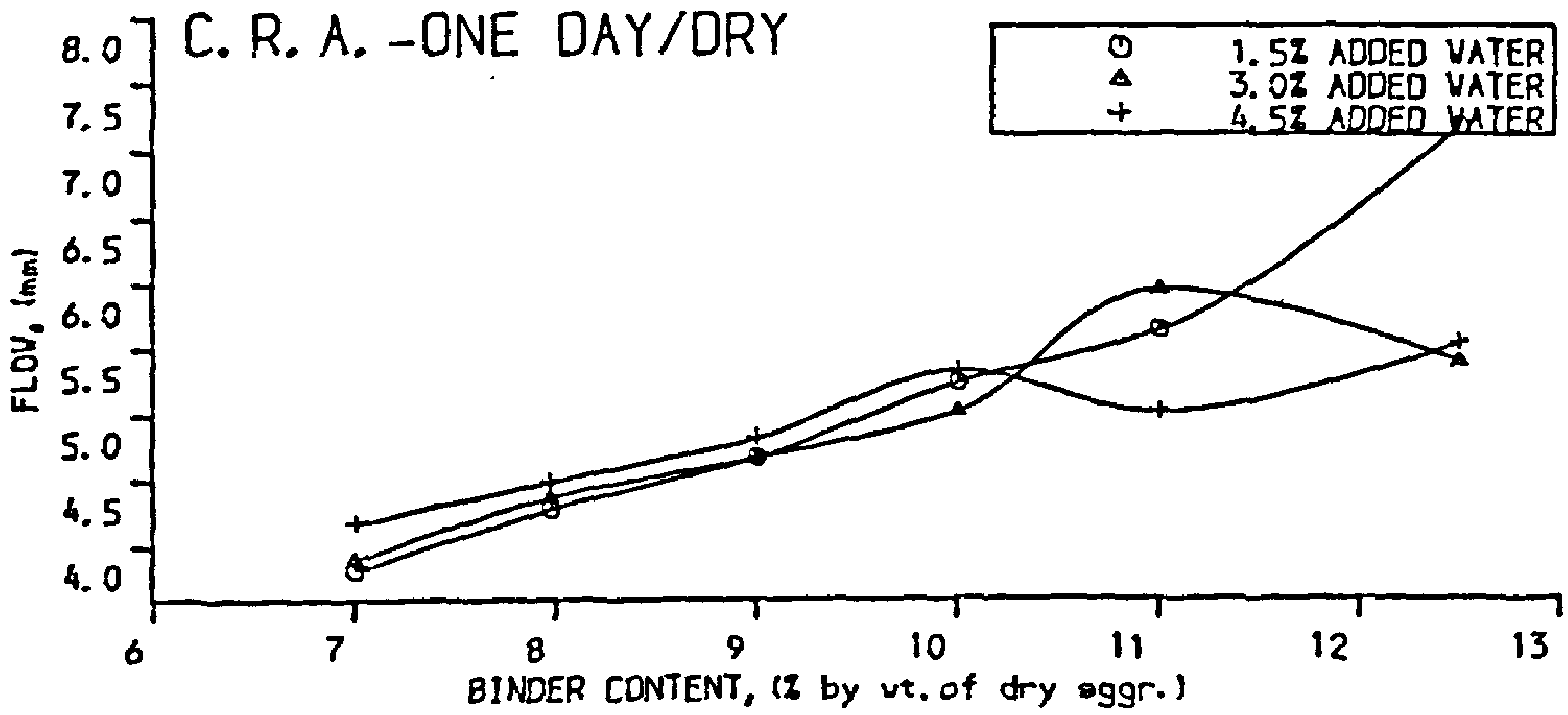


Fig. 8.7 MARSHALL FLOW v BINDER CONTENT

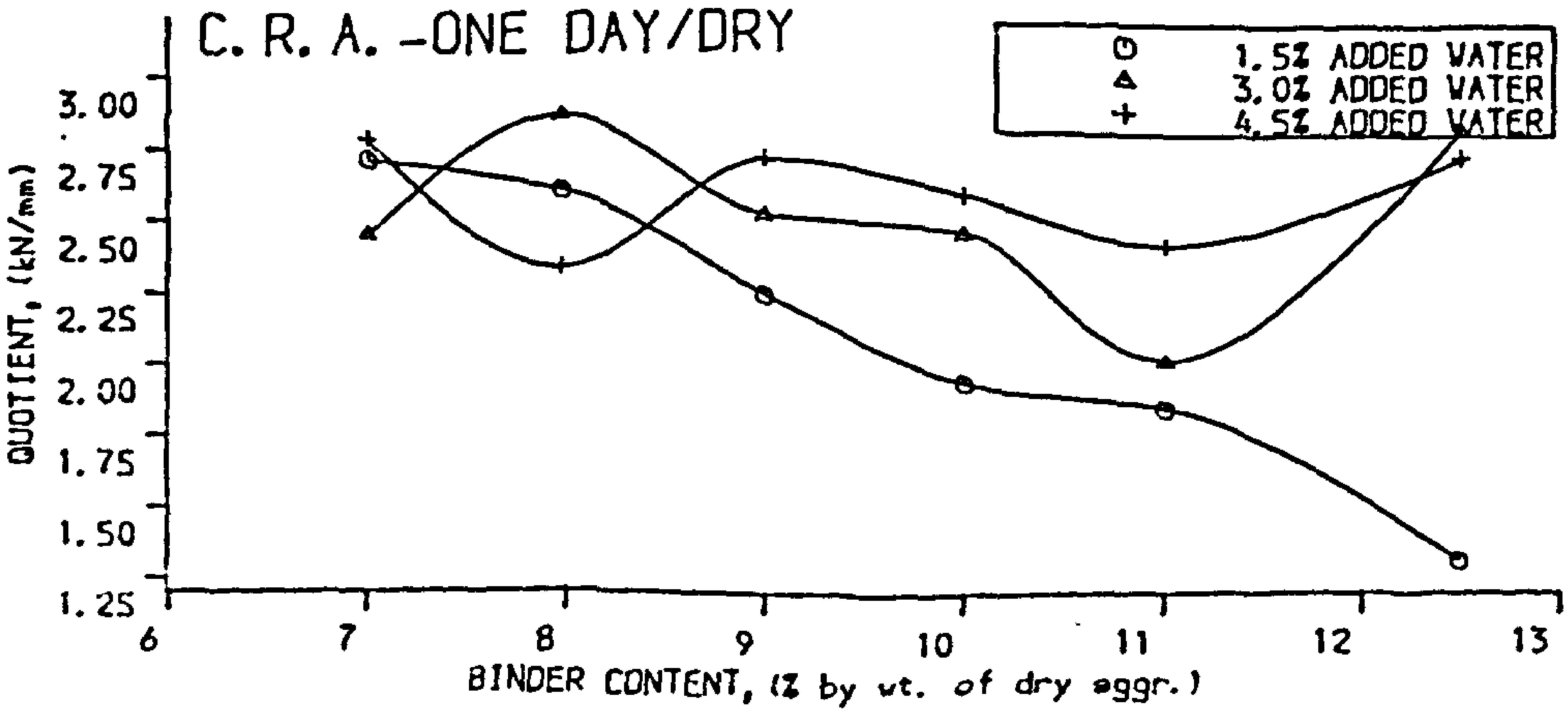


Fig. 8.8 MARSH. QUOTIENT v BINDER CONT.

disadvantages. These are the prolonged curing time and the "run-off" of the binder. The wetter mixtures will certainly require longer time for the water to evaporate in order to reach a certain content for compaction, and consequently a longer time for the emulsion to break completely. During the period of curing (because of the wetness of the mixture) the binder flows away from the aggregate, "run-off", and settles onto the bottom of the tray. Consequently this results in a reduction of the overall binder content of the mixture, which in turn leads to lean mixtures with low stability. It was found that mixtures with a 6.0 percent added water required double the curing time of other mixtures in order to reduce the total water content down to 3.0 percent. Despite the acceptable low dry stability results, these mixtures had to be abandoned due to the impracticability of drying the excessive amount of water down to the required total water content.

The dry Marshall flow values are given in Figure 8.7 and in general, they increase as the binder content increases. The rate of increase seems to slow down at high binder contents.

The mixture with 4.5 percent added water originally had slightly higher dry flow values than the other two. After a certain binder content however, (10 percent), the mixture with the least amount of added water possessed the highest flow values. The statistical analysis has shown, Table 8.3, that all factors significantly affect the dry Marshall flow, which reinforces the fact that the differences of flow values shown on Figure 8.7 are indeed significant.

It was suggested by Brien (195) that a better representation of the properties of conventional Hot Rolled Asphalt mixtures, certainly with respect to permanent deformation (196),was obtained by using the Marshall Quotient parameter. Marshall Quotient was defined as the ratio of stability (MS) over flow (F), (MS/ F). Dry Marshall quotient (MQ) values were plotted against binder content and are shown in Figure 8.8.

It can be seen that the MQ decreases as the binder content increases, with exception of the mixtures with 3.0 percent added water, which shows a maximum value at 8 percent binder content. Different added water contents produced mixtures with different MQ. The statistical analysis shows that this was statistically significant. As well as the interaction of the main factors, the binder content was also found to be statistically significant. The dry MQ values were found to range between 1.3 and 2.8 KN/mm.

8.4.1.3.2. The effect on "wet" Marshall properties

Statistical analysis of the "wet" stability data have shown, Table 8.3, that as well as the dry stability, the wet stability is also significantly affected by the two main factors and their interaction. Contrary to the trend of dry stability, the wet stability continues to increase as the binder content increases, Figure 8.9, but their values are lower than the dry stability values. Mixtures with 1.5 percent added water possessed lower wet stability values, but at the upper end of the binder content the mixtures with 4.5 percent possessed the lowest values.

The wet flow values were found to change erratically with binder content, Figure 8.10. There was no definite pattern, with respect to added water content and the statistical analysis showed that only the binder content and the interaction between binder and water affect the wet flow values (at a relatively lower level of significance of 5 percent).

The variability of the wet flow results and the low wet stabilitiy values is attributed to the fact that the specimens, during the hour capillary soaking, absorbed an appreciable amount of water, Figure 8.12. The absorbed water may have penetrated between the binder film, and the aggregate surface, causing a reduction in the bonding and adhesion between the aggregate particles. The percentage of absorbed water was

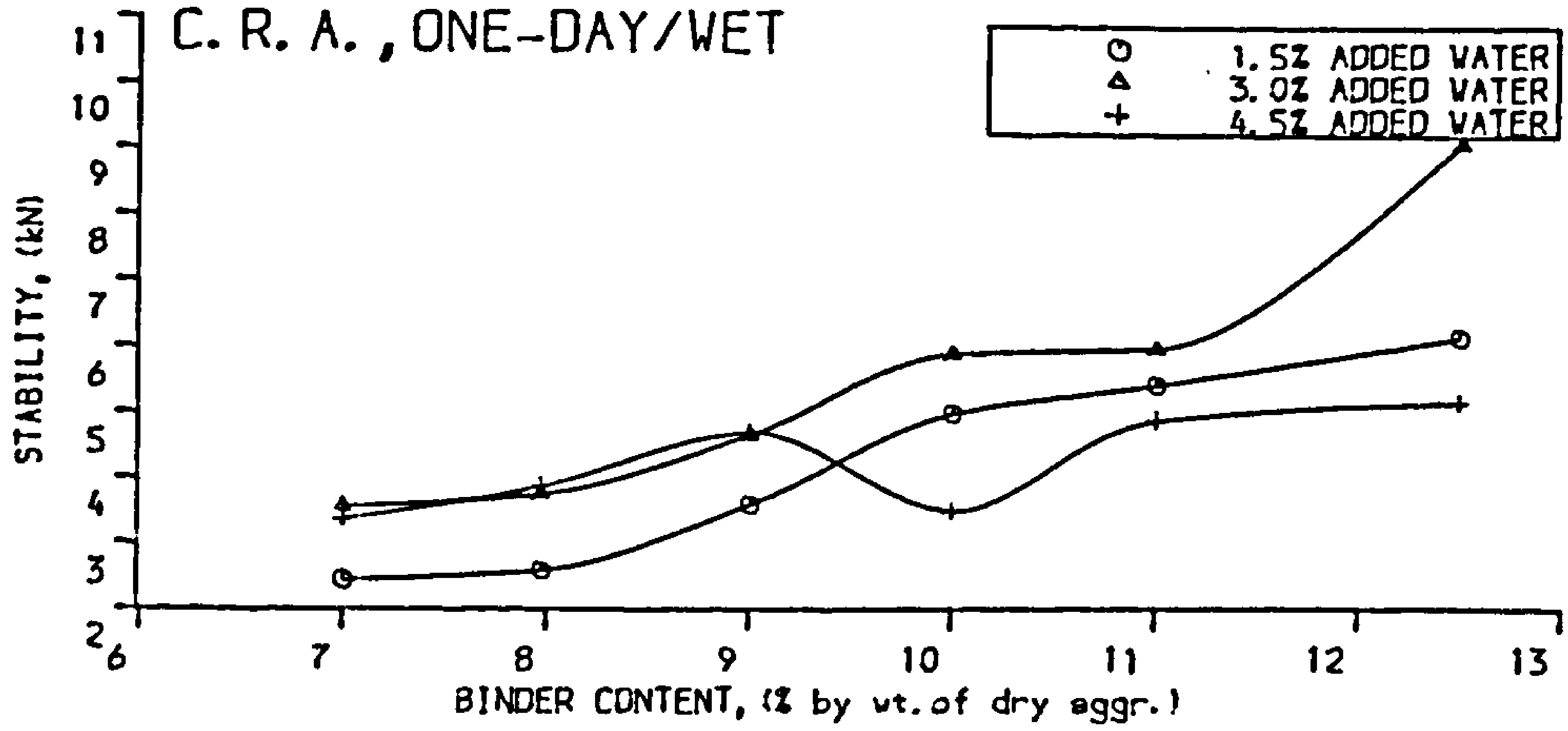


Fig. 8. 9 MARSH. STABILITY v BINDER CONT.

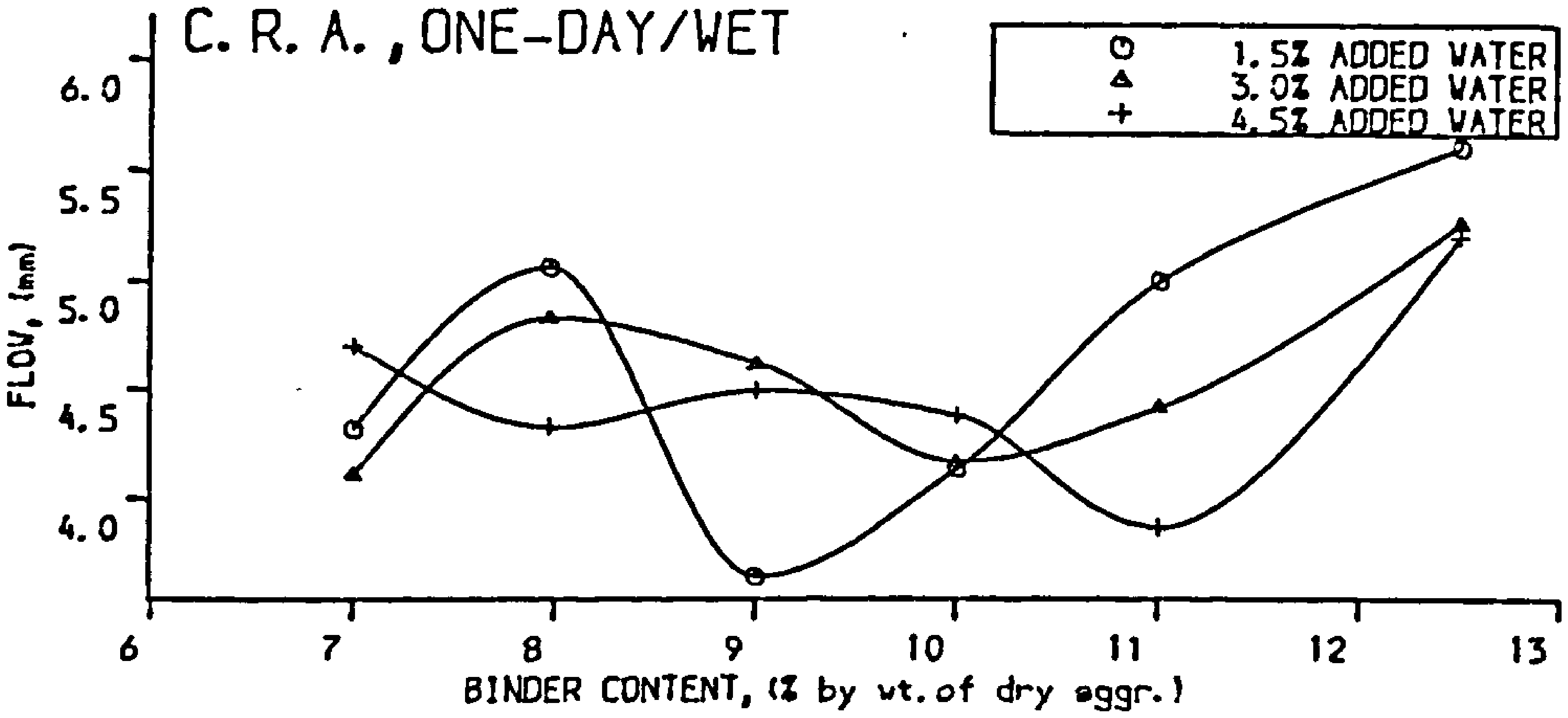


Fig. 8. 10 MARSHALL FLOW v BINDER CONT.

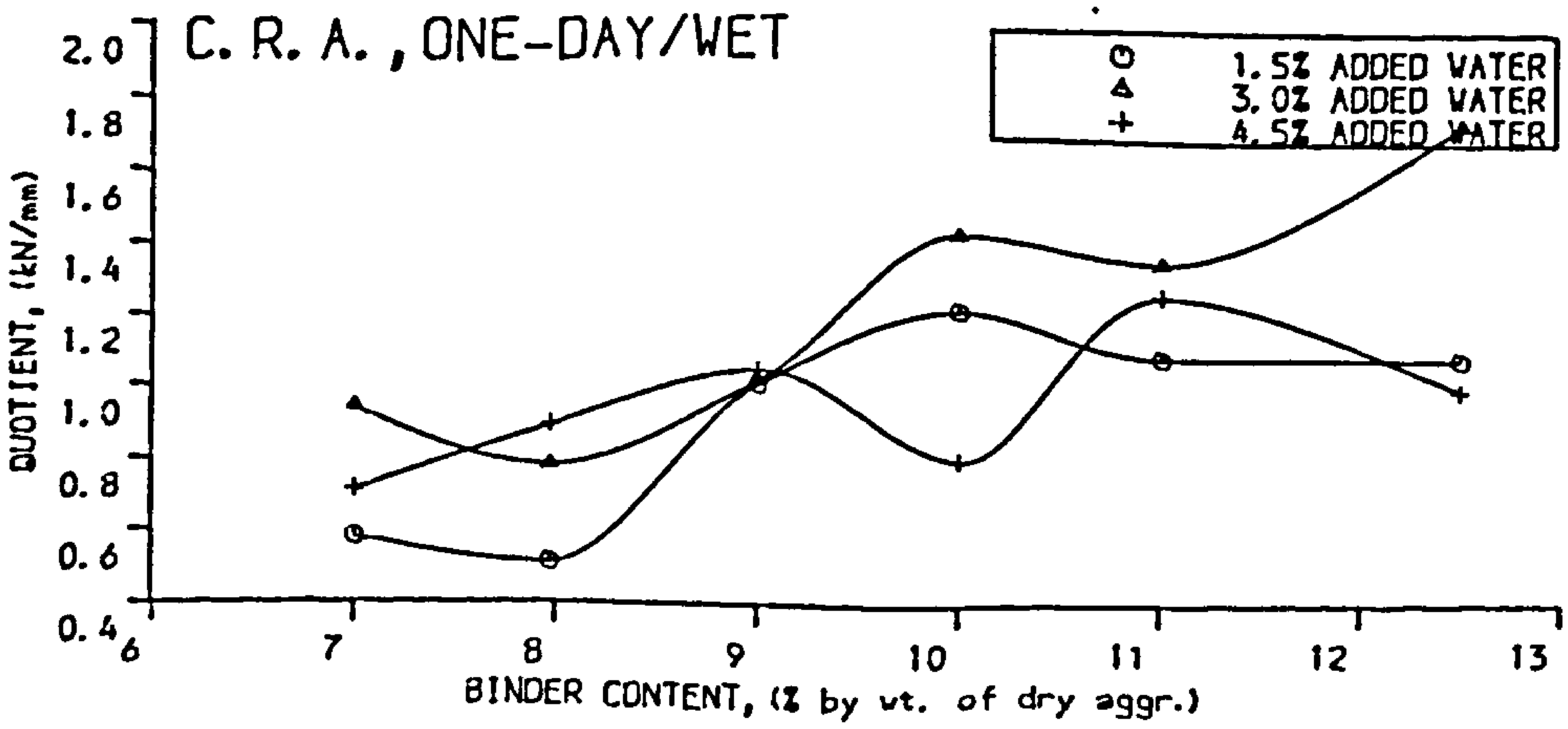


Fig. 8. 11 MARSH. QUOTIENT v BINDER CONT.

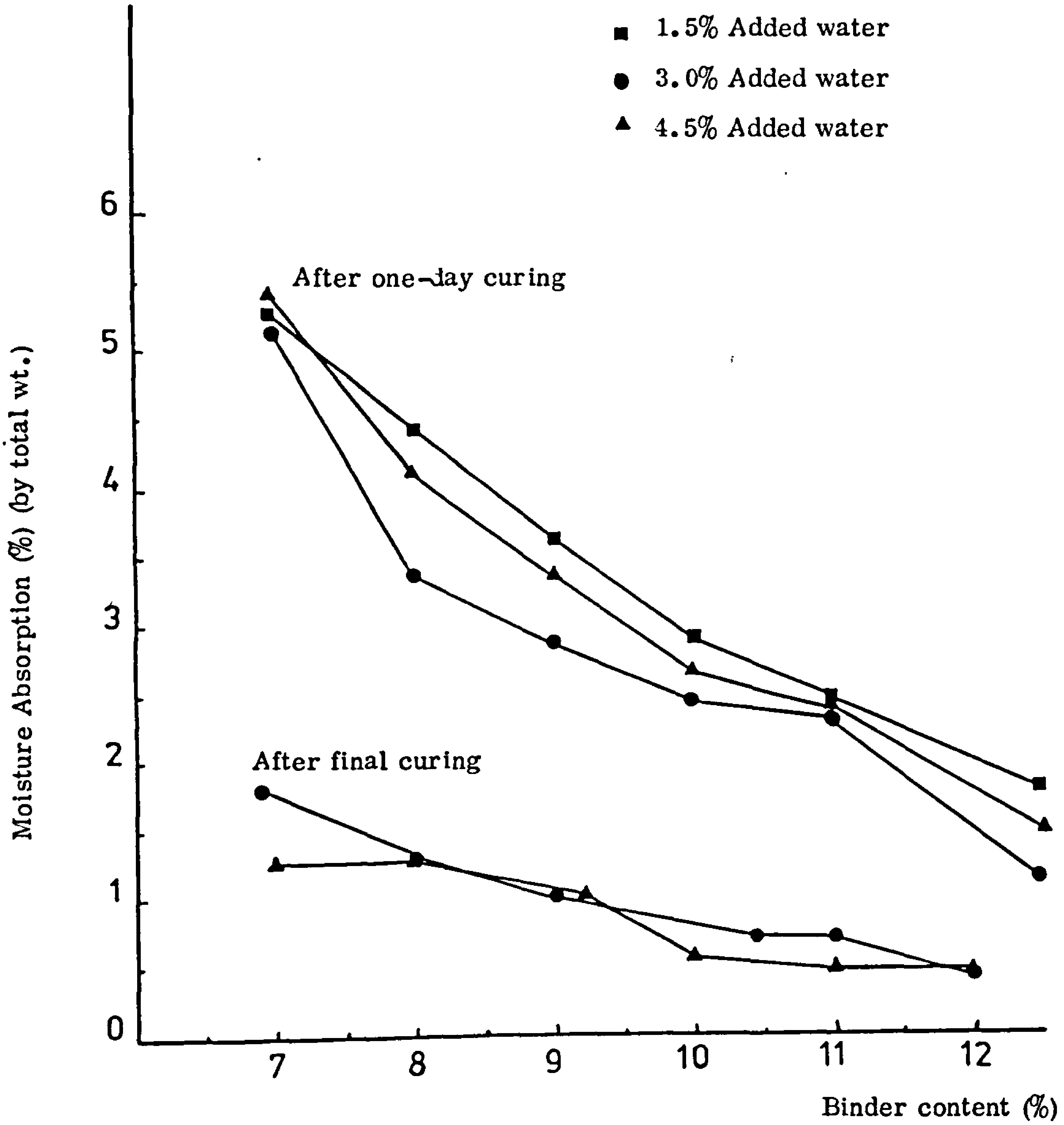


Fig.812 MOISTURE ABSORPTION AFTER 96h SOAKING vs BINDER CONTENT (after one-day and final curing)

found to be directly related to the percentage of air voids of the mixtures. Since added water does not affect the air voids, all air voids at all three levels of added water were plotted against absorbed water and a good correlation was found to exist. The linear relationship between absorbed water and air voids gave a correlation coefficient $r = 0.941$, which is highly significant ($r_{(16, 99.9)} = 0.708$ for two tail test, at 99.9 percent level of significance). (Figure 8.13).

The pattern of changes in wet Marshall Quotient with respect to binder content was completely different to that of the dry MQ. Due to the continuous increase of wet stability with binder, the wet MQ was increased with the binder content, and since the wet stability values were lower than the dry ones, the resulting wet MQs were lower than the dry MQ (the wet flow values remained almost the same). Mixtures with 3.0 percent added water gave higher wet MQ values than the other two mixtures.

A good representation of the effect of water on the stability of the mixtures at the early state of curing can be obtained by plotting the Retained Stability (wet stability over dry stability) against binder content. Figure 8.14 shows that the Retained Stability increases as the binder content increases for mixtures with 1.5 and 3.0 percent added water. Mixtures with 4.5 percent added water do not show any noticeable increase of Retained Stability with increase in binder content.

8.4.1.4. The effect on air permeability

The importance of air permeability on the properties of C.R.A. has been documented in the literature review and as it was stated the measurement of air permeability provides information about the distribution of air voids and their interconnection.

The permeability of the compacted specimens was measured as

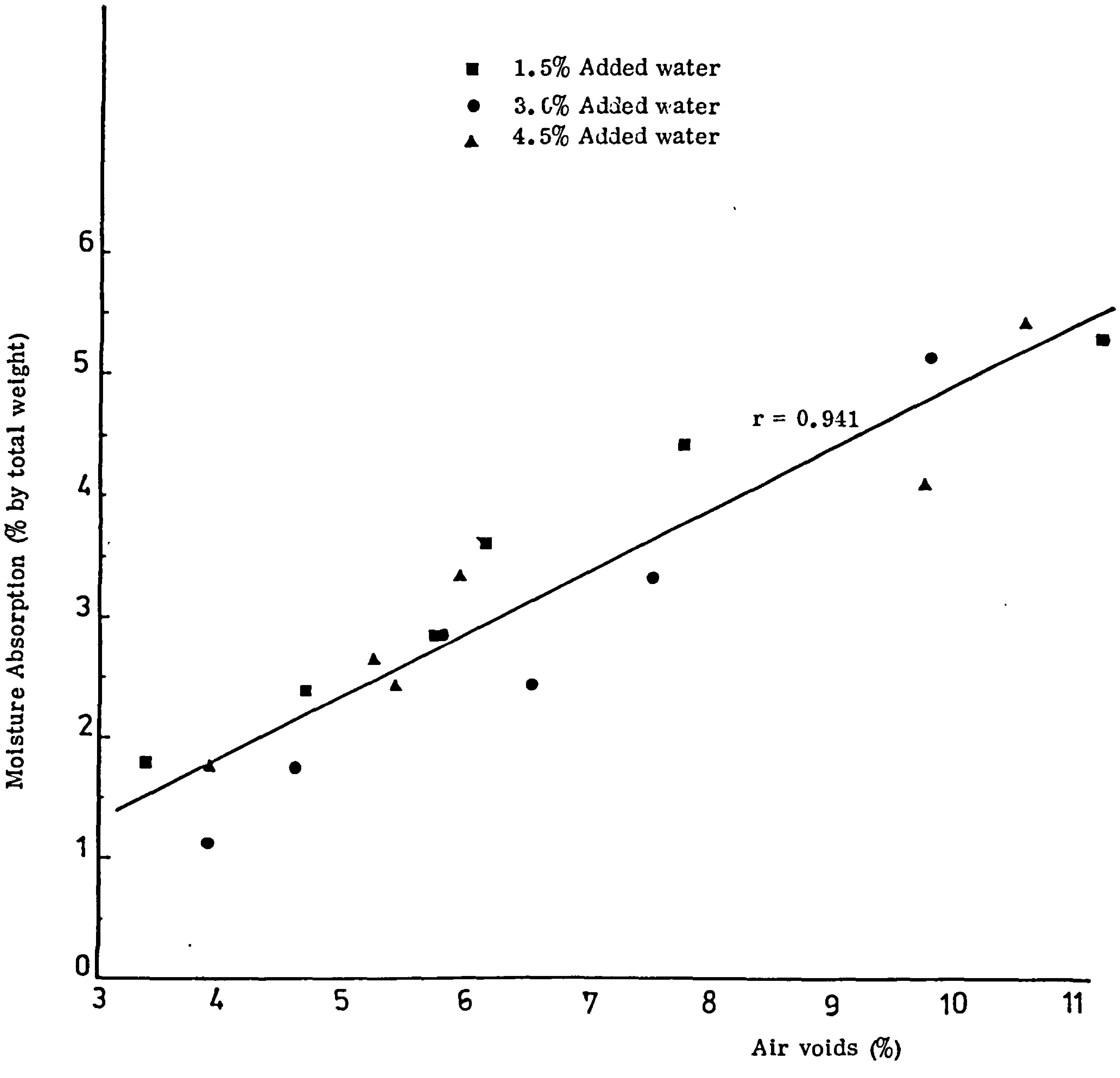


Fig. 8.13 MOISTURE ABSORPTION vs AIR VOIDS

(One day curing)

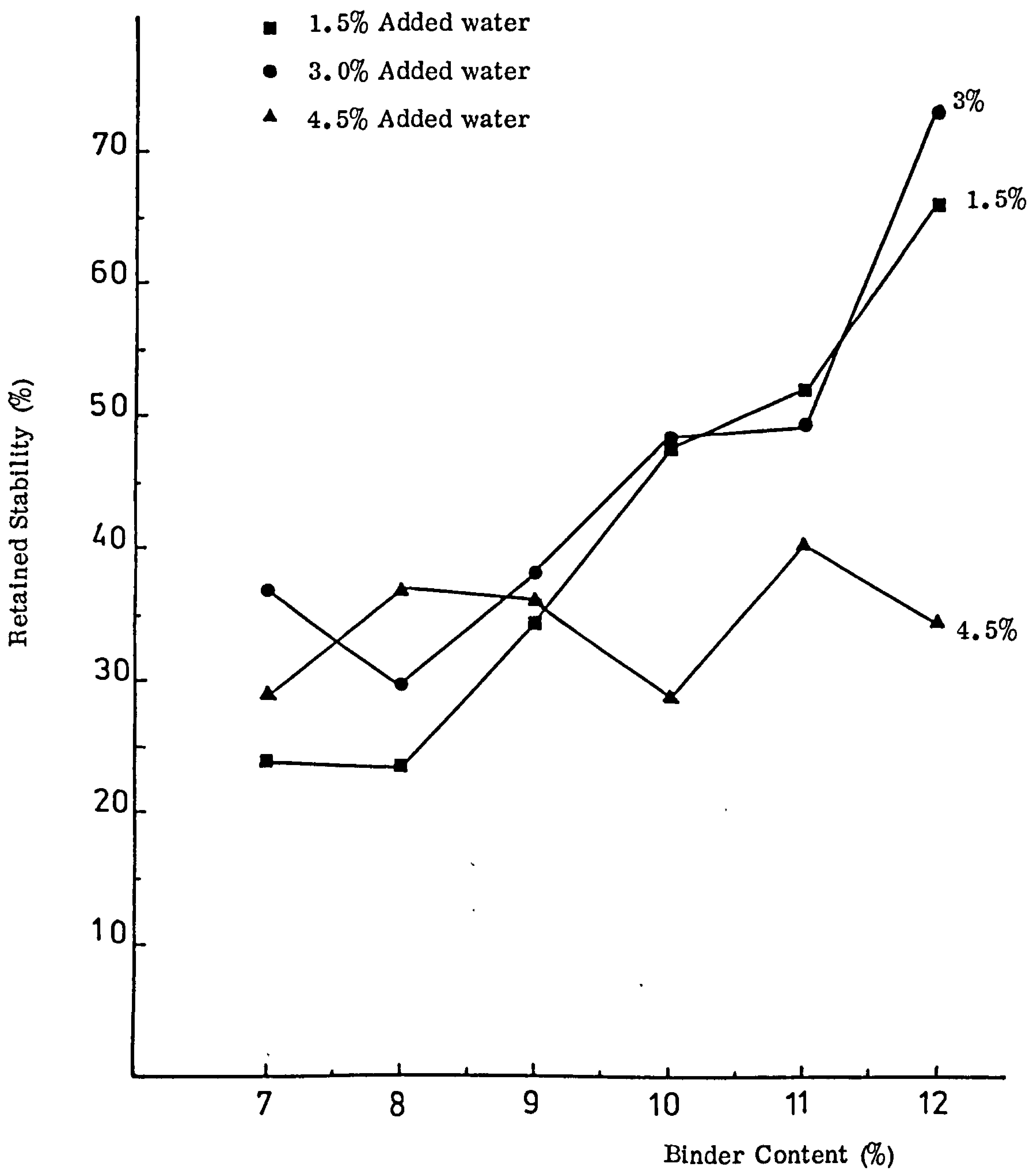


Fig. 8·14 RETAINED STABILITY vs BINDER CONTENT

(One day curing - soaking for 96h)

explained in Chapter 5. The results are shown in Figure 8.15. Statistical analysis of these results was also carried out and it was found, Table 8.2, that, the main two factors i.e. binder content and added water, and their interaction affect significantly the air permeability of the mixtures.

It can be seen, Figure 8.15, that as the binder content increases the air permeability decreases at a diminishing rate. The permeability values varied from 2.16×10^{-8} to 8.9×10^{-10} cm^2 (or 2.16×10^{-3} to 8.9×10^{-5} cm/sec); according to Table 3.2, given in Chapter 3, the mixtures can be classified as mixtures with "poor permeability" to "practically impervious".

An attempt was made to relate permeability with air voids. It was found that a good relation exists between the two variables, Figure 8.16, at all levels of added water; the correlation coefficients "r" found to be equal to 0.904, 0.918, 0.840 for 1.5, 3.0 and 4.5% of added water, (correl. coefficient for 95% confidence limits and four degrees of freedom is 0.811). It can be seen that, as the air voids increase the permeability of the mixtures increases. It is interesting to note from Figure 8.16 that for the same air voids, mixtures with 1.5% added water possess lower permeability than the other two mixtures.

It was logical to assume that air permeability was related to moisture absorption after 96 hour capillary soaking, and therefore, air permeability values were plotted against moisture absorption in Figure 8.17. It was found that a good linear relationship existed, with correlation coefficients 0.934, 0.958 and 0.952 for the 1.5, 3.0 and 4.5% added water mixtures. It must be noted that these correlation coefficients were slightly better than the ones obtained by the permeability vs air voids relationship. An examination of Figure 8.17 shows that at the same air permeability, mixtures with 1.5 percent added water absorb more water than the other two mixtures despite the

(To convert cm^2 to cm/sec multiply by 10^5)

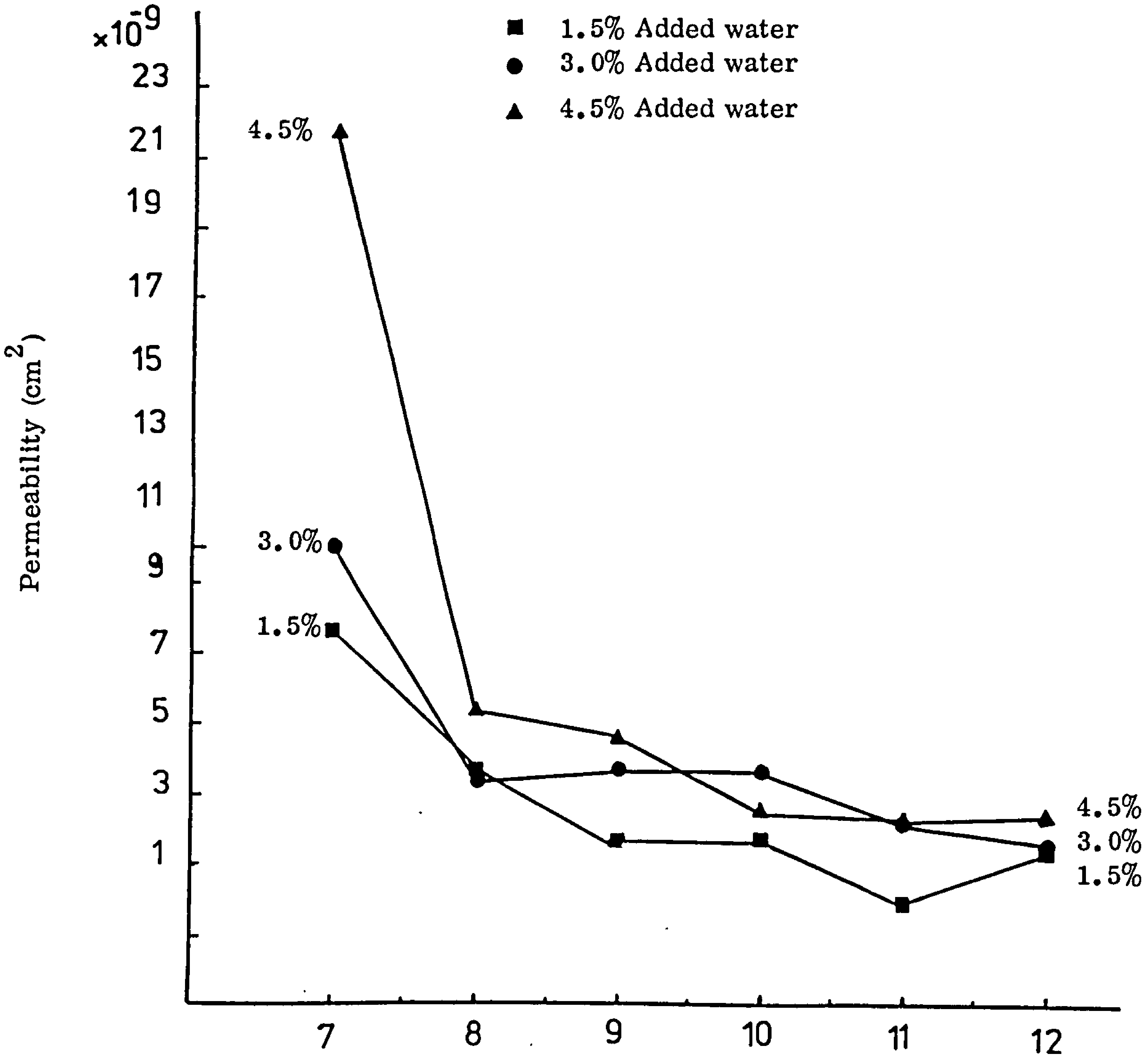


Fig 8.15 PERMEABILITY vs BINDER CONTENT

(One day curing)

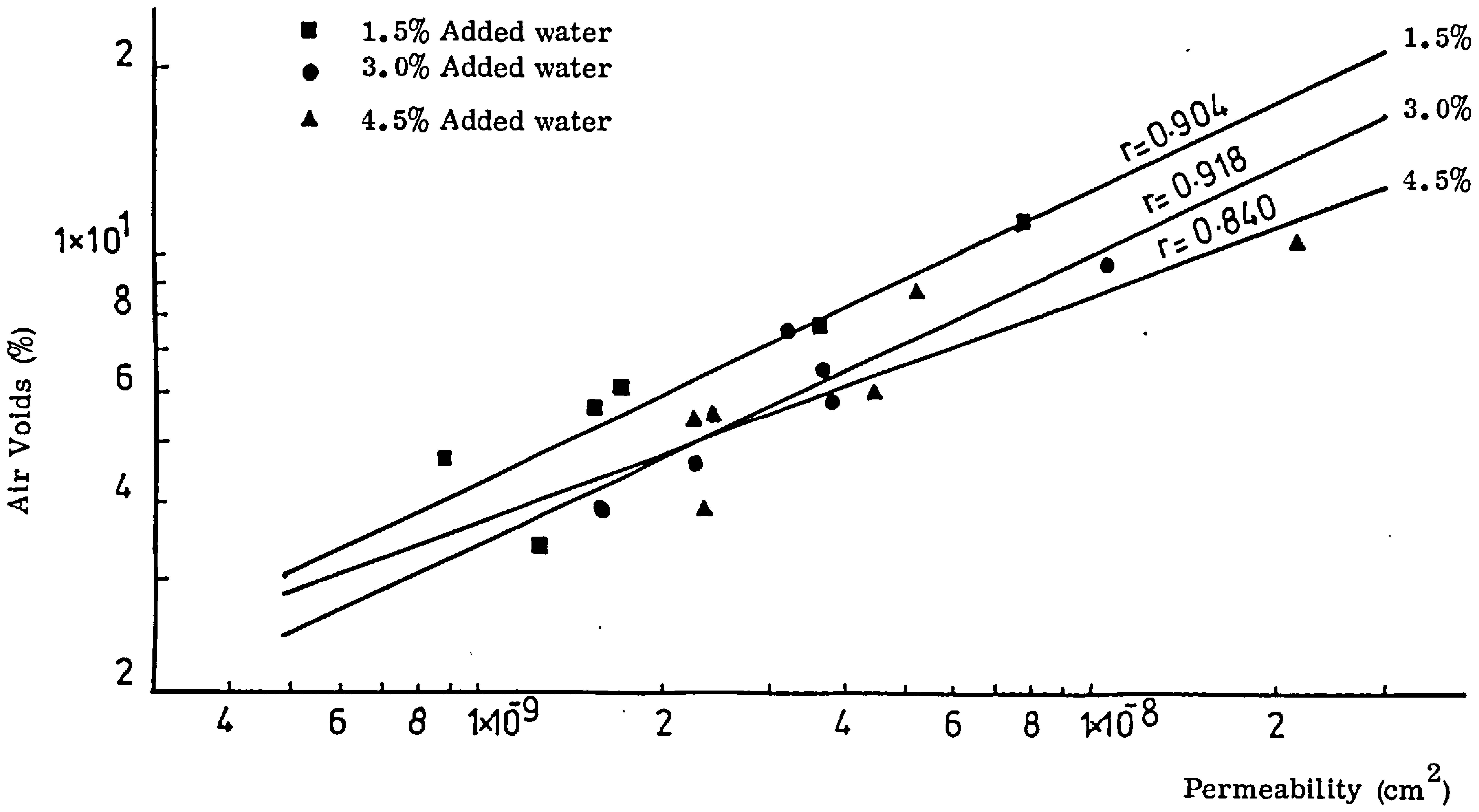


Fig. 8.16 AIR VOIDS vs PERMEABILITY

(One-day curing)

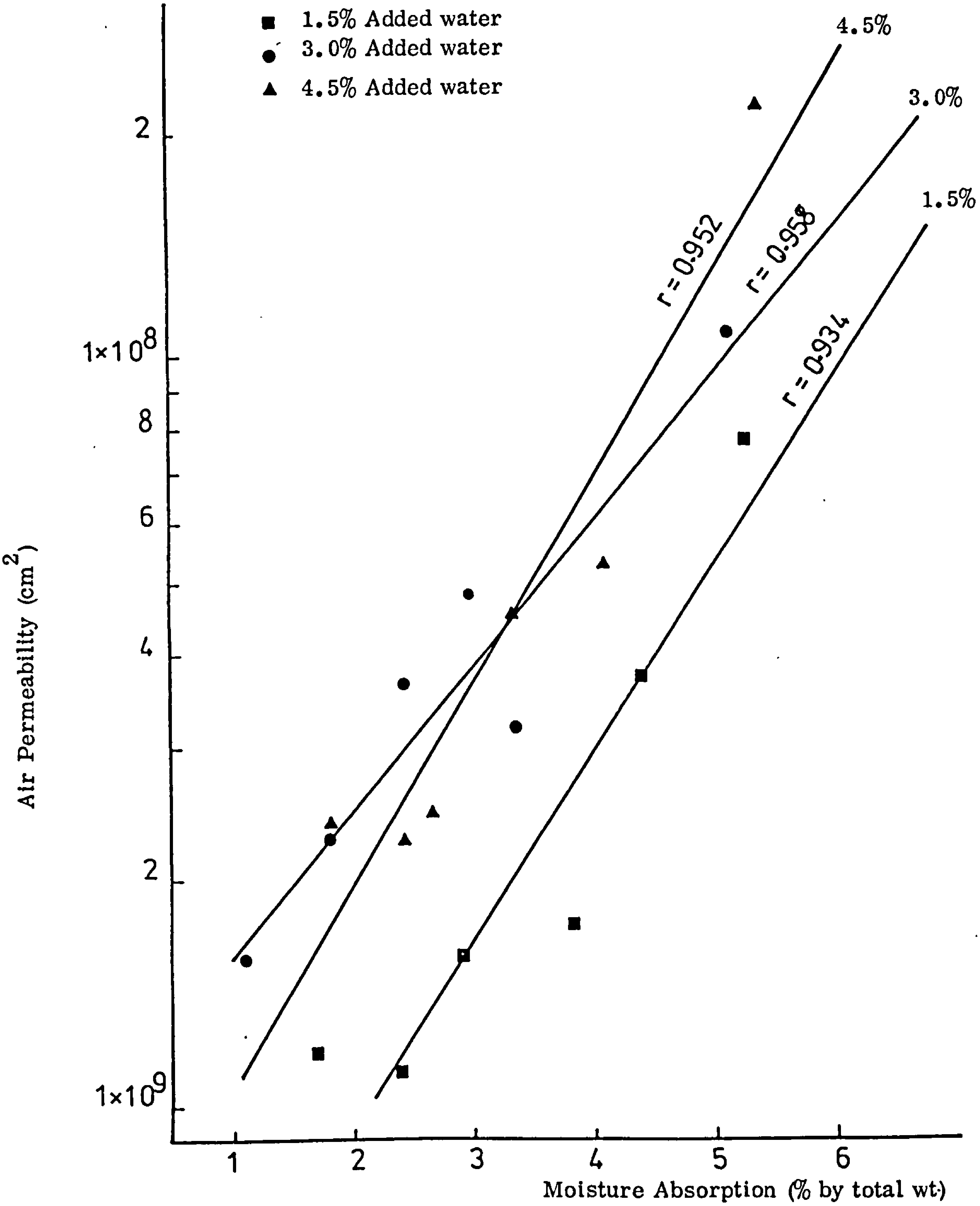
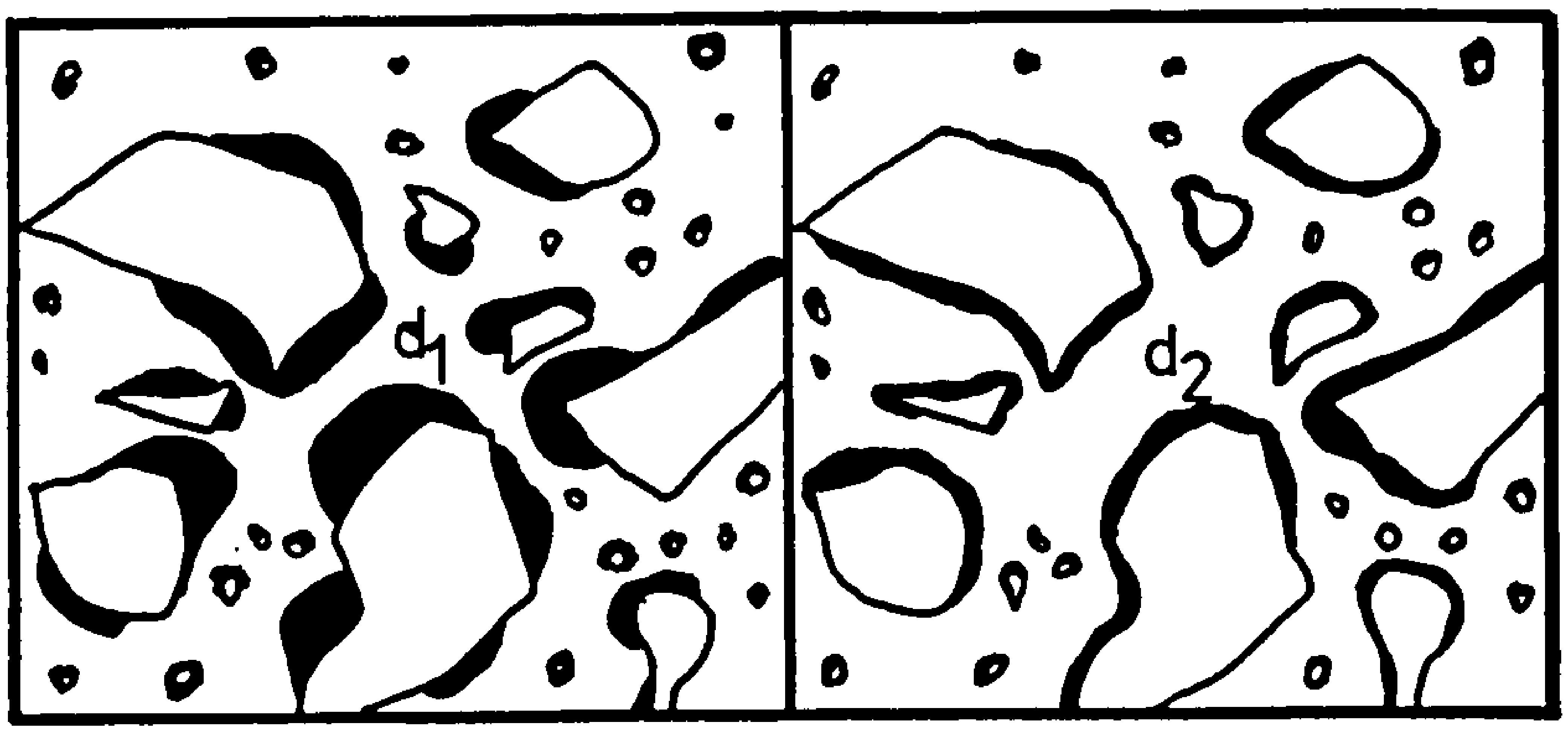


Fig. 8.17 AIR PERMEABILITY vs MOISTURE ABSORPTION

(One-day curing)

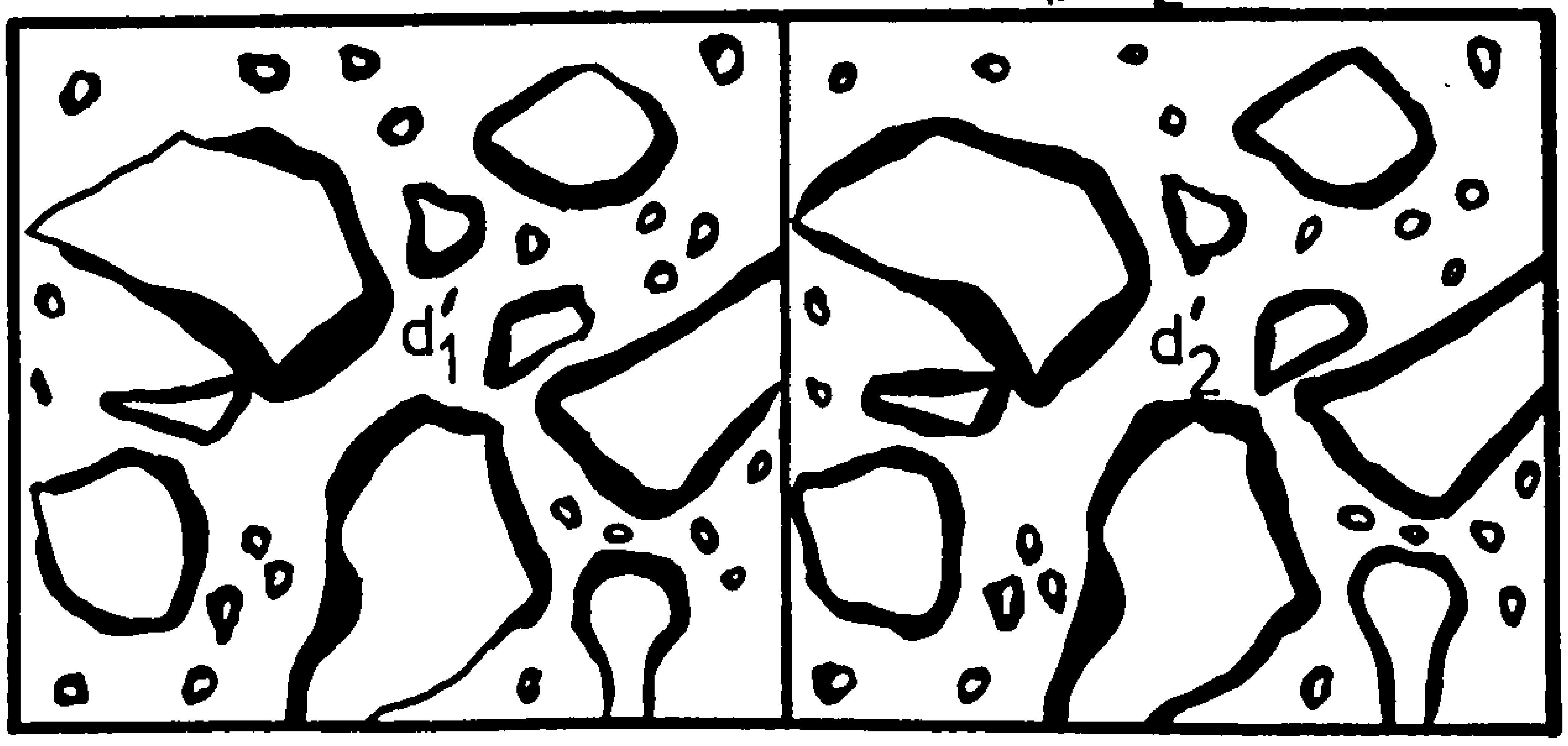
fact that, overall, they possess lower permeability values, Figure 8.15.

The above is not in disagreement with the fact that mixtures with a high permeability will absorb, in general, more water than mixtures with a lower permeability. It can be explained by considering permeability (porosity) and pore size diameter (distribution). The diameters of the pores of the mixtures with 1.5% added water are smaller than the pores diameters of the mixtures with 3.0 or 4.5% added water. See Figure 8.15a below.



(a) Low % of added water (a/w) (b) High % of a/w

Low binder content - $d_1 > d_2$



(c) Low % of a/w (d) High % of a/w

High binder content - $d_1' \approx d_2'$

FIG. 8.15a SCHEMATIC REPRESENTATION OF THE EFFECT OF ADDED WATER ON THE DISTRIBUTION OF BINDER, AND THE RESULTED PORE DIAMETER (d_1, d_2, d_1', d_2' denotes pore diameter)

This is due to the poor distribution of binder in the mixtures with 1.5% added water. Mixtures with small average pore diameter are less permeable (porous). Since the soaking test is one of capillary absorption, smaller pore diameter mixtures will absorb larger amounts of water. Hence, mixtures with 1.5% added water, having lower average pore diameter absorbed higher percentage of water, Figure 8.17.

8.4.2. The effect of binder content and added water on the properties of C.R.A. mixtures - Final stage of curing

The final stage of curing was defined in Chapter 5 as, "curing the specimens for five days in the air, in a room with controlled air temperature and humidity level ($21^oC \pm 1^oC$, and 65^o humidity) and then for a further 48 hours in a 60^oC air ventilated oven". After this curing process most of the water evaporates. It must be emphasised that all the water in the matrix cannot be easily removed, because some of it gets trapped under the binder film and/or absorbed by the aggregate. As Figure 5.8, Chapter 5, shows, the amount of water remaining in the system after final curing is dependent on the binder content and varies, on average, between 1.1 and 1.8 percent of the total weight. Nevertheless, the above curing procedure may correspond to conditions on site after one or two years depending on the climatic conditions and control of the level of the water table under a pavement.

The data of the factorial design, shown in Table 8.1, was processed by the computer programme given in the Appendix E , and the results were analysed using the analysis of variance method. The mathematical model used is shown in equation 8.1. The only difference with the one day curing is that the levels of added water are reduced to two, hence, suffix $j = 2, 3$. The summary of the results of the statistical analysis is given in Table 8.4 and 8.5.

FINAL CURING - C.R.A.						
Independent \ Dependent Factors	Bulk Density	Air Voids	Total Voids	V.M.A.	Permeability	Water Content at Testing
Binder Content	S**	S**	S**	S**	S**	S**
Added Water	S*	NS	NS	NS	S**	S*
Binder Content and Added Water	NS	NS	NS	NS	S**	NS

S** = Significant at 1% level of significance

S* = Significant at 5% level of significance

NS = Not significant at 5% level of significance

TABLE 8.4 SUMMARY OF STATISTICAL ANALYSIS OF DENSITY, VOIDS, V.M.A., PERMEABILITY AND WATER AT TESTING (FINAL CURING)

FINAL CURING - C.R.A.						
Independent \ Dependent Factors	Stability		Flow		Quotient	
	Dry	Wet	Dry	Wet	Dry	Wet
Binder Content	S**	S**	S**	S**	S**	S**
Added Water	S**	S*	S**	NS	S**	S**
Binder Content and Added Water	S**	S**	S*	NS	S**	S*

S** = Significant at 1% level of significance

S* = Significant at 5% level of significance

NS = Not significant at 5% level of significance

TABLE 8.5 SUMMARY OF STATISTICAL ANALYSIS OF MARSHALL STABILITY, FLOW AND QUOTIENT AT DRY AND WET CONDITION (FINAL STAGE CURING)

8.4.2.1. The effect on bulk density and compacted aggregate density

The results of the bulk densities and compacted aggregate densities are shown in Figures 8.18 and 8.19. Both relations fail to show a clear maximum density or compacted aggregate density. The mixtures with 3.0% added water gave higher density values than the mixtures with 4.5% added water.

Statistical analysis showed that unlike one day cured mixtures, both factors affect the bulk densities significantly. This suggests that in the long run not only does the binder content affect the bulk density of the mixture, but also the percentage of added water. The interaction of the two main factors had no significant effect.

8.4.2.2. The effect of Air Voids, Total Voids and VMA

The trend of changes in air voids, total voids and VMA with respect to binder content, at two levels of added water, is shown in Figures 8.20, 8.21, 8.22 respectively. As was observed before (one day cured mixtures) the air voids and total voids decreased as binder content increased. The interesting result was that after final curing both mixtures (3.0 and 4.5%) possessed more or less the same values of air and total voids. The statistical analysis also confirmed that the binder content was the only factor which significantly affects the air voids and total voids, after final curing.

Figure 8.22 shows that the value of VMA increases as the binder content increases. This trend confirms the trends shown for the compacted aggregate density versus binder content i.e. the C.A.D. decreases with increasing binder content.

The added water has no statistical significance on the V.M.A. values, Table 8.4, or air voids or total voids values.

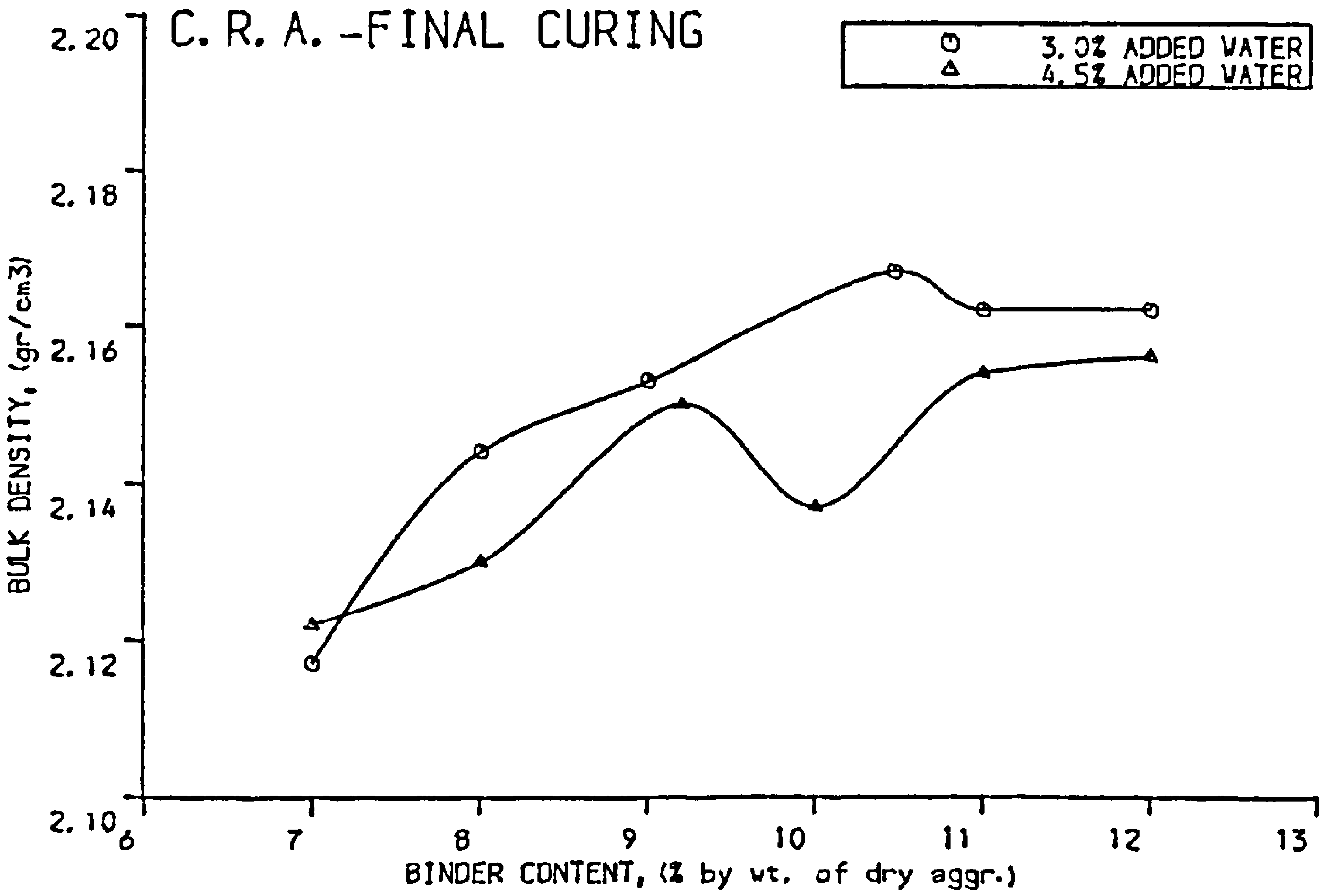


Fig. 8. 18 BULK DENSITY v BINDER CONTENT

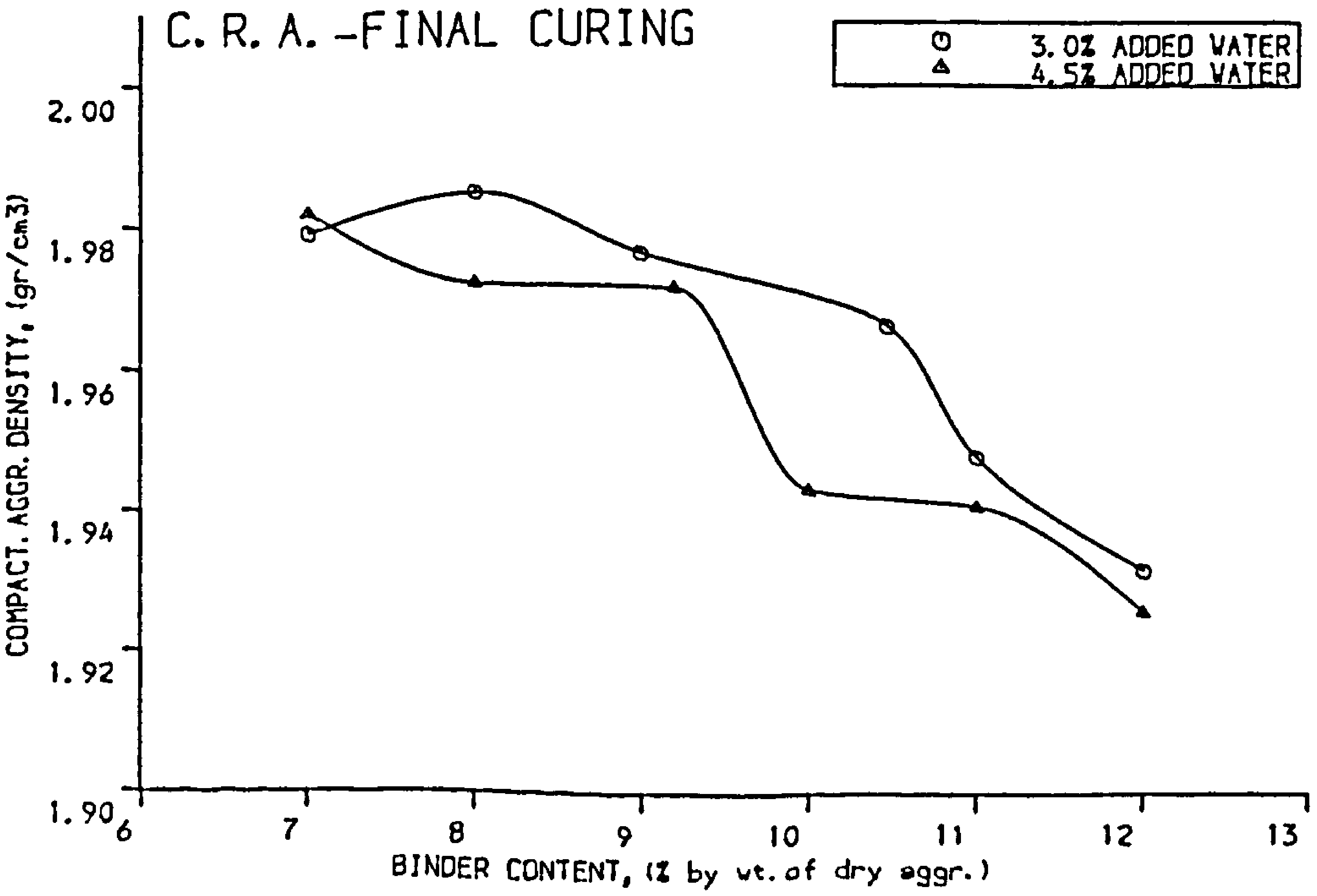


Fig. 8. 19 COMP. AGGR. DENS. v BINDER CONT.

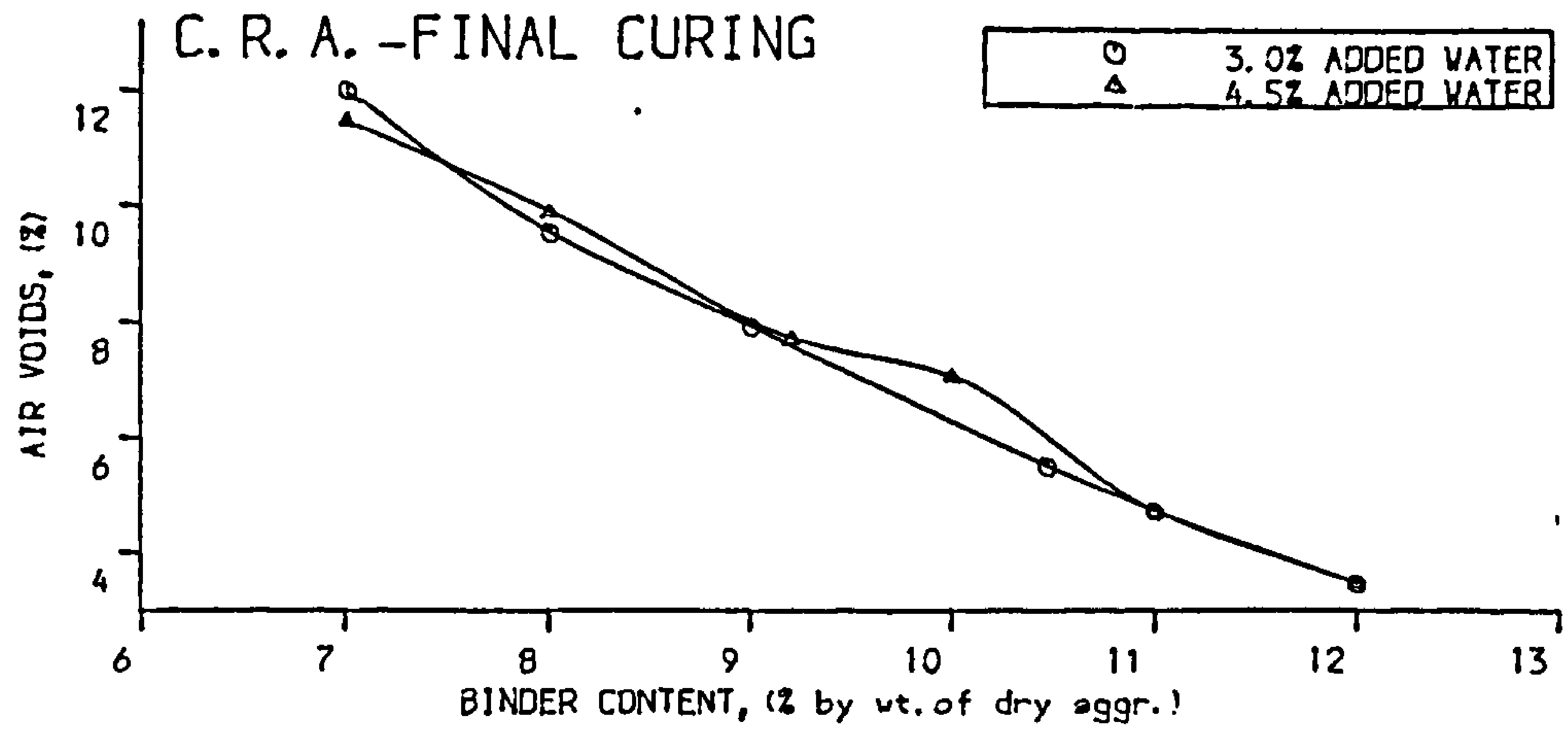


Fig. 8.20 AIR VOIDS v BINDER CONTENT

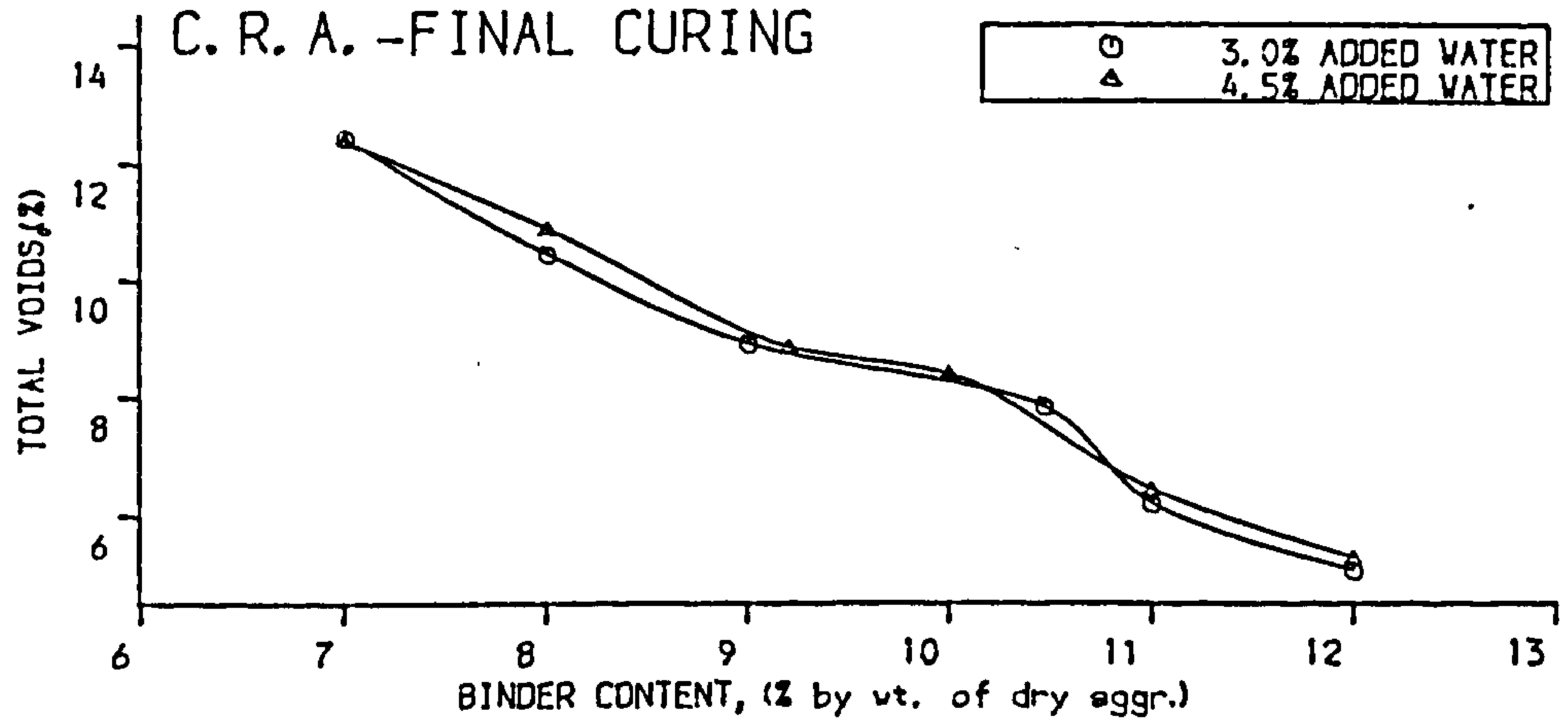


Fig. 8.21 TOTAL VOIDS v BINDER CONTENT

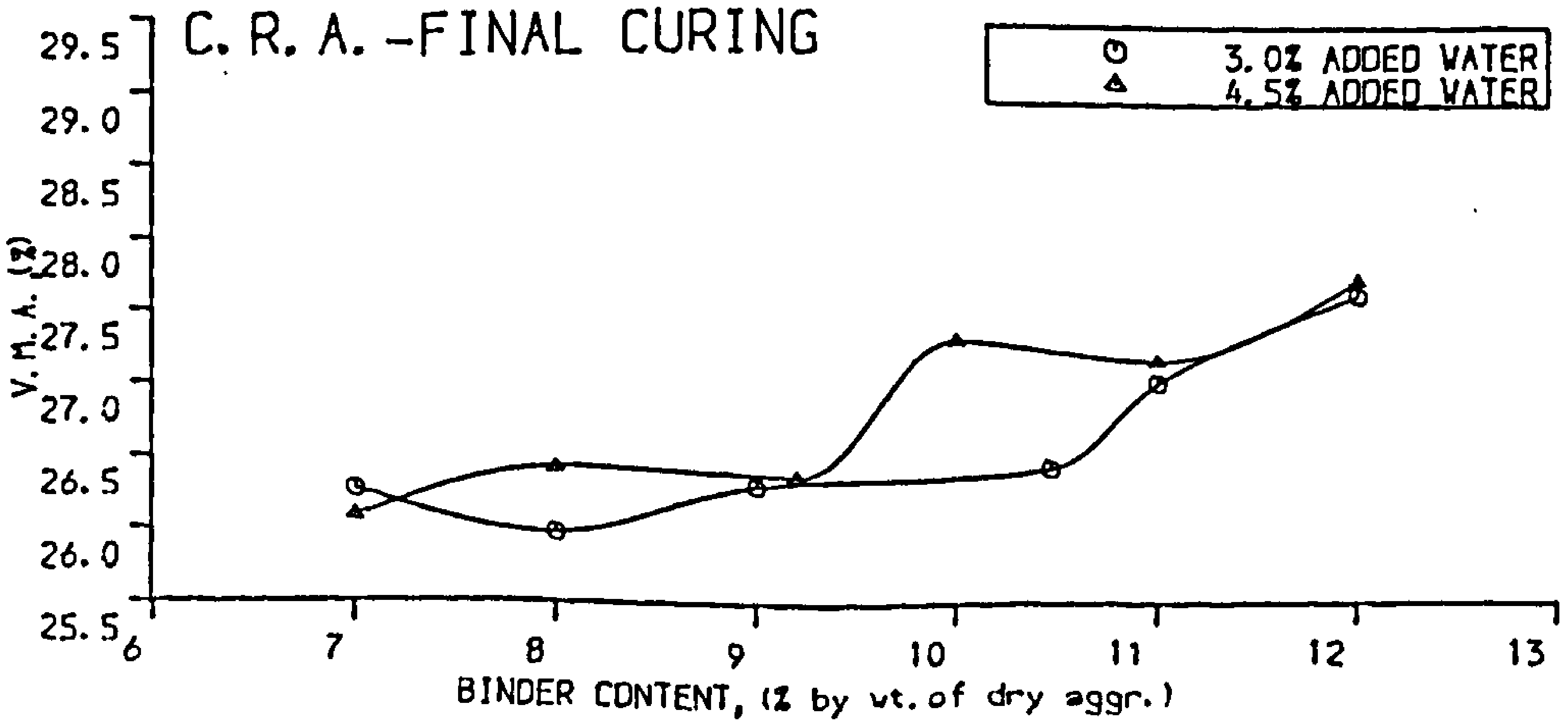


Fig. 8.22 V.M.A v BINDER CONTENT

8.4.2.3. The effect on Marshall Stability (MS) Flow and Marshall Quotient (MQ)

The effect of binder content and added water on both dry and soaked mixtures was examined, after they had been cured for five days in the air and two days in the oven.

The statistical analysis had shown, Table 8.5, that all Marshall properties, apart from "wet" flow, were significantly affected by both main factors and their interaction. The "wet" flow was significantly affected, only, by the binder content.

Figure 8.23 shows that the "dry" Marshall stability decreases continuously as the binder content increases, at both levels of added water.

When the "wet" stability values of the two mixtures were compared, Figure 8.26, it was found that the mixture with 3.0% added water possessed higher wet stability values between 7 to 10.5% binder content. This suggests that the 3.0% mixture has better resistance to water. The most interesting feature of the wet stability curves was that they both showed a maximum wet stability at a certain binder content. This binder content is the optimum binder content and it can be used for the determination of optimum binder content of the mixture.

Comparing the dry stability with the wet stability values, it was found that there was hardly any loss in stability, due to 96 hour capillary soaking, despite the small amount of absorbed water, 0.4 to 1.3%, Figure 8.12, Figure 8.29.

The "wet" flow curves, for the two mixtures, Figure 8.27, as was mentioned earlier, did not shown any significant difference due to added water, and hence, the wet flow values were only affected by the binder content.

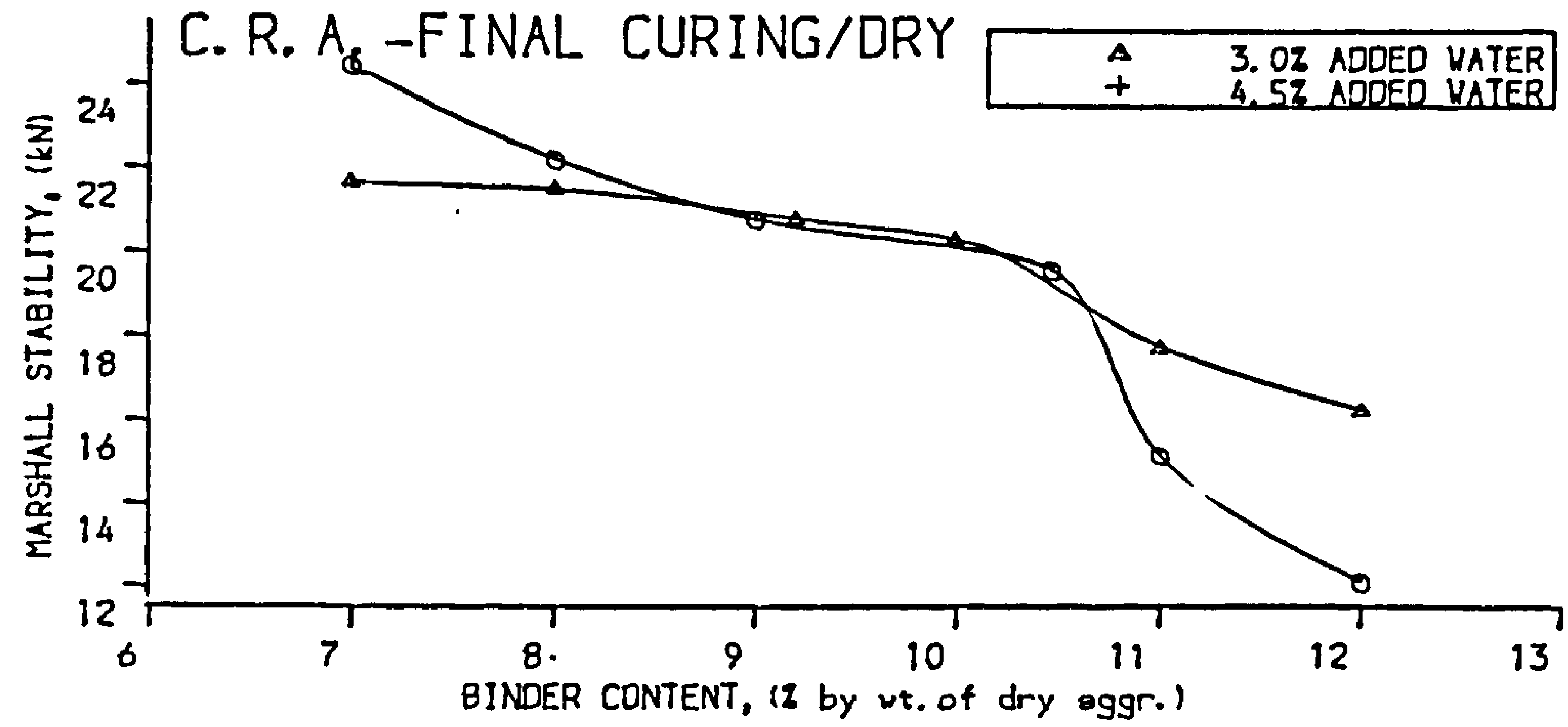


Fig. 8. 23 MARSH. STABILITY v BINDER CONTENT

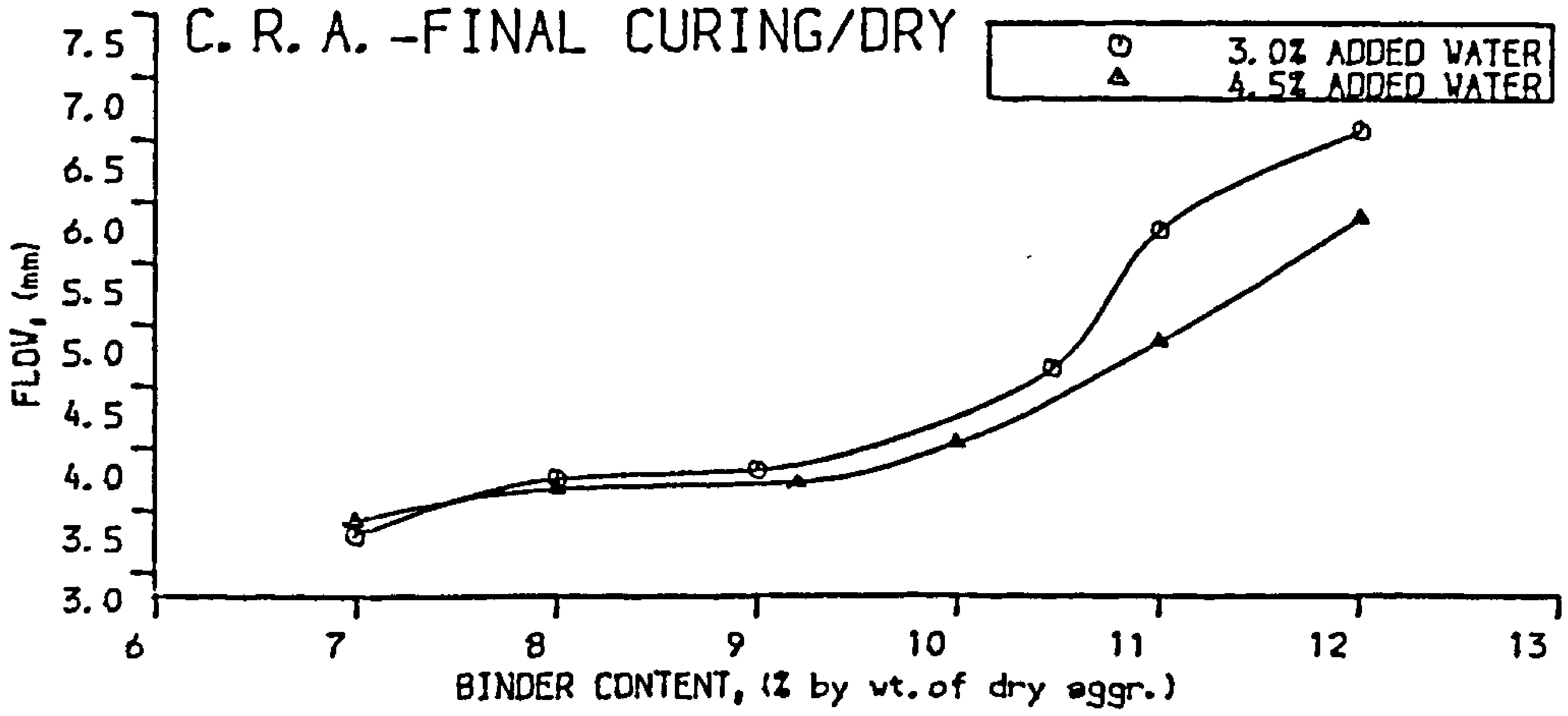


Fig. 8. 24 FLOW v BINDER CONTENT

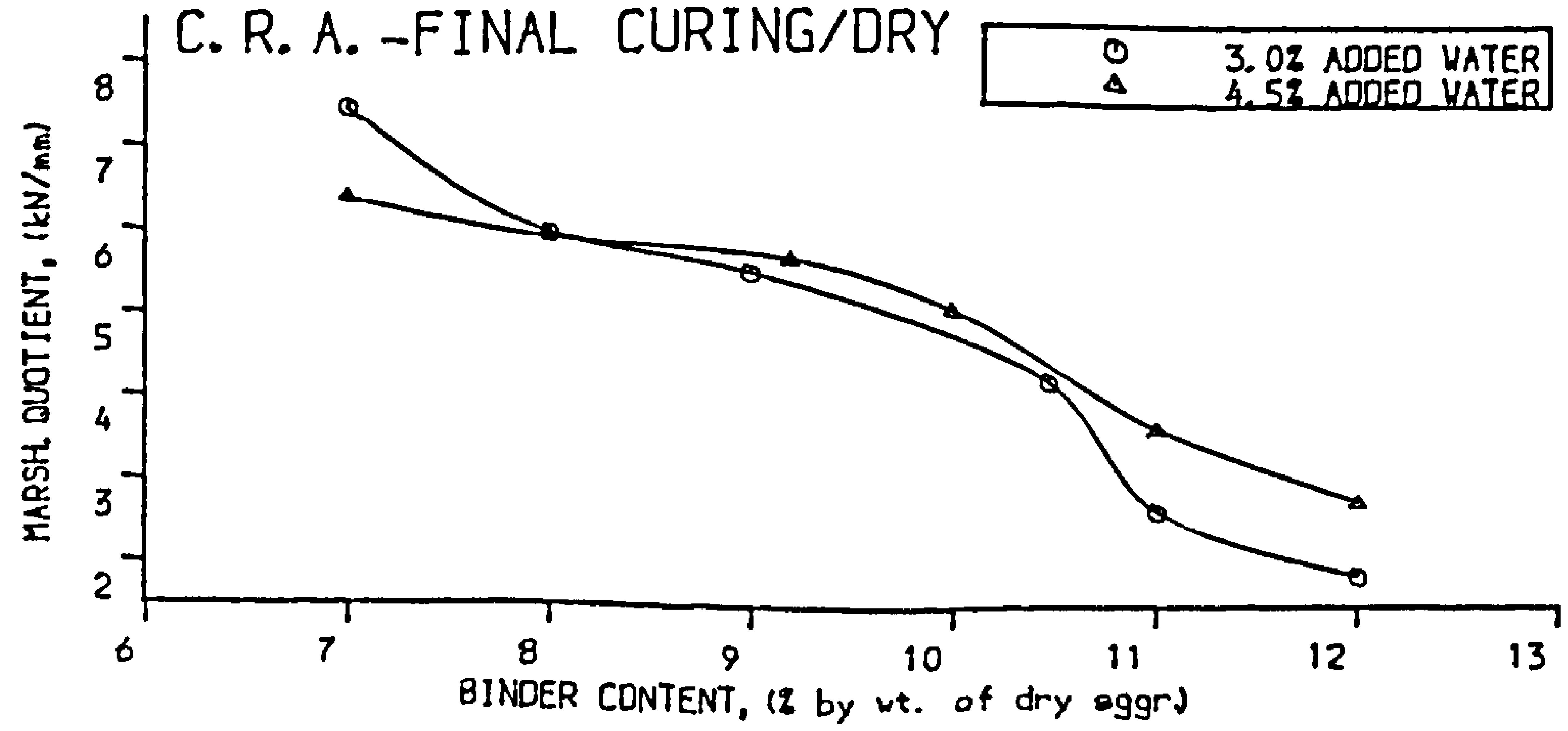


Fig. 8. 25 MARSH. QUOTIENT v BINDER CONT.

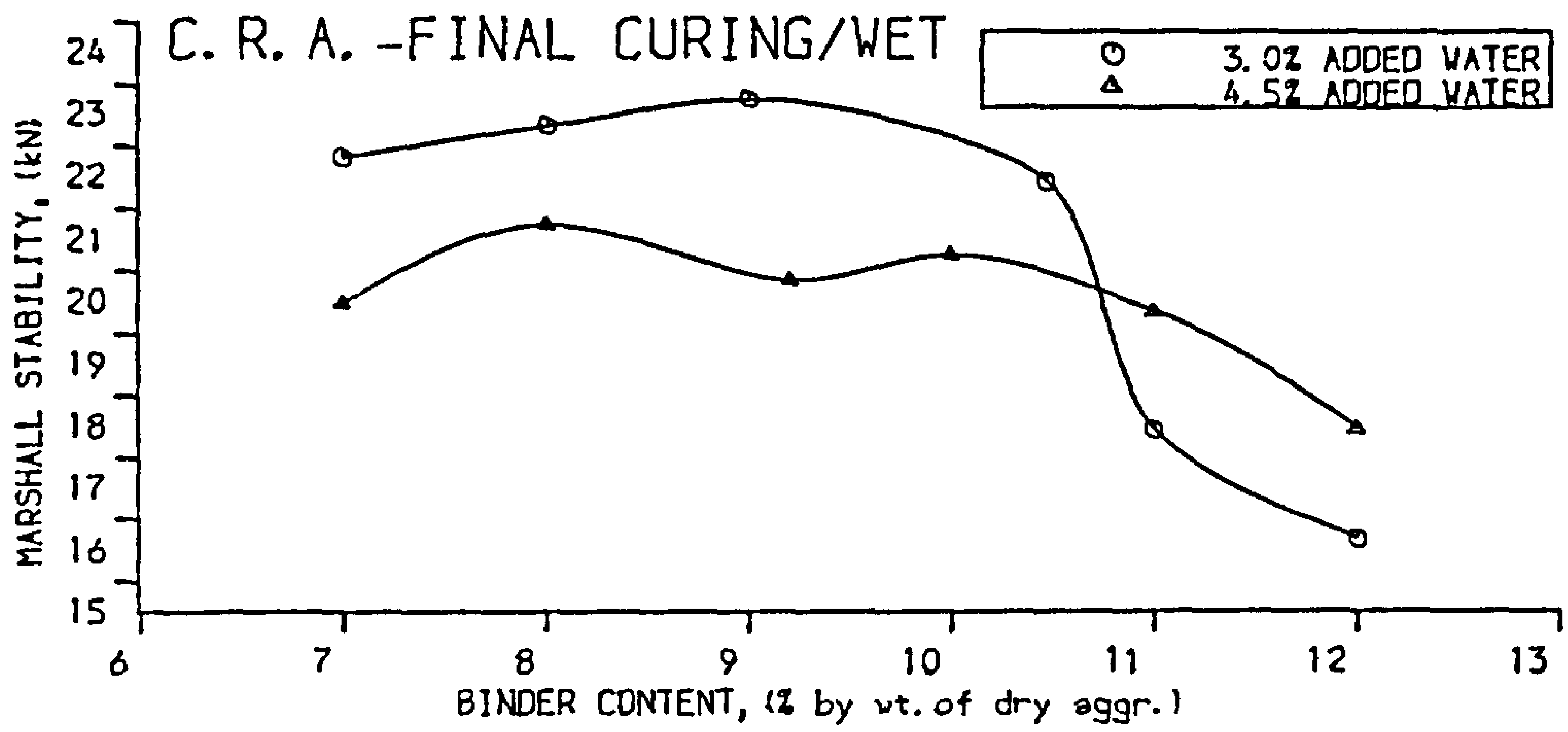


Fig. 8. 26 MARSH. STABILITY v BINDER CONTENT

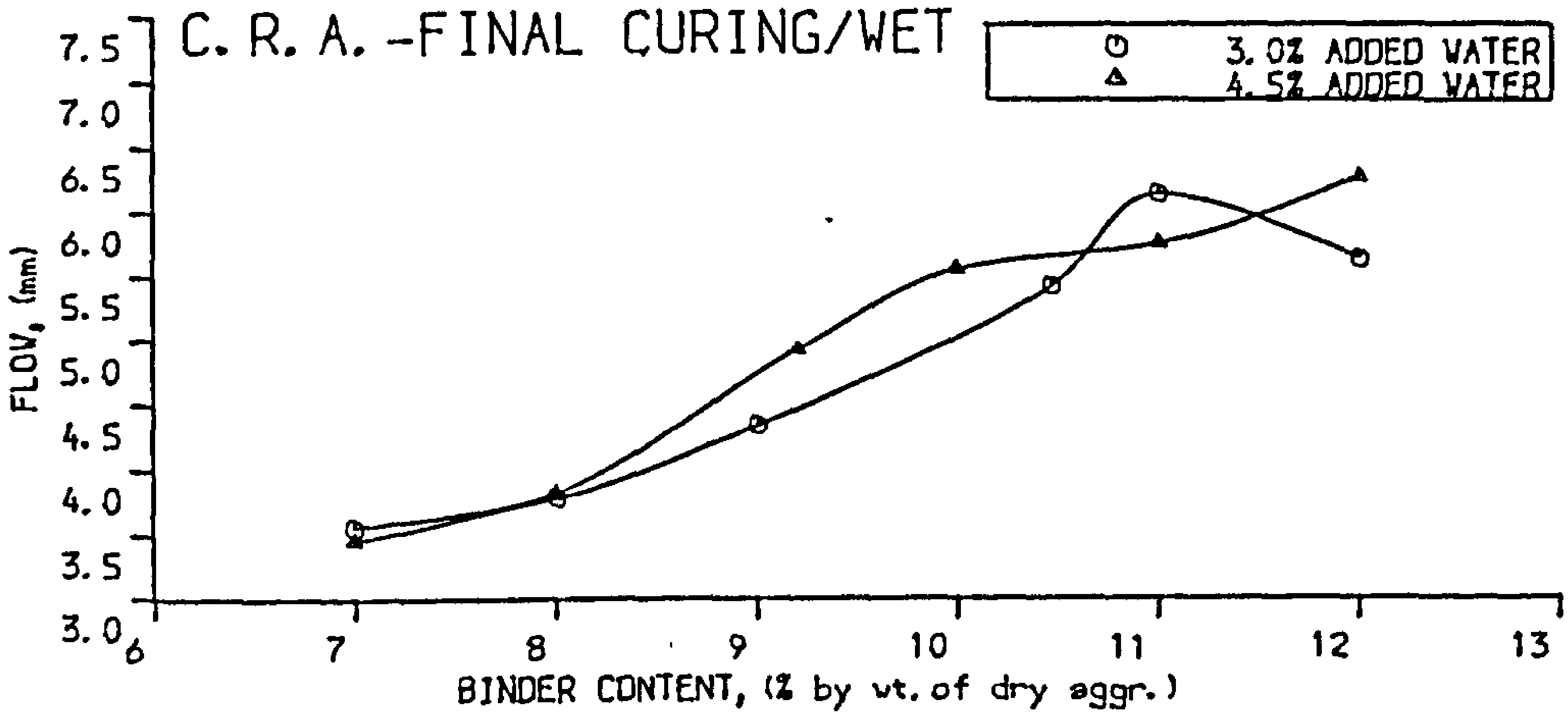


Fig. 8. 27 FLOW v BINDER CONTENT

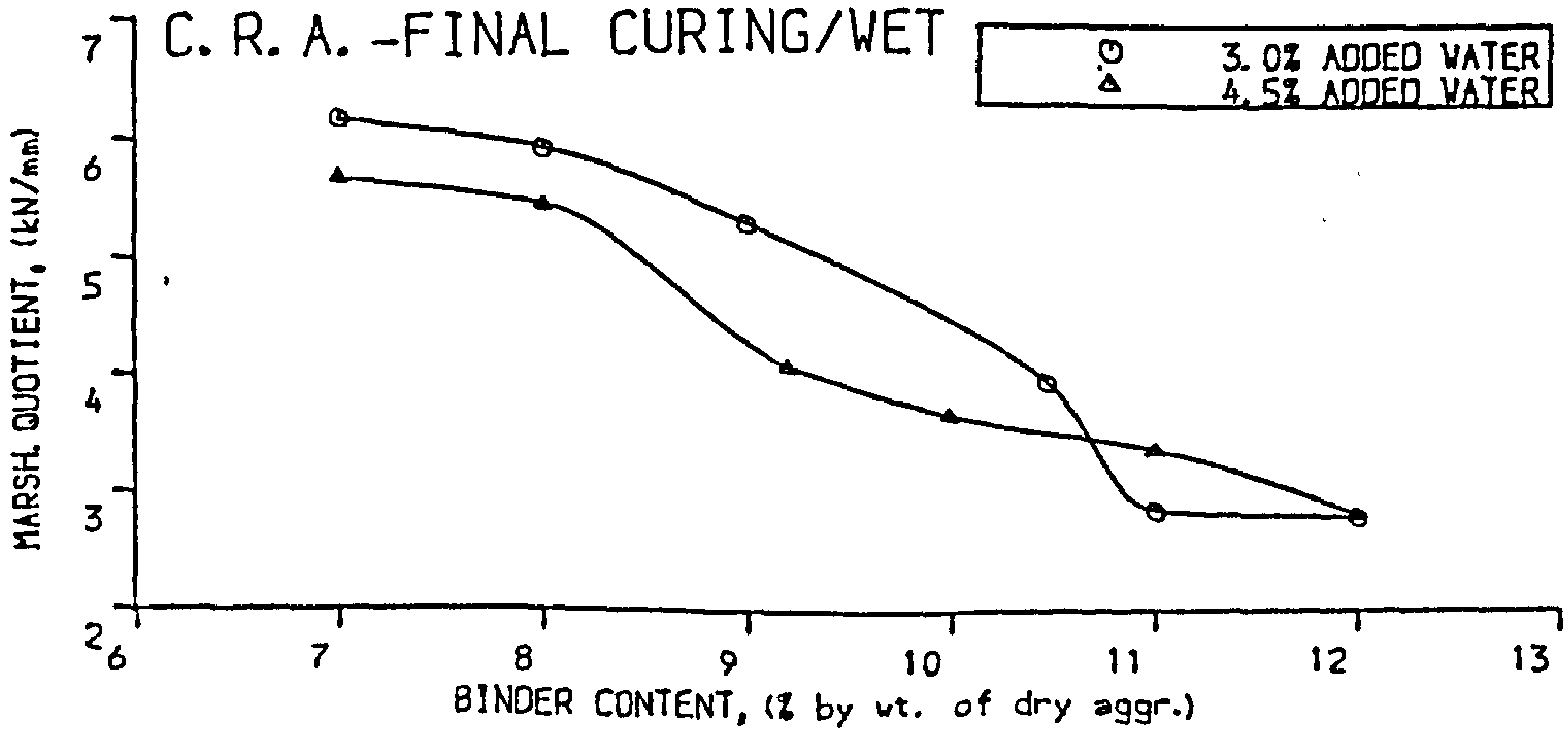


Fig. 8. 28 MARSH. QUOTIENT v BINDER CONT.

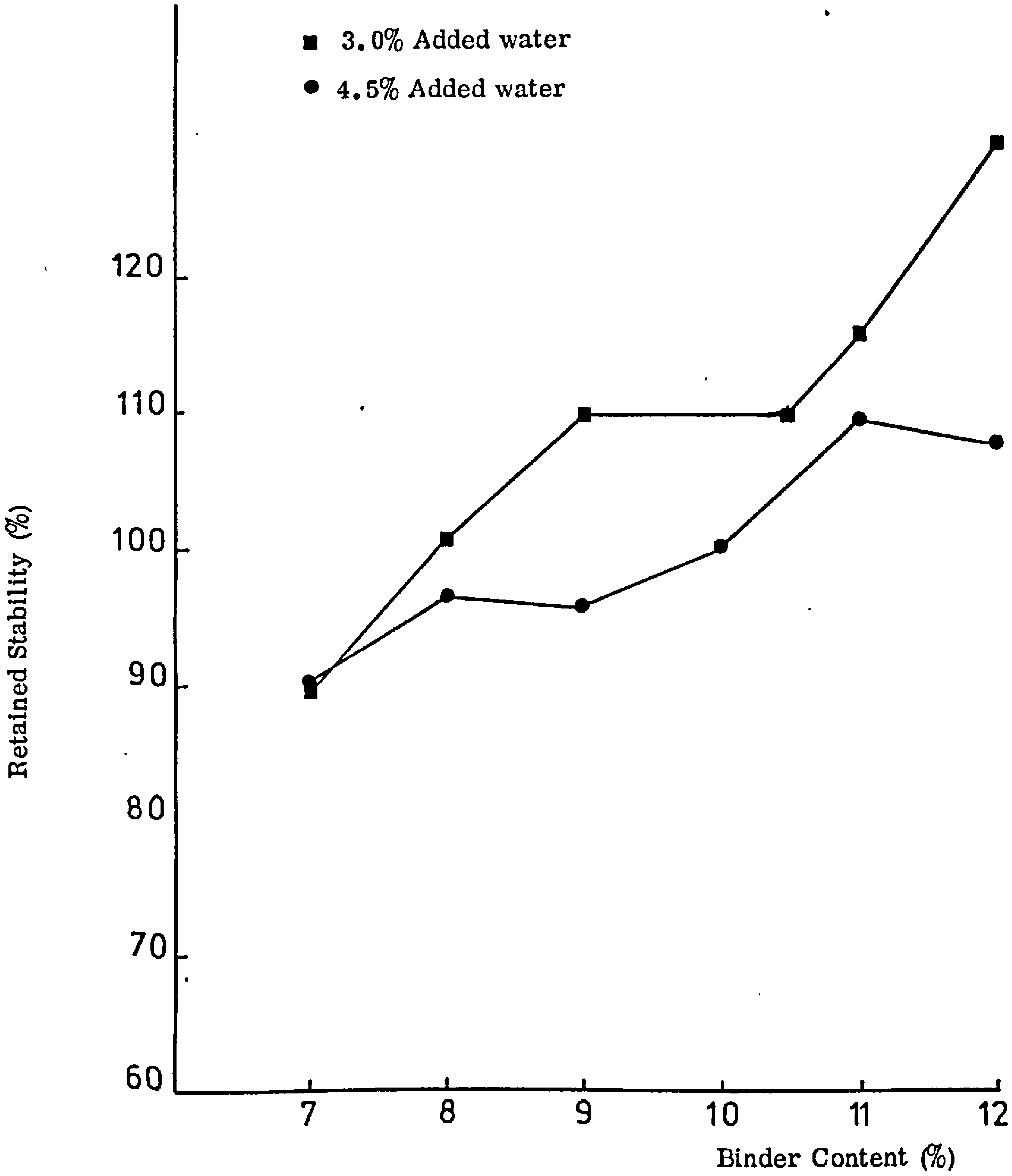


Fig. 8.29 RETAINED STABILITY vs BINDER CONTENT (after final curing)

Finally the "dry" and "wet" Marshall quotient values were significantly affected by both the binder content and added water, and their interaction, Figures 8.25 and 8.28. Both figures showed that the Marshall quotient decreased as the binder content increased. The "wet" MQ values ranged between 2 and 7.5 kN/mm; these values are far higher than the one-day MQ values.

8.4.2.4. The effect on air permeability

The statistical analysis has shown that both main factors and their interaction significantly affect the air permeability of the CRA mixtures after final curing. Figure 8.30 shows that different levels of added water produce mixtures with different air permeabilities.

The permeability value decreases rapidly with increasing percentage of binder. For both systems, i.e. 3% and 4.5% added water, the permeability-binder content relations shows a clear minimum value, for a binder content of 10 to 11%. Increasing the binder content beyond this value increases the permeability value in both systems.

Figure 8.30 shows that at binder contents below 10-11% the permeability value is lower for 3% added water mixtures but that beyond this range of binder contents the trend is reversed i.e. permeability of the 4.5% added water mixtures is smaller. A qualitative explanation of these trends is quite evident assuming the relations shown in Figures 8.20 and 8.32. At lower binder contents permeability is influenced by the volume of voids, while at higher binder contents the permeability appears to be strongly influenced by the volume of water remaining in the voids. Mixtures with 4.5% added water contain a higher percentage of water in the low volume of voids zone and thus exhibit lower values of permeability, than mixtures with 3% added water content.

(To convert cm^2 to cm/sec multiply by 10^5)

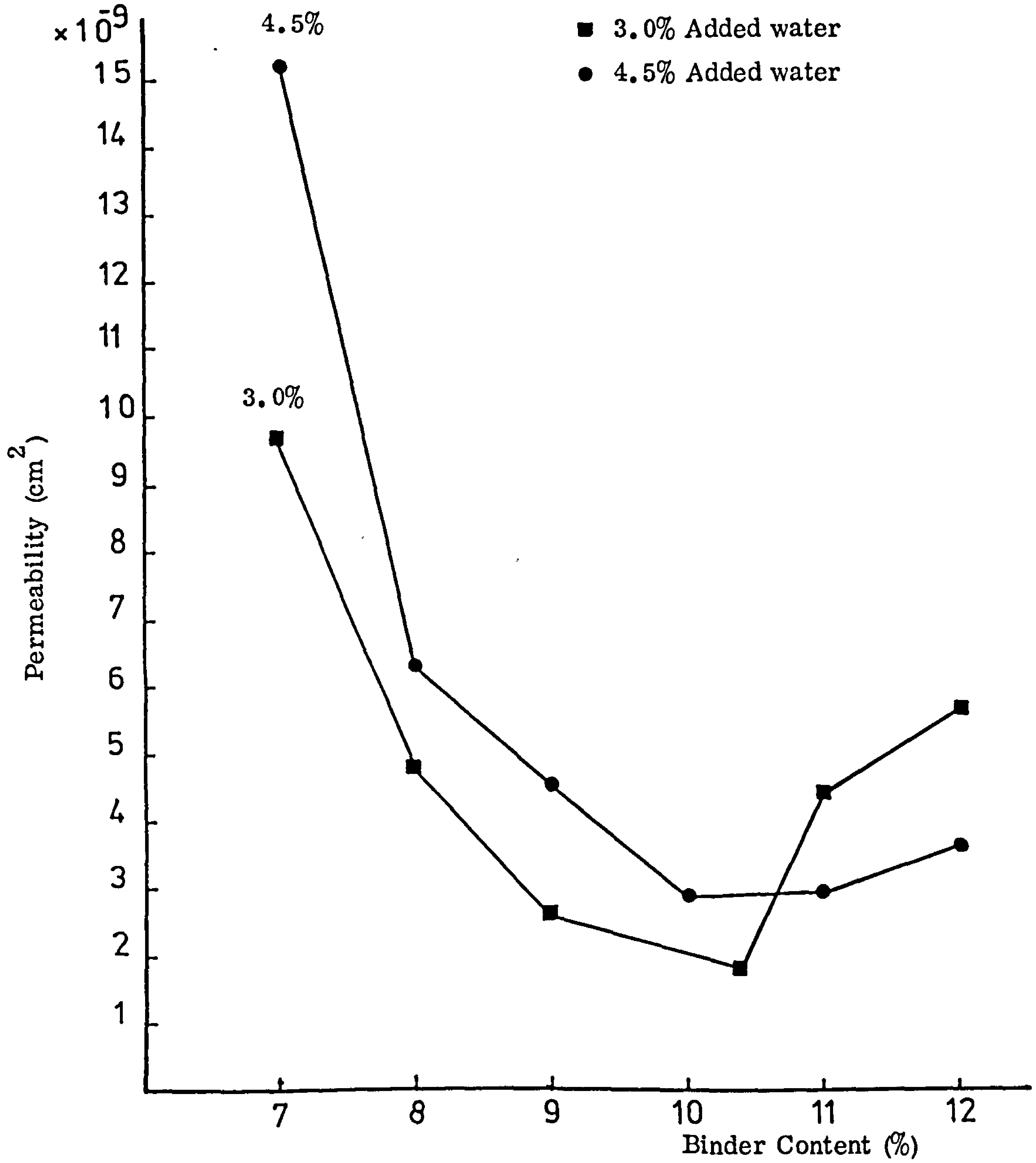


Fig. 8.30 PERMEABILITY vs BINDER CONTENT
(Final curing)

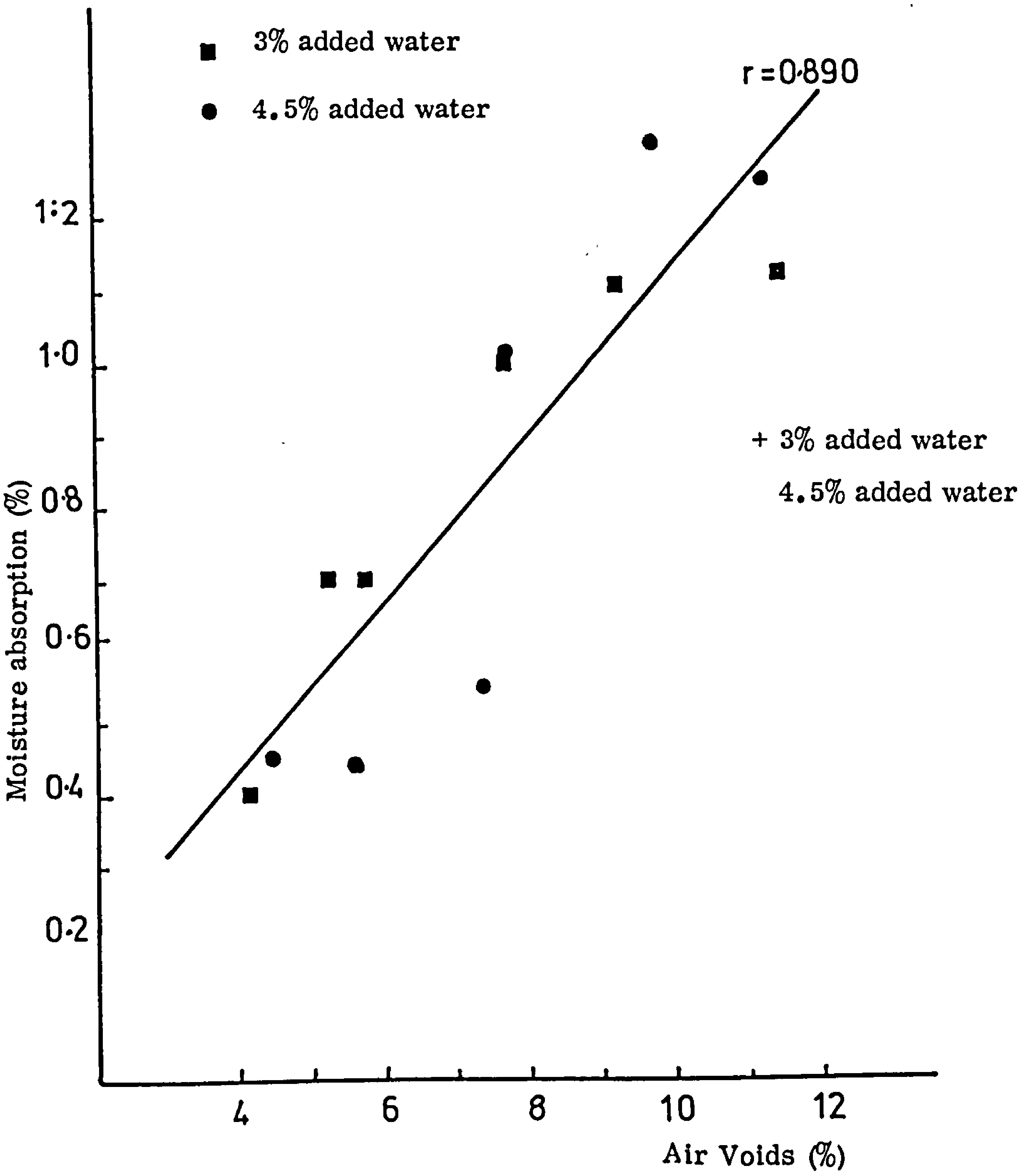


Fig. 8.31 MOISTURE ABSORPTION v TOTAL VOIDS

(Final Curing)

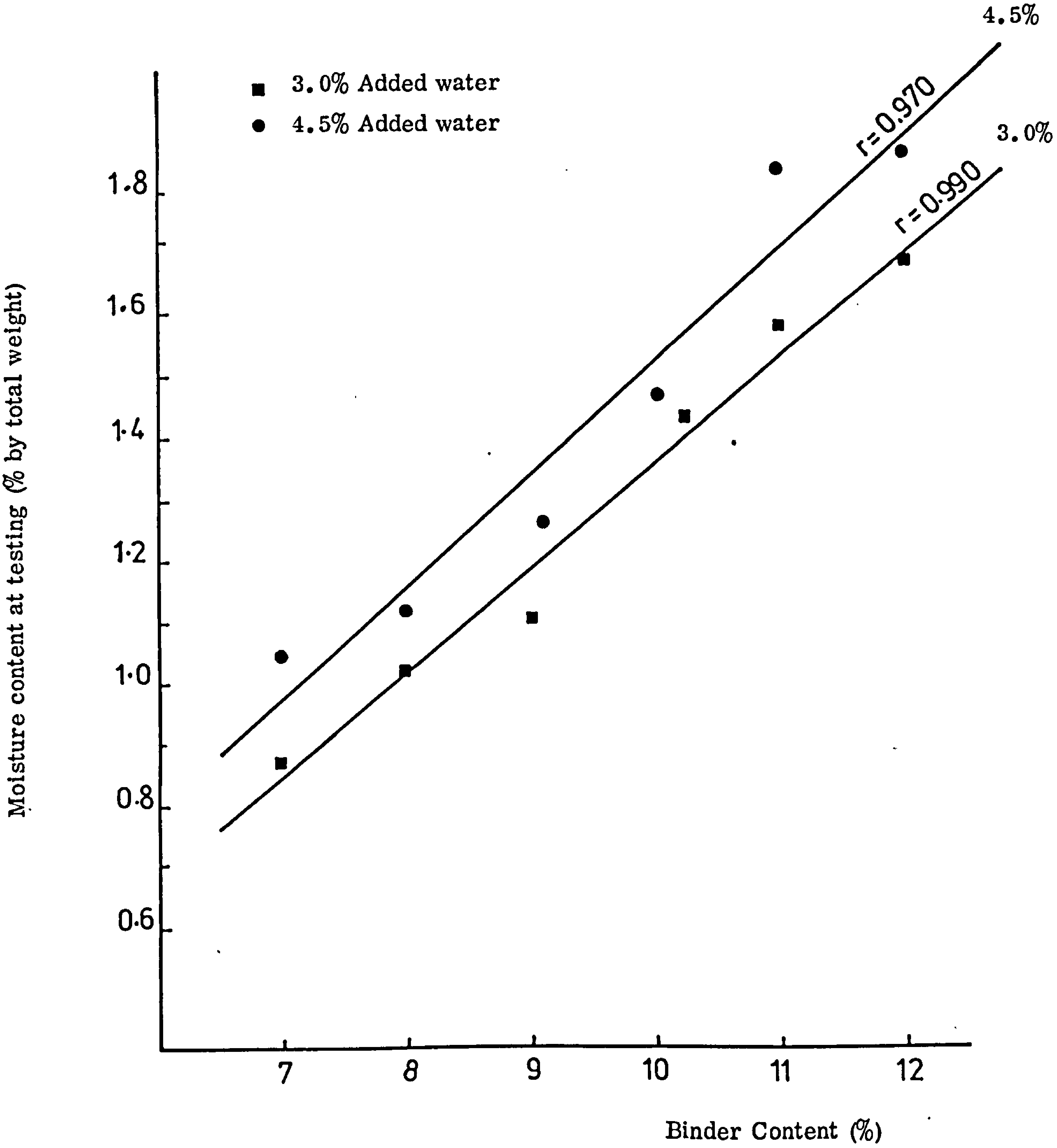


Fig. 8,32 MOISTURE CONTENT AT TESTING vs BINDER CONTENT (after final curing)

8.4.2.5. The effect on the percentage of retained water content

It has been shown in Chapter 5, Figure 5.5, that after 28 days of air curing, followed by 2 days of oven curing at 60°C, there is a remaining amount of water which cannot be removed easily. From these results it was apparent that the amount of retained water is a function of binder content.

The results of the statistical analysis, Table 8.4, show that retained moisture content is not only significantly affected by the binder content but also by the percentage of added water. As Figure 8.32 shows, there is an excellent correlation between moisture content at testing and binder content, at both levels of added water (correlation coefficients were as high as 0.970 and 0.991 for 3.0 and 4.5% added water respectively).

The amount of moisture remaining in the system, although small, will certainly cause a reduction in adhesion between the aggregate surface and the binder and thus it may increase the risk of stripping if water is present in the pores of the C.R.A. mixtures.

8.4.3. The effect of compaction temperature on the properties of C.R.A. mixtures

The volume of total voids of the Cold Rolled Asphalt (C.R.A.) mixtures were found to range between 5 to 12.7 percent. These values are relatively high when compared with values obtained with Hot Rolled Asphalt mixtures. It is reasonable to expect that reduction of the volume of total voids would improve the properties of the C.R.A. mixtures, especially stability after water exposure. Better compaction may be achieved by increasing the temperature of the mixture at the compacting stage. The compacting temperature has to be high enough to bring the desired reduction in the percentage of total voids, but not so high as to become an expensive operation. For example, the temperatures of 80 to 90°C used by various organisations (5, 7) for surface dressing were considered to be both high and costly.

In some countries during the summer months, the environmental temperature during construction reaches 40-45°C, thus a temperature of 40°C was selected as a realistic and not very expensive part of the process. During the laboratory investigation this temperature was obtained by allowing the mixture to cool down from 60°C to 40°C (see Chapter 5). The properties of the C.R.A. mixtures were measured, under these compacting conditions and compared with the properties of the C.R.A. mixtures compacted at room temperature (21°C ± 1°C).

8.4.3.1. The effect on bulk density voids and compactability of the mixtures

When compaction was carried out at 40°C, the bulk density of the mixtures, at all binder content levels, was increased, Figures 8.33 to 8.36, and the volume of the voids was decreased, Figures 8.37 to 8.42. It was found that the average reduction of total voids was approximately 17%.

The compaction of the mixtures was carried out with the Gyratory Testing Machine (G.T.M.), which enabled the monitoring of the reduction of the height of the specimens, and hence of the voids, during compaction (see Appendix C for formulae used). When the volume of total voids was plotted against the number of gyratory revolutions, the compactability of the mixtures could be determined. One mixture would be more compactable than another, at the same level of binder content, if at any stage of compaction the volume of voids is lower than the other. Figure 8.43 shows the compaction curves (Total voids vs number of gyratory revolutions) of the mixtures compacted at 21°C and 40°C. It is apparent that at any binder content level the compactability of the mixtures compacted at 40°C is higher than mixtures compacted at 21°C. It can also be seen that the slope of the compaction curves changes with

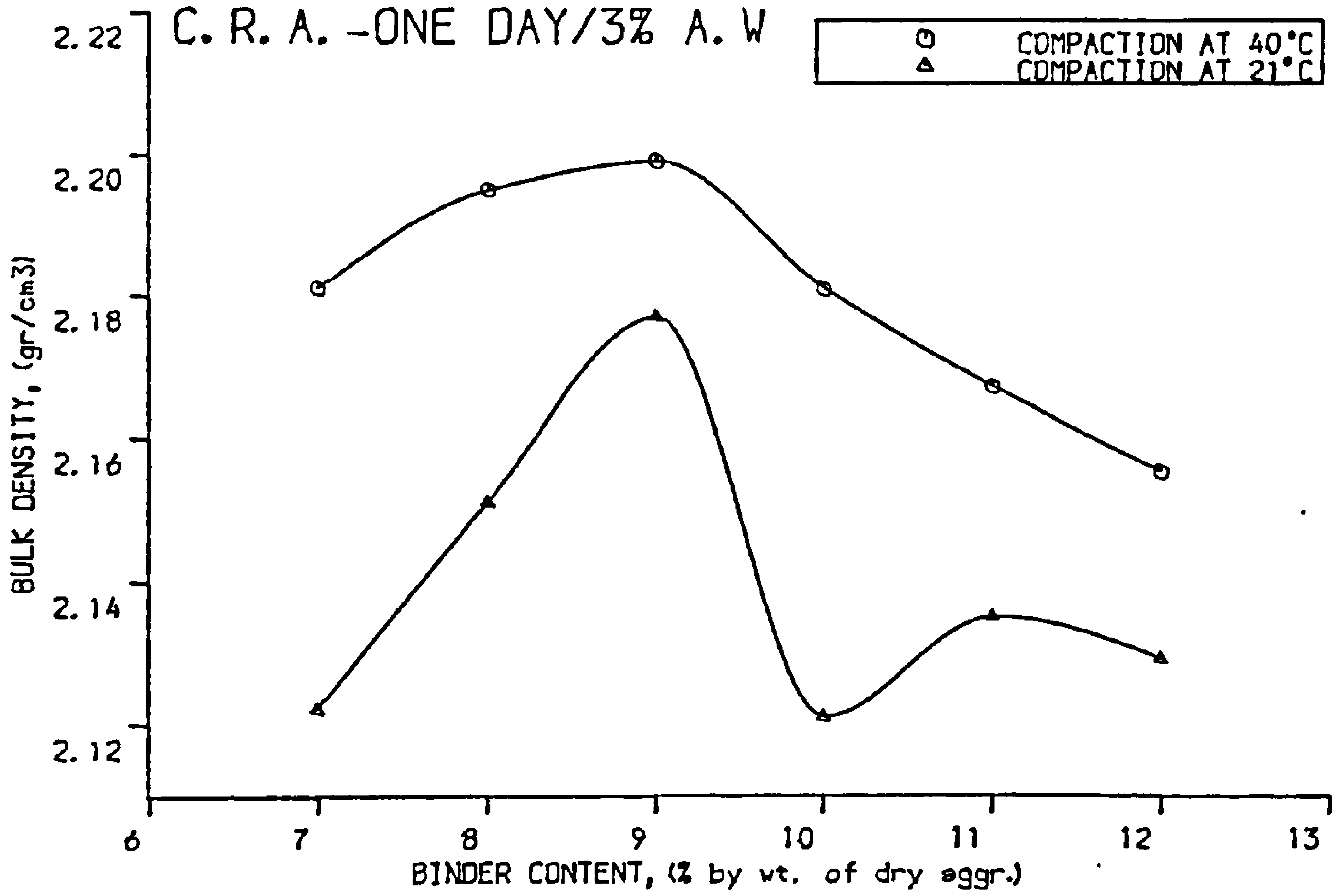


Fig. 8. 33 BULK DENSITY v BINDER CONTENT

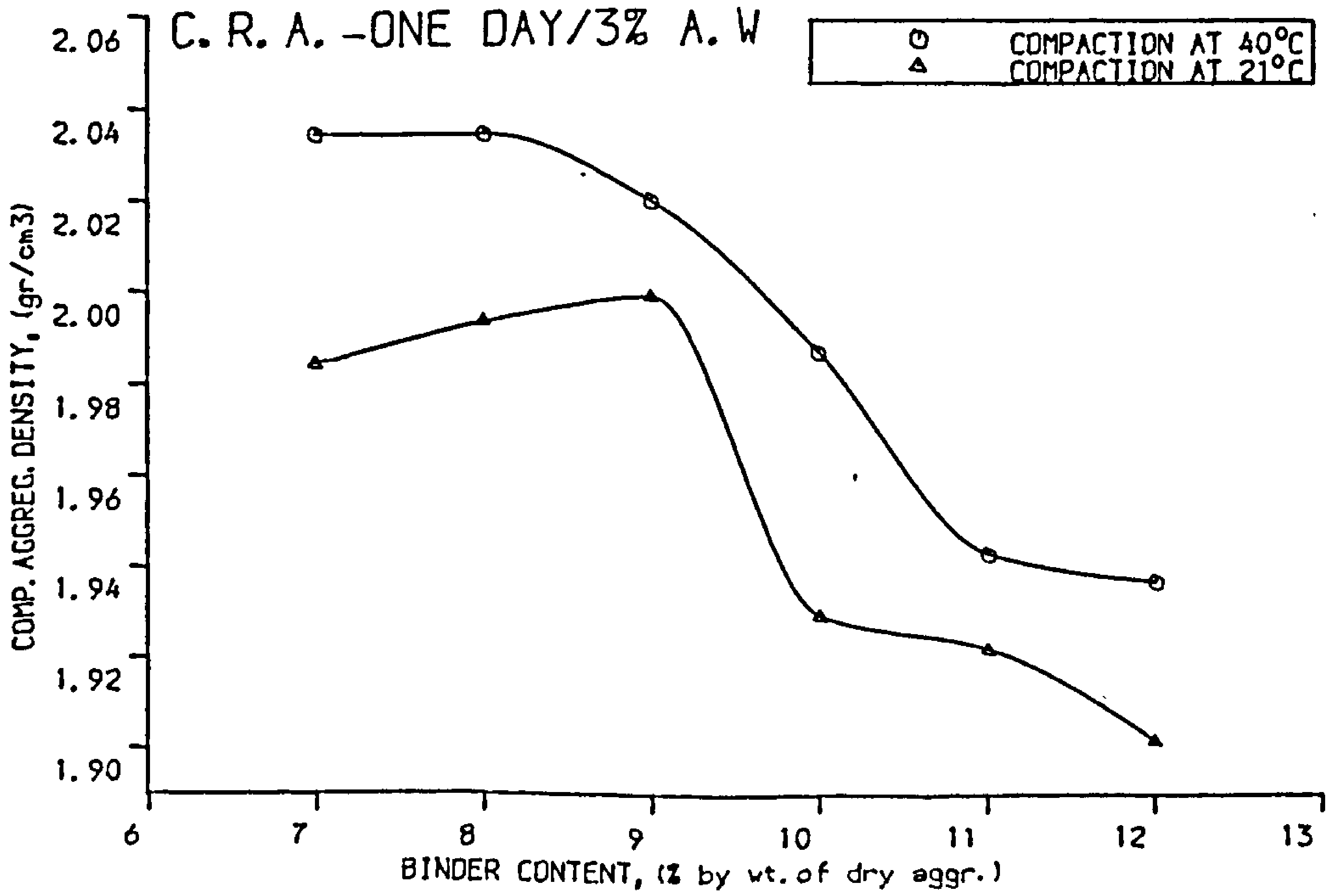


Fig. 8. 34 COMP. AGGR. DENSITY v BINDER CONT.

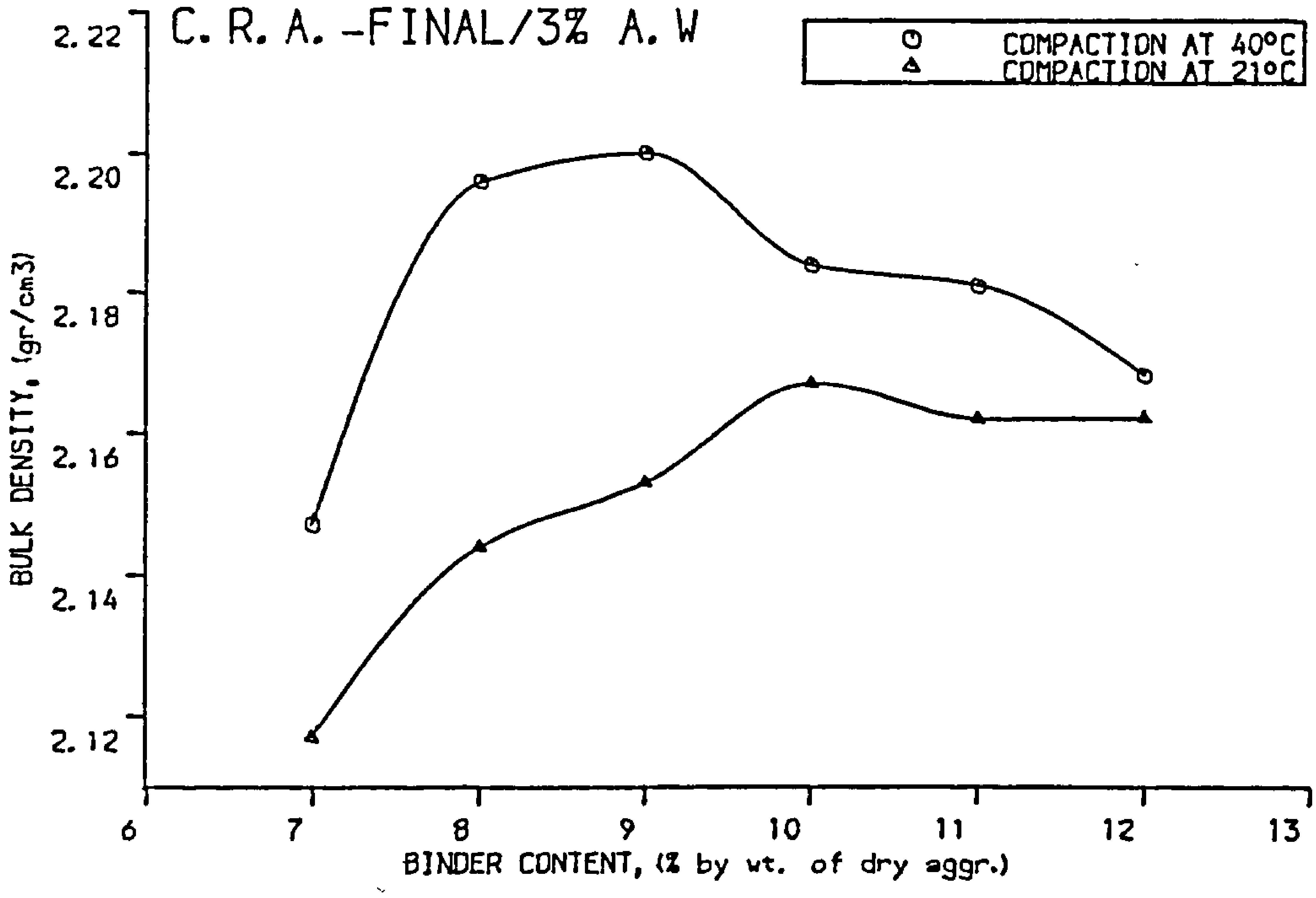


Fig. 8.35 BULK DENSITY v BINDER CONTENT

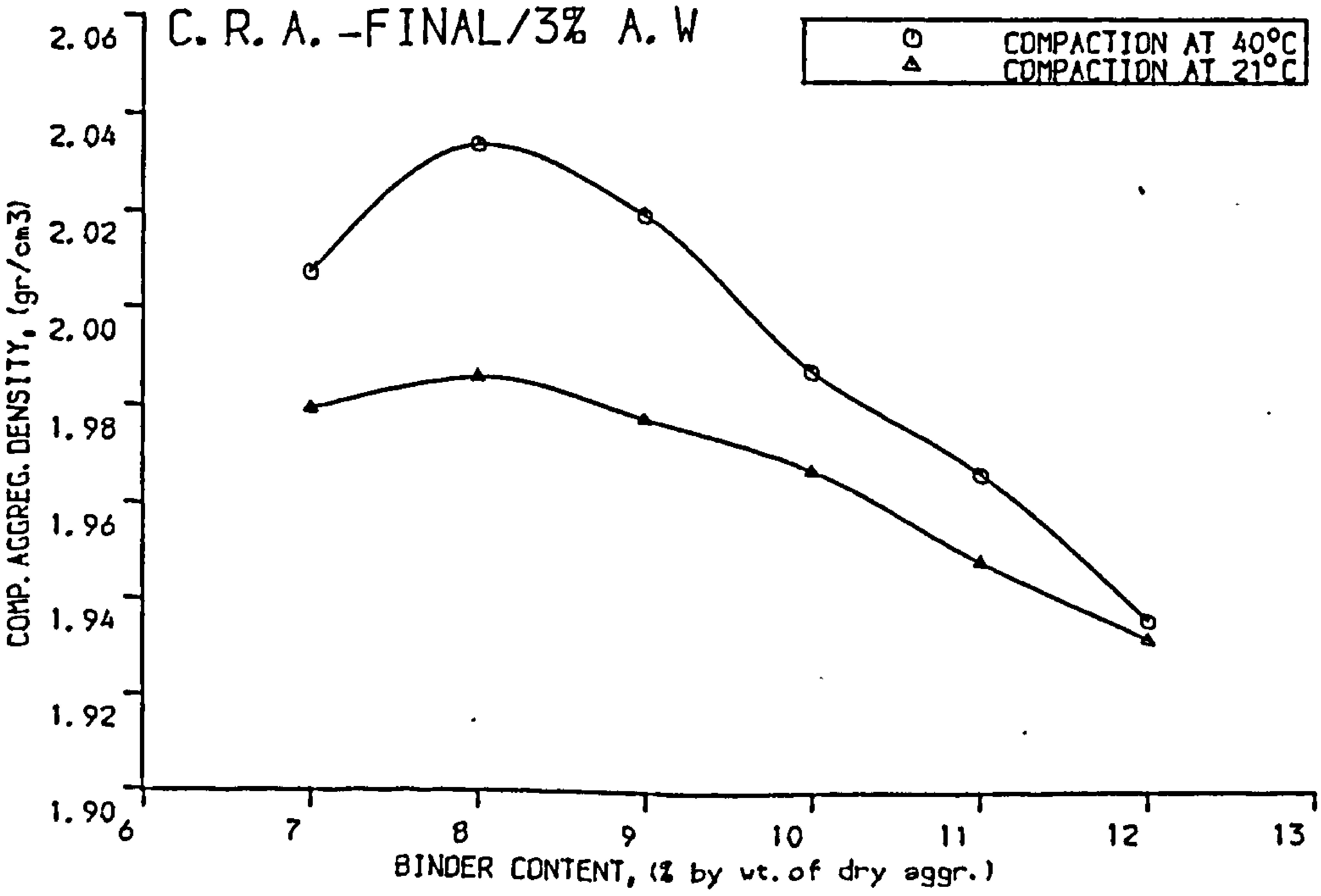


Fig. 8.36 COMP. AGGR. DENSITY v BINDER CONT.

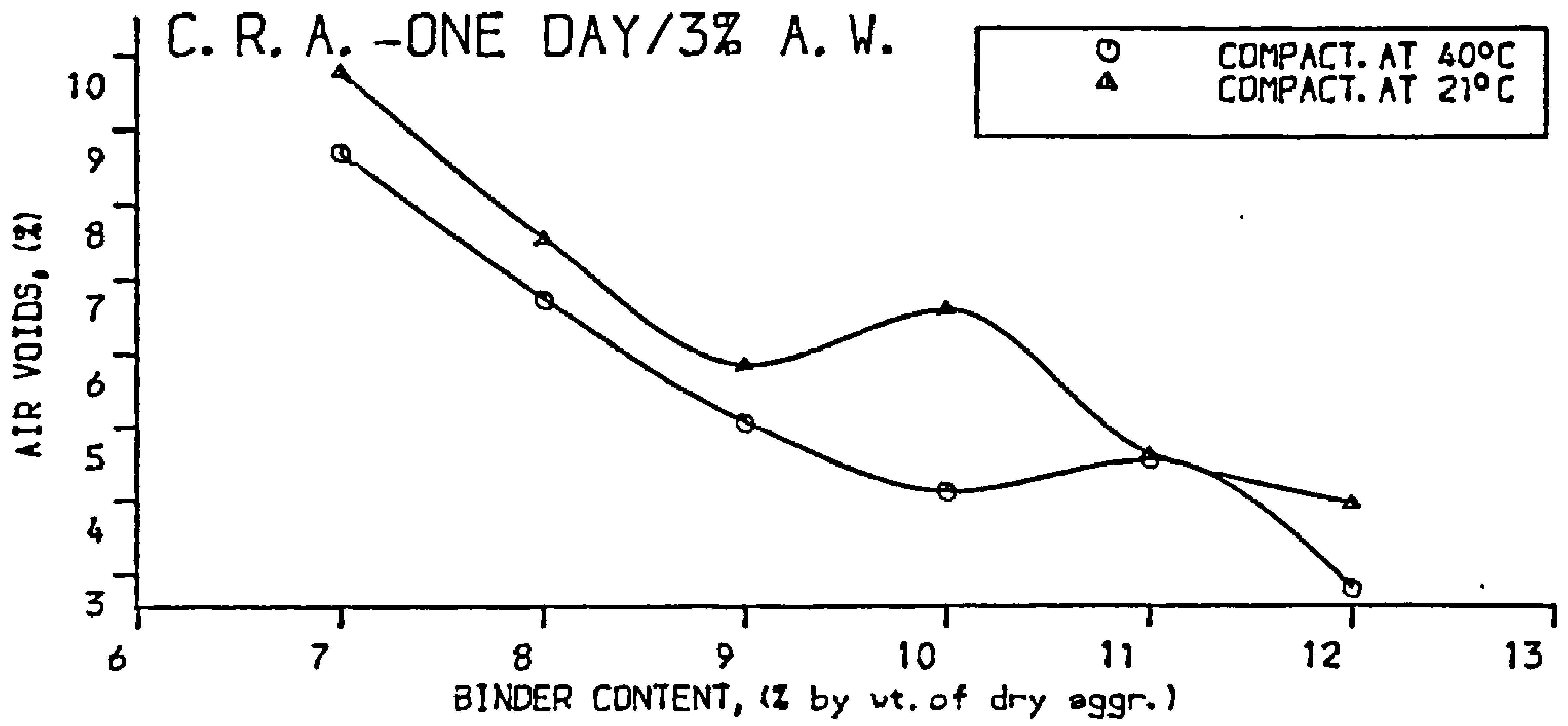


Fig. 8.37 AIR VOIDS v BINDER CONTENT

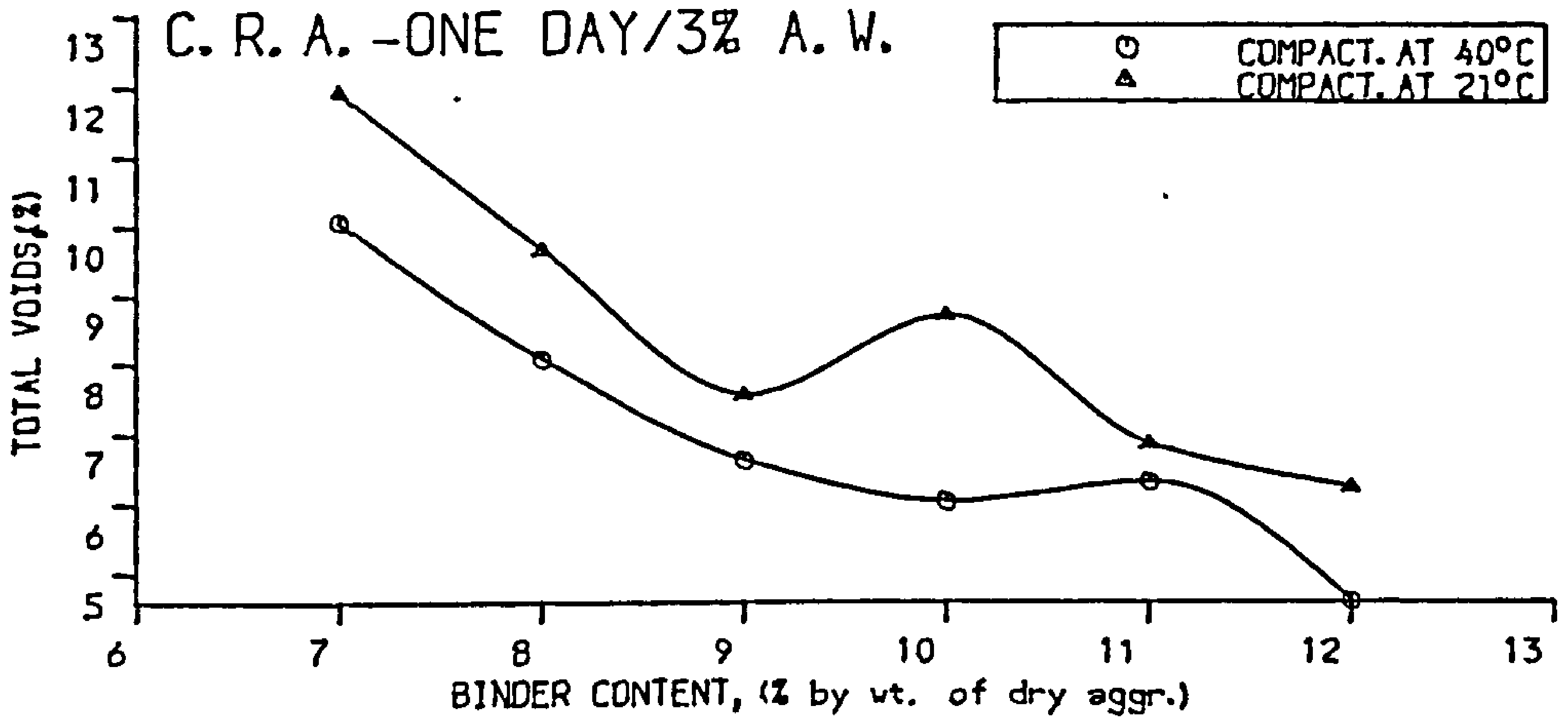


Fig. 8.38 TOTAL VOIDS v BINDER CONTENT

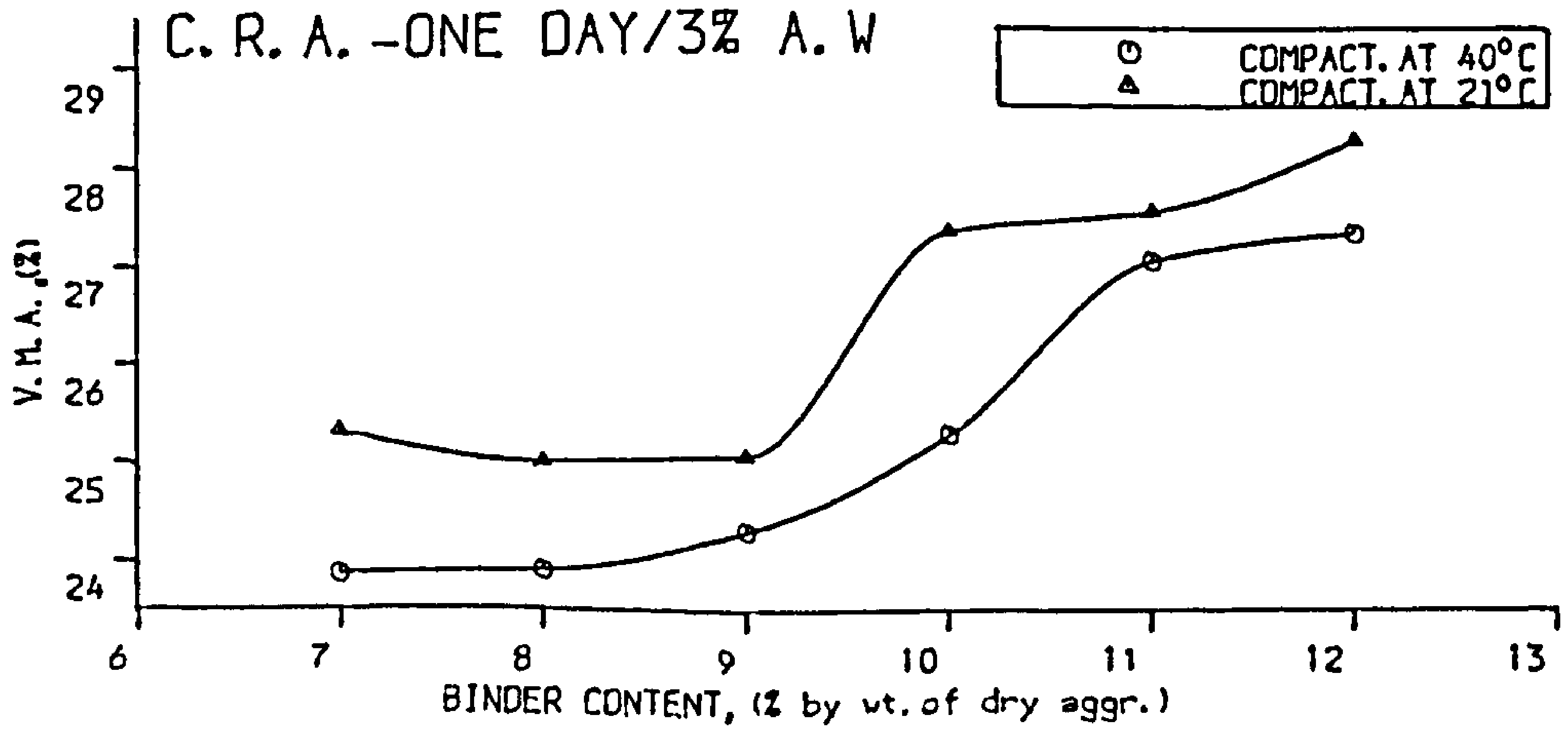


Fig. 8.39 V.M.A v BINDER CONTENT

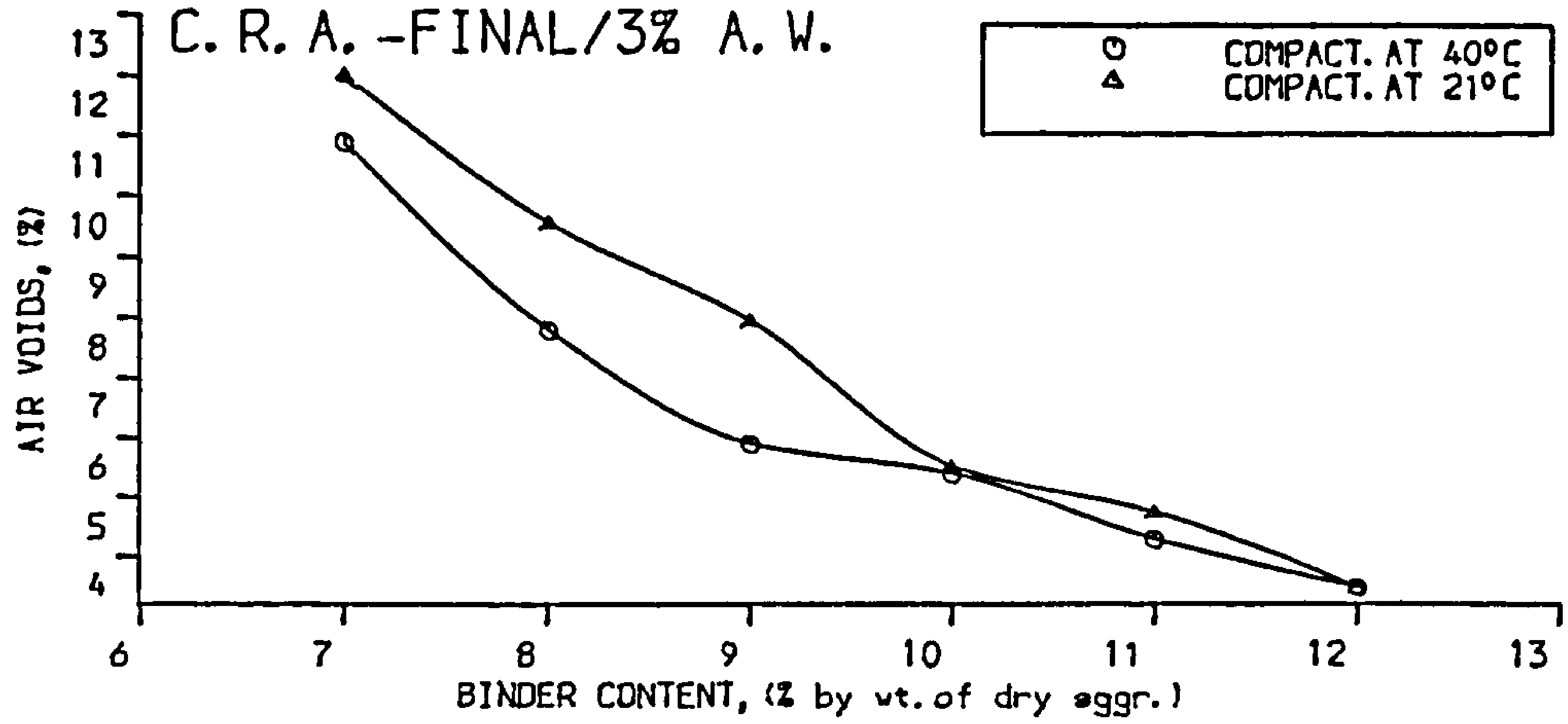


Fig. 8.40 AIR VOIDS v BINDER CONTENT

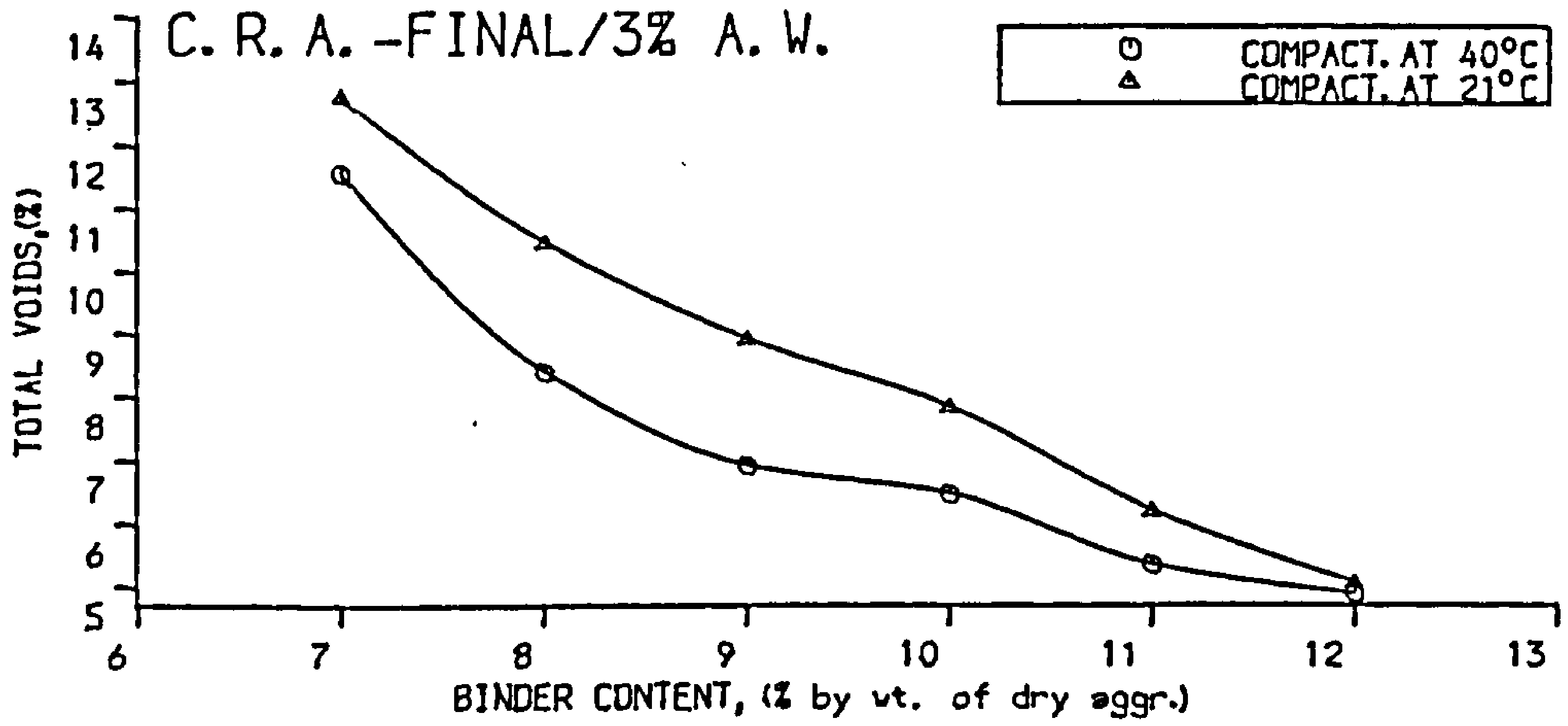


Fig. 8.41 TOTAL VOIDS v BINDER CONTENT

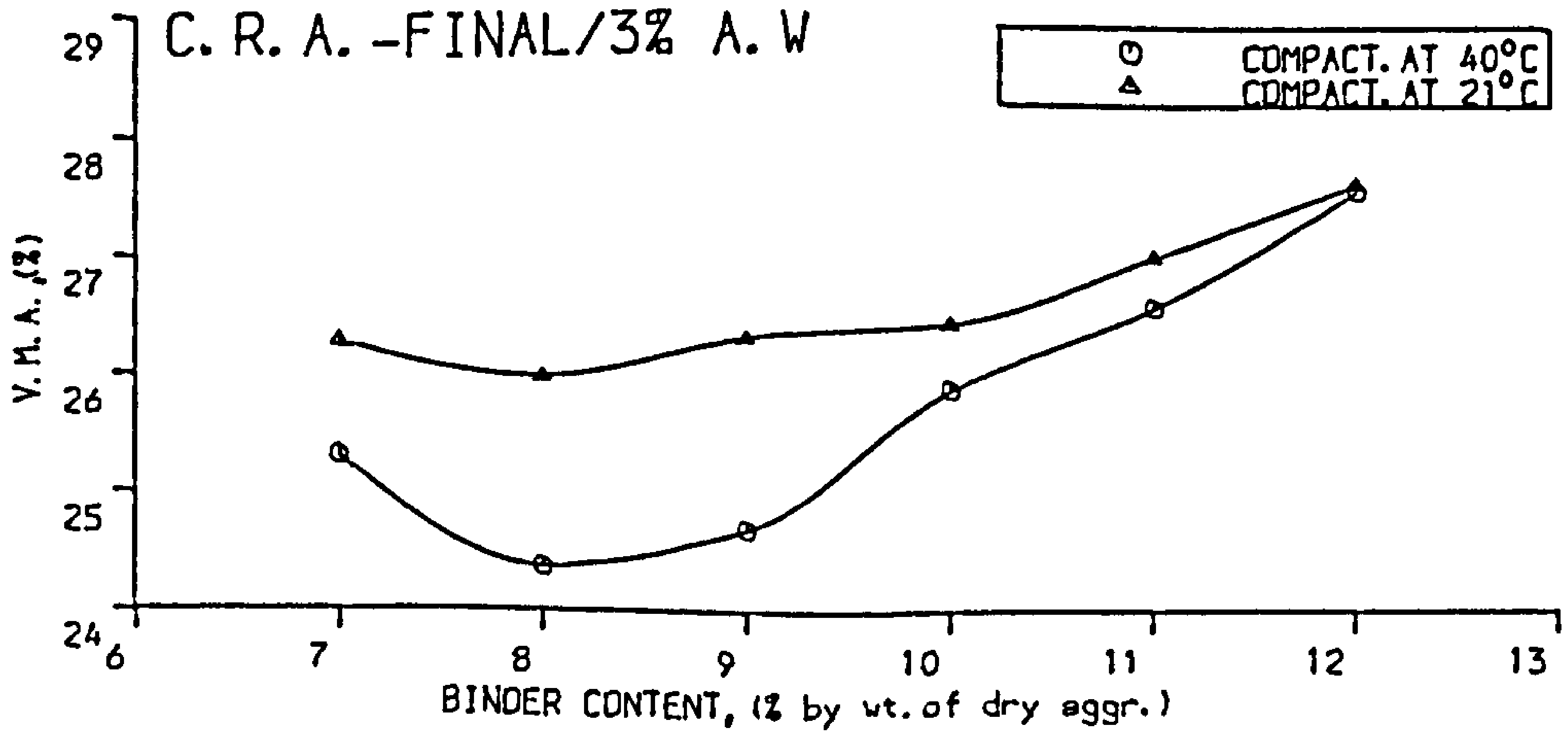


Fig. 8.42 V. M. A v BINDER CONTENT

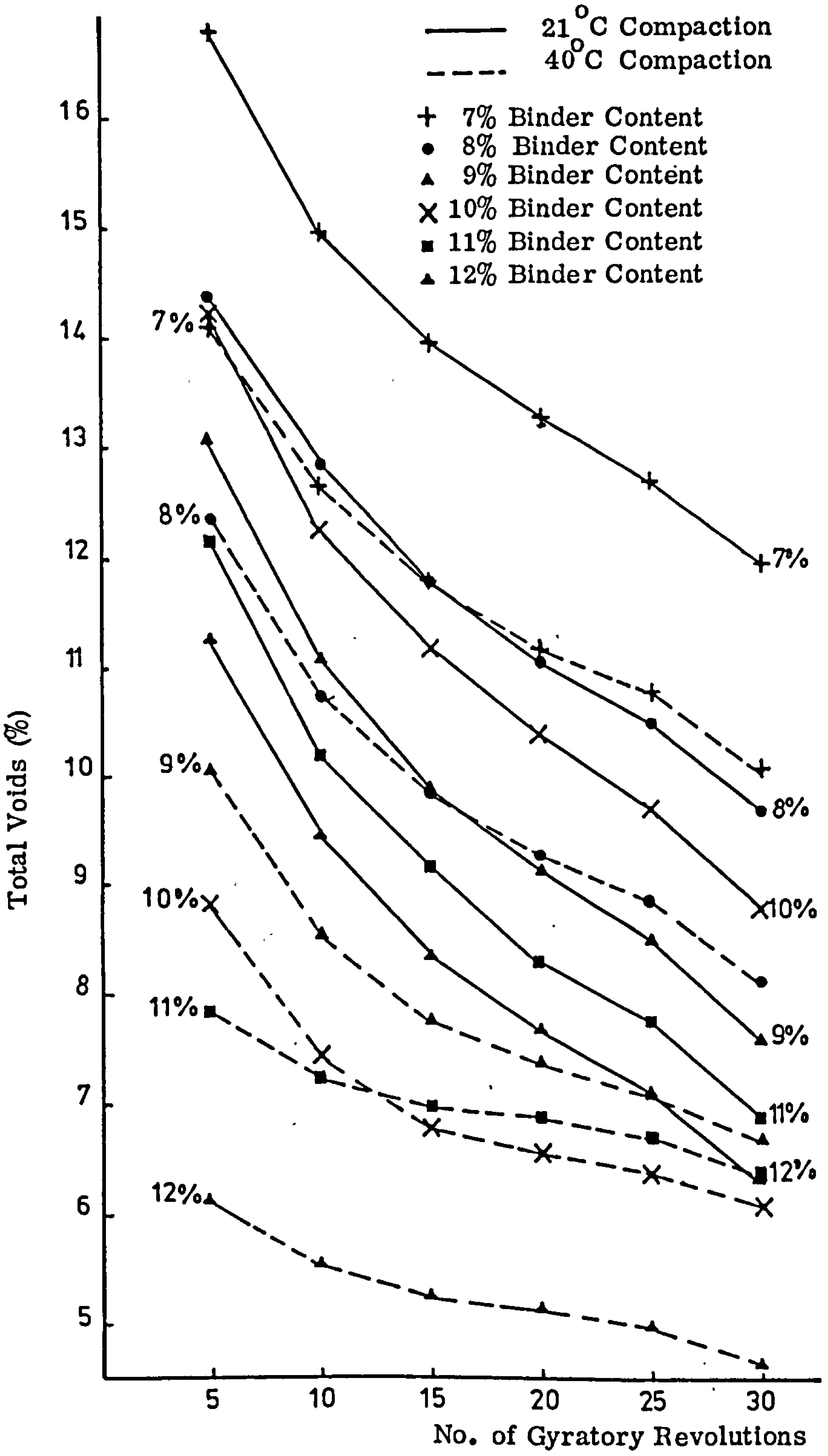


Fig. 8.43 COMPACTION CURVES OF MIXTURES COMPACTED AT TWO DIFFERENT TEMPERATURES

(Water content at compaction = 3%, one day curing, 3% added water) binder content. The best linear relation, between the total voids and the number of gyratory revolutions, was found when the results were plotted in a semi-logarithmic scale, see Table 8.6. When the slope of the straight lines were plotted against binder content, it was found that the slope is dependent on the binder content, Figure 8.44. The slope, ie. the rate of compaction, increases with binder content, and a maximum value occurs at a certain binder content. This maximum value could only be seen clearly on the mixtures compacted at 40°C, because the viscosity of the binder was much lower than at 21°C. The maximum value of the rate of compaction suggests that, if compaction takes place at 40°C, the compaction of the mixture having binder content greater than the optimum will not be as effective as the mixture having the optimum binder content. This finding may be used as an additional parameter for the determination of optimum binder content of the C.R.A. mixtures.

It can therefore be said that when the C.R.A. mixtures were compacted at 40°C their compactability was increased which resulted in higher densities, and lower volume of voids. Additionally, compaction at 40°C gives valuable information of the optimum binder content for the most effective compaction.

8.4.3.2. The effect on Marshall properties

The results of "dry" Marshall properties, after one day of curing, have been plotted in Figures 8.45 to 8.47, and the "wet" equivalent values in Figures 8.48 to 8.50. It can be seen that although the dry stability, Figure 8.45, was not improved, the "wet" stability was significantly improved due to compaction at 40°C. As a result, the retained stability was increased, and all mixtures, apart from the leanest, had a retained stability (after one day of curing) of more than 40 percent Figure 8.51. In comparison, only three mixtures compacted at 21°C had retained stability greater than 40%.

40^o COMPACTION				21^o COMPACTION			
$Y = 10^{(aX + b)}$				$Y = 10^{(aX + b)}$			
Binder Content (%)	a $\times 10^{-3}$	b	Correlation r*	Binder Content (%)	a $\times 10^{-3}$	b	Correlation r*
7	-5.63	1.17	-0.98	7	-5.65	1.24	-0.98
8	-6.95	1.11	-0.98	8	-6.66	1.18	-0.99
9	-6.76	1.01	-0.96	9	-8.95	1.14	-0.99
10	-5.96	0.95	-0.94	10	-8.06	1.18	-0.99
11	-3.31	0.90	-0.98	11	-9.41	1.11	-0.99
12	-4.42	0.80	-0.98	12	-9.74	1.08	-0.99

Y = Total Voids, X = No. of revolutions

*For two-tailed test and for 99% confidence limit, r = 0.917 (4 D.F)

TABLE 8.6 COEFFICIENTS FOR LINEAR RELATIONSHIP BETWEEN TOTAL VOIDS AND NUMBER OF GYRATORY REVOLUTIONS. (AVERAGE OF 6 READINGS, SEE APPENDIX G)

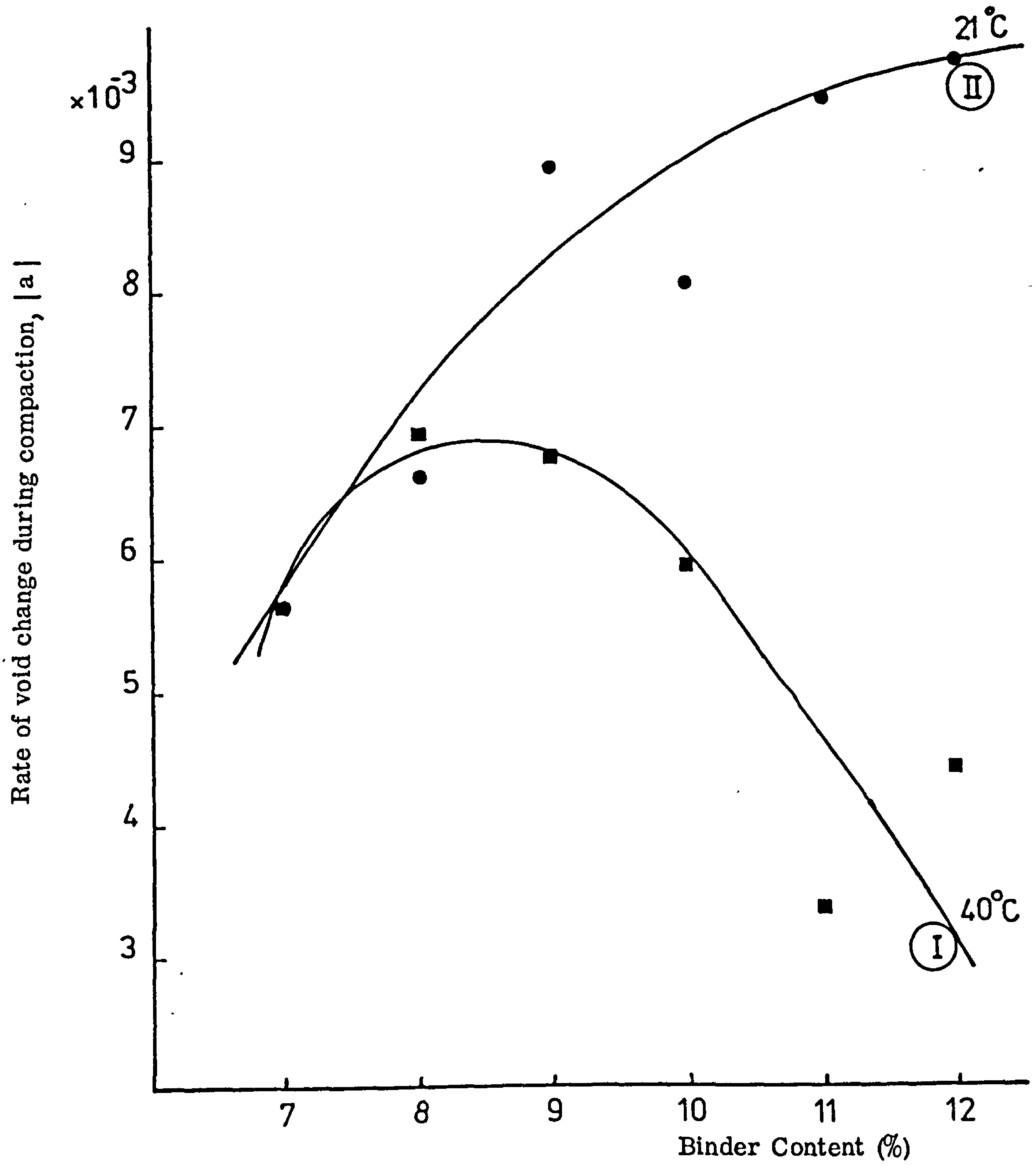


Fig. 8.44 SLOPE "a" vs BINDER CONTENT, TWO COMPACTION TEMPERATURES, ONE-DAY CURING

(Average values of six specimens, see Appendix G)

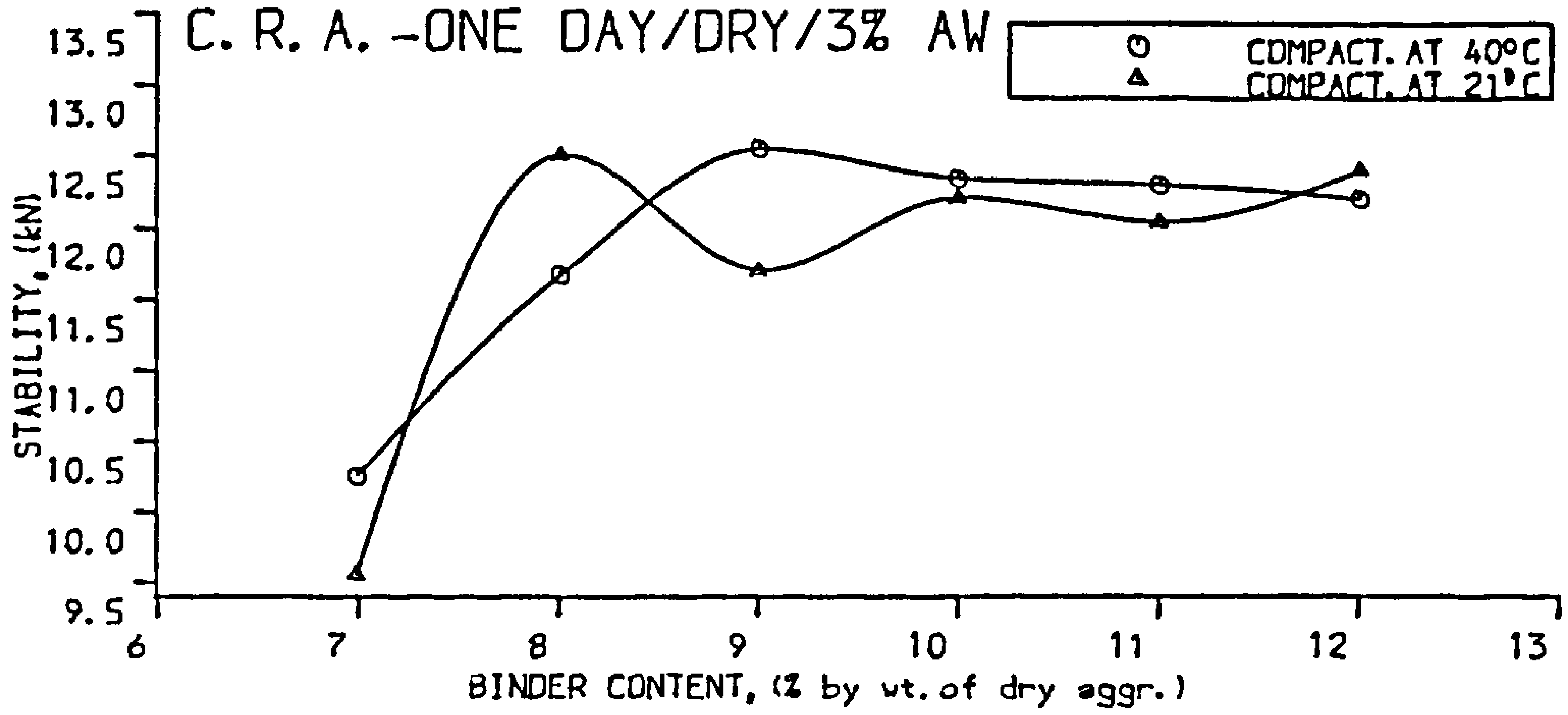


Fig. 8.45 MARSH. STABILITY v BINDER CONT.

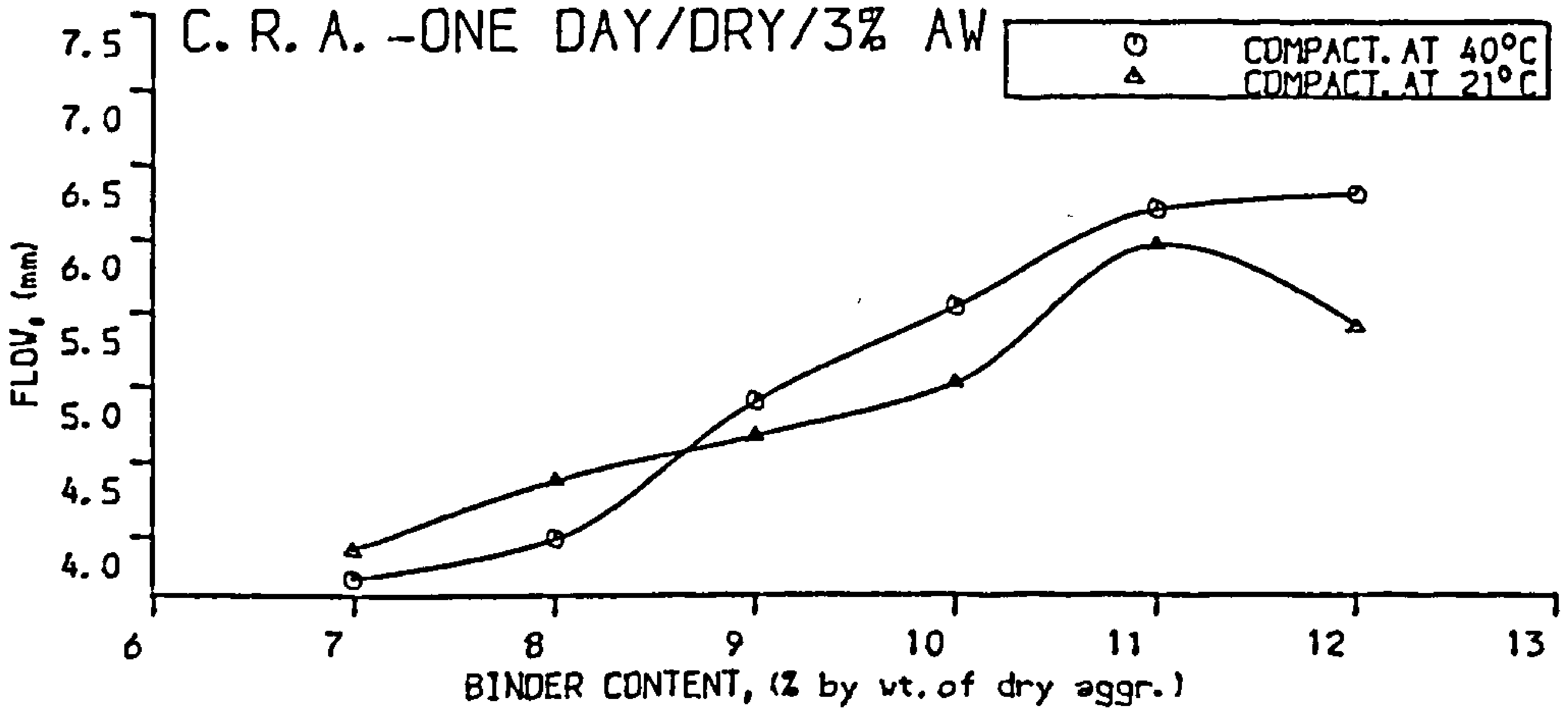


Fig. 8.46 MARSHALL FLOW v BINDER CONT.

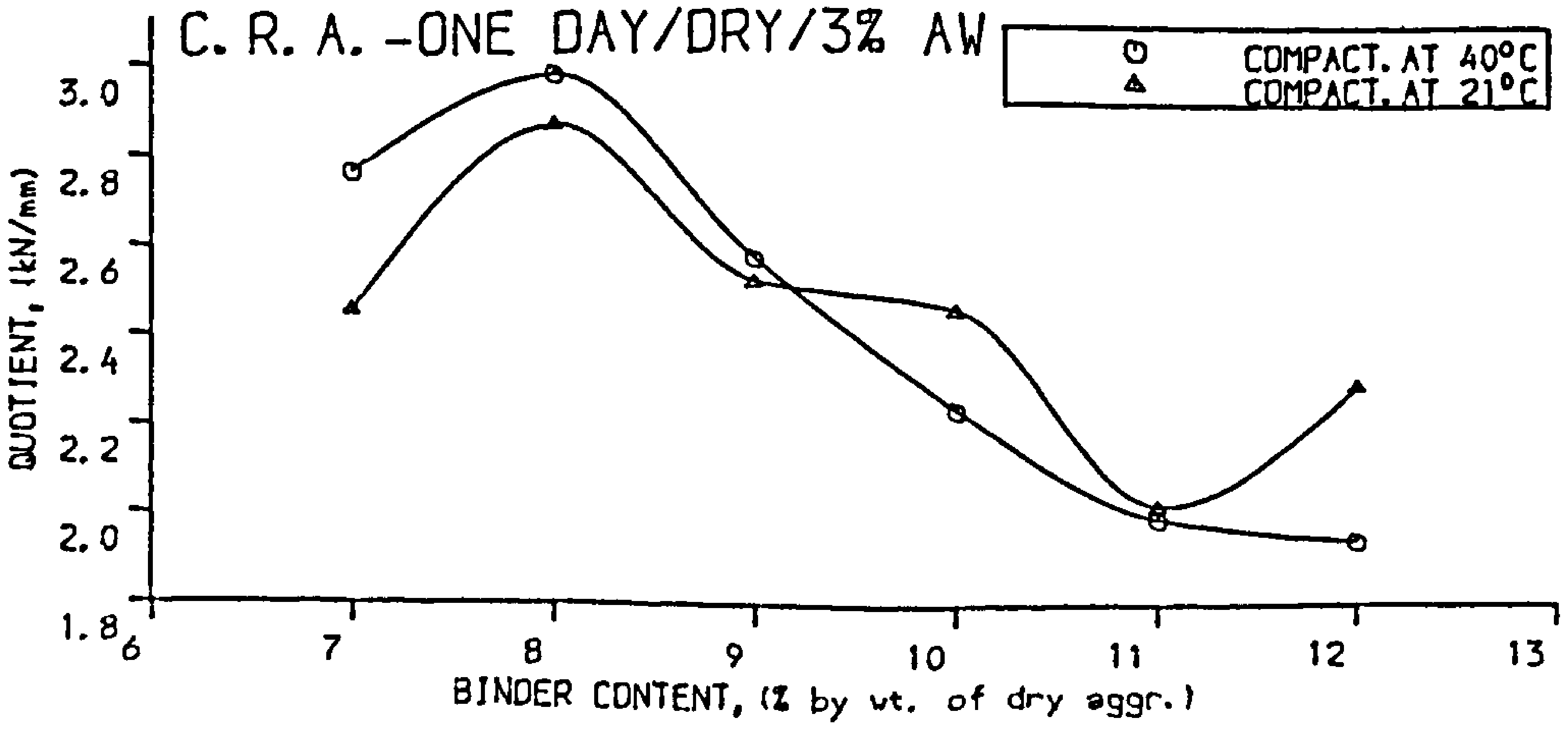


Fig. 8.47 MARSH. QUOTIENT v BINDER CONT.

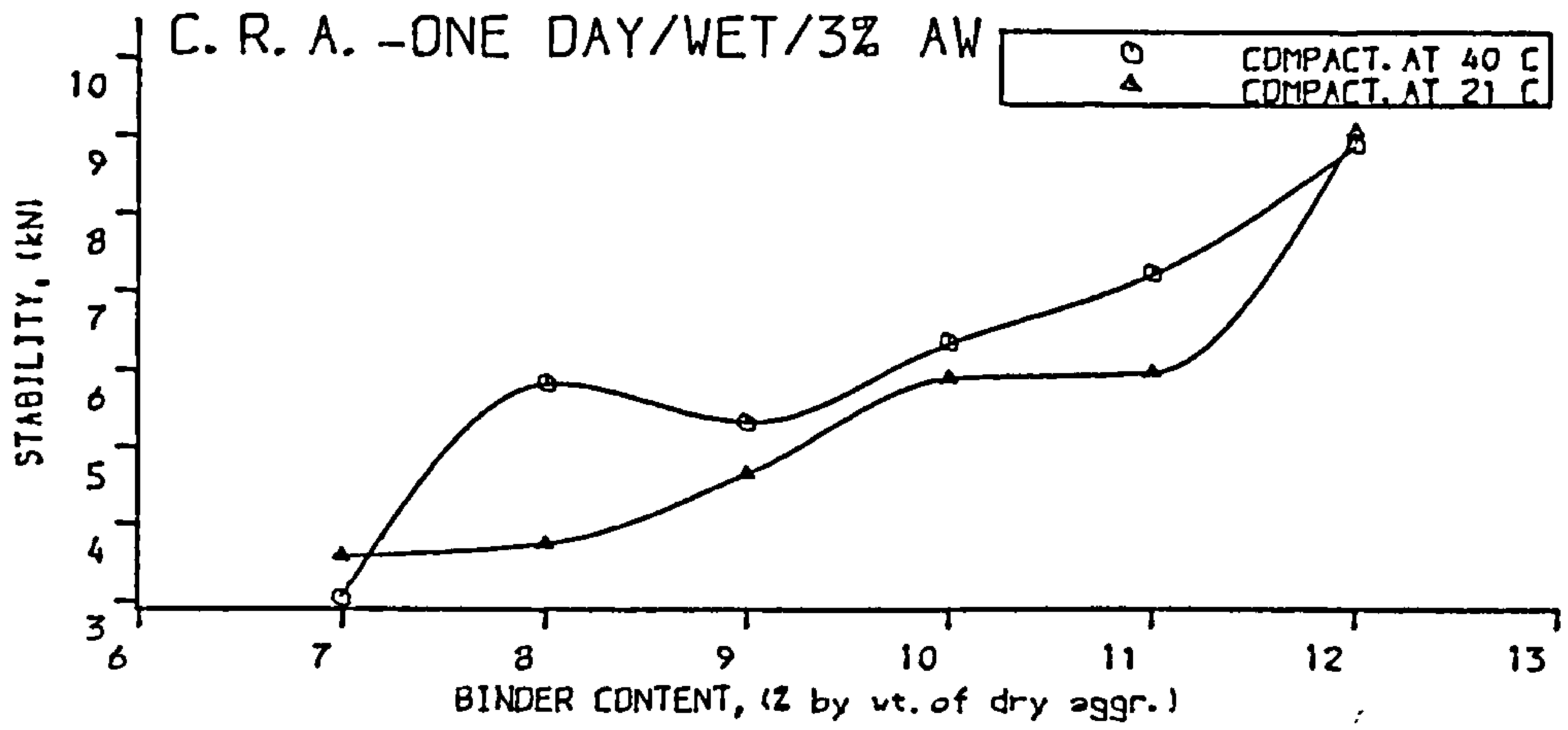


Fig. 8. 48 MARSH. STABILITY v BINDER CONT.

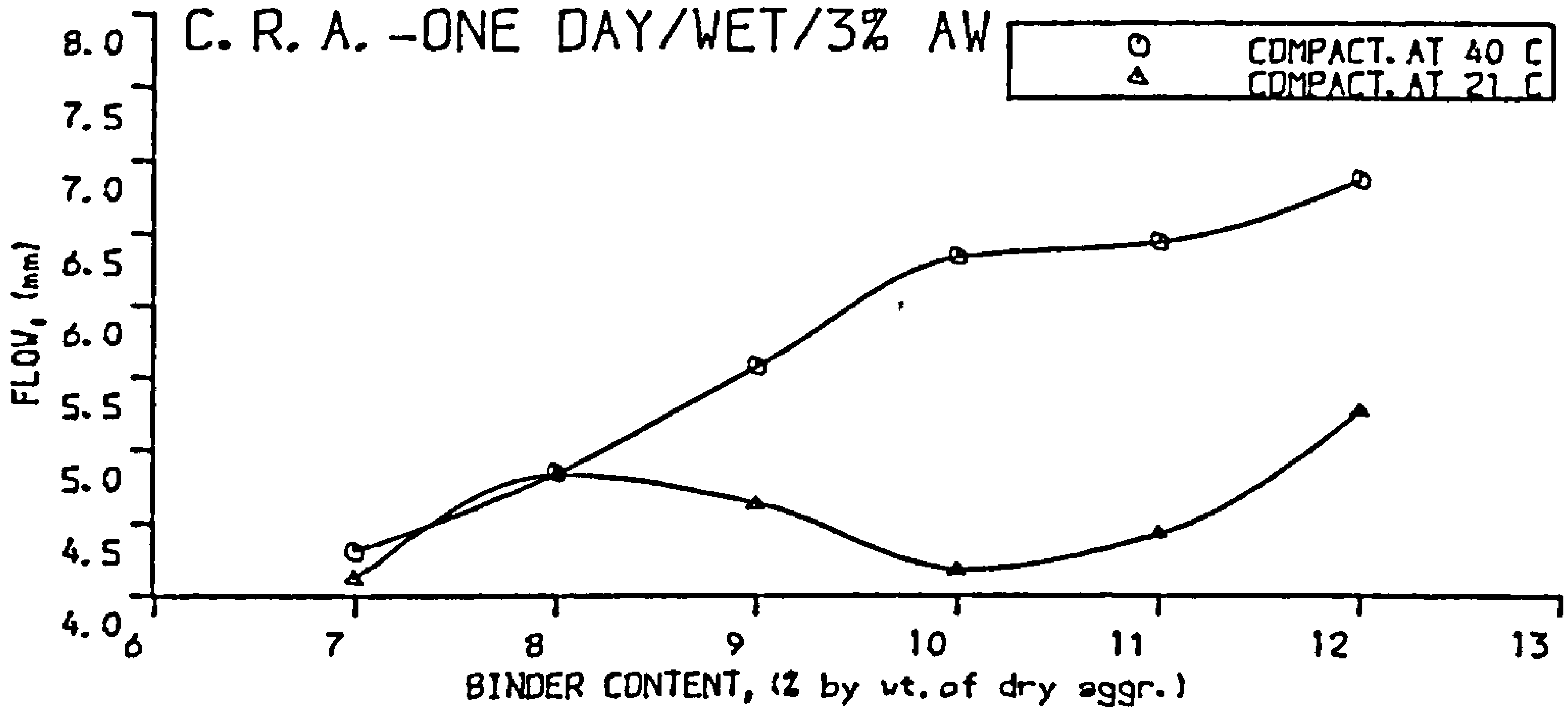


Fig. 8. 49 MARSHALL FLOW v BINDER CONT.

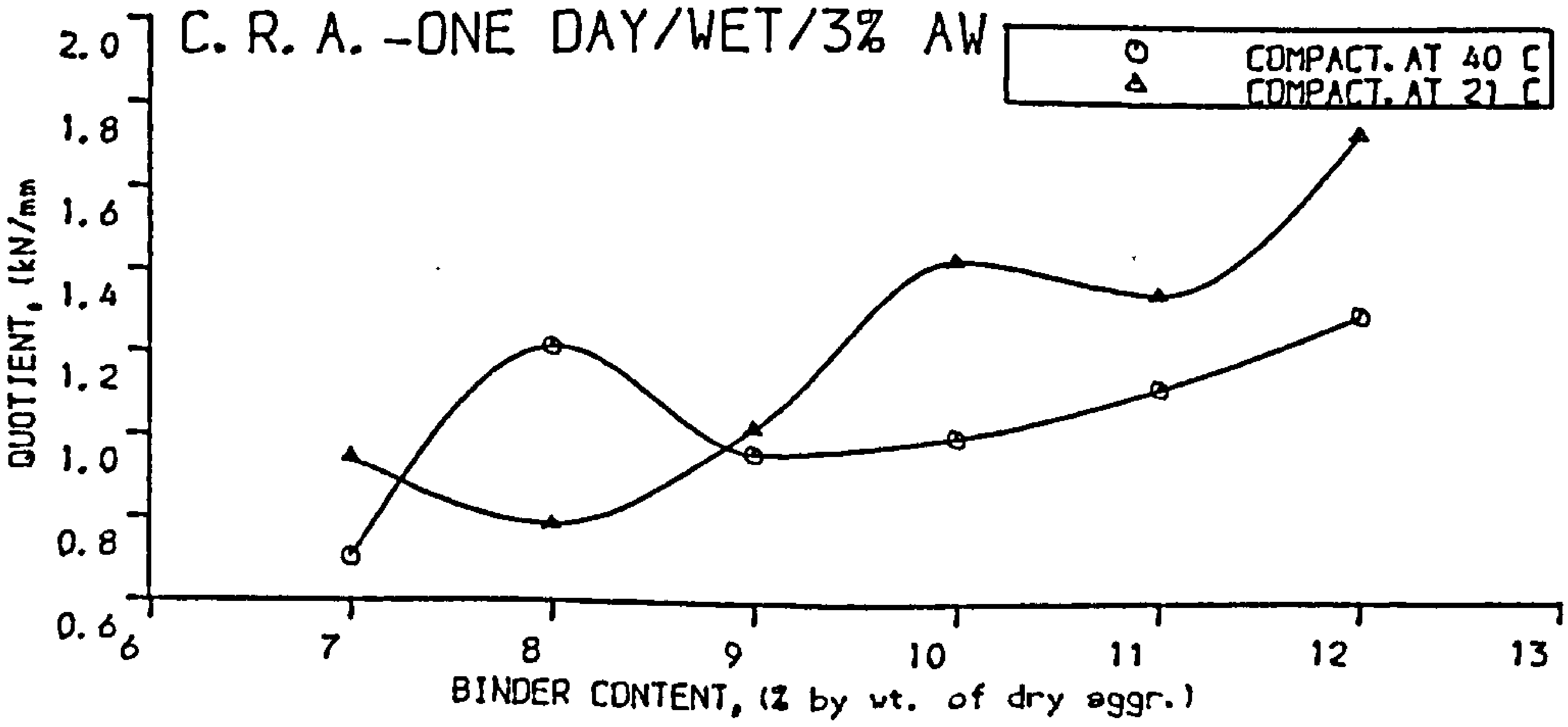


Fig. 8. 50 MARSH. QUOTIENT v BINDER CONT.

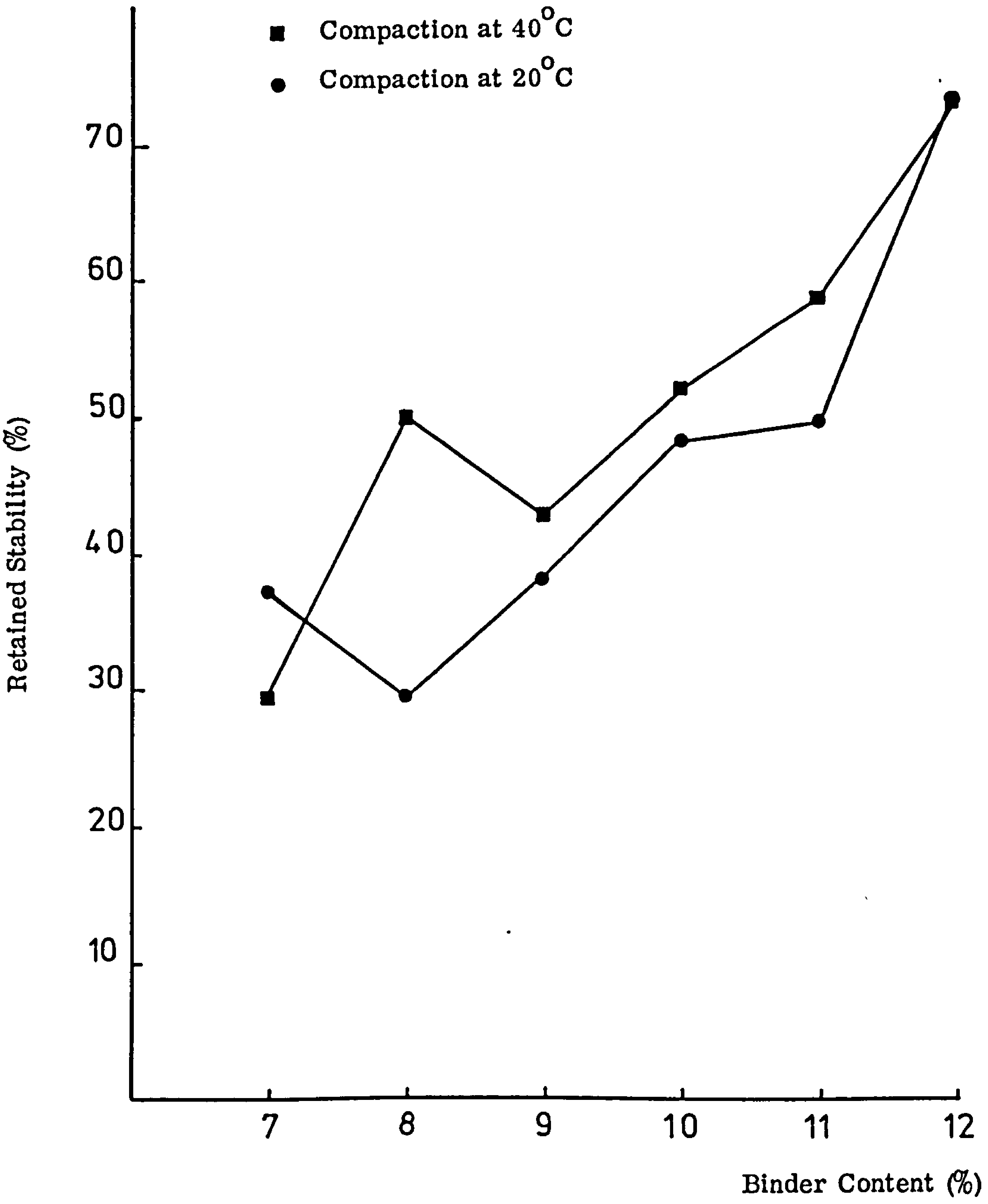


Fig. 8.51 RETAINED MARSHALL STABILITY vs BINDER CONTENT, ONE - DAY OF CURING (3% Added water)

The improvement of "wet" stability and hence retained stability was due to less amount of water absorbed by the specimens during capillary soaking, Figure 8.52. It was found that the increase in bulk density and the reduction of volume of voids due to compaction at $40^{o}C$, reduced the amount of absorbed water by 37% on average. A good correlation was found between water absorption and air voids, Figure 8.53.

When the specimens were soaked for 48 hours after "final" curing, no appreciable reduction in the amount of absorbed water was found, compared to mixtures compacted at $21^{o}C$, Figure 8.52. Similarly, the "wet" stability of the mixtures compacted at $40^{o}C$ was the same as of the mixtures compacted at $21^{o}C$, Figure 8.54.

The "dry" flow values of the mixtures compacted at $40^{o}C$ were almost the same as of the mixtures compacted at $21^{o}C$, Figure 8.56 and as a result the Marshall Quotient values were almost the same.

8.4.3.3. The effect on permeability

Since air permeability is related to volume of voids, Section 8.4.1.4. it was inevitable that the reduction of voids due to compaction at $40^{o}C$ would cause reduction of the air permeability of the mixtures. Figures 8.57 and 8.58 show that indeed the permeability of the mixtures compacted at $40^{o}C$ is lower than of the mixtures compacted at $21^{o}C$.

The interesting feature on the permeability of C.R.A. mixtures is that although permeability decreases with an increase of binder content, after a certain binder content it starts to increase rapidly. This can be seen more clearly on mixtures compacted at $40^{o}C$, where the viscosity of the bitumen is lower than $21^{o}C$. The increase of the permeability, after a certain level of binder content, is difficult to explain at this stage. It can only be hypothesized that it is due to a

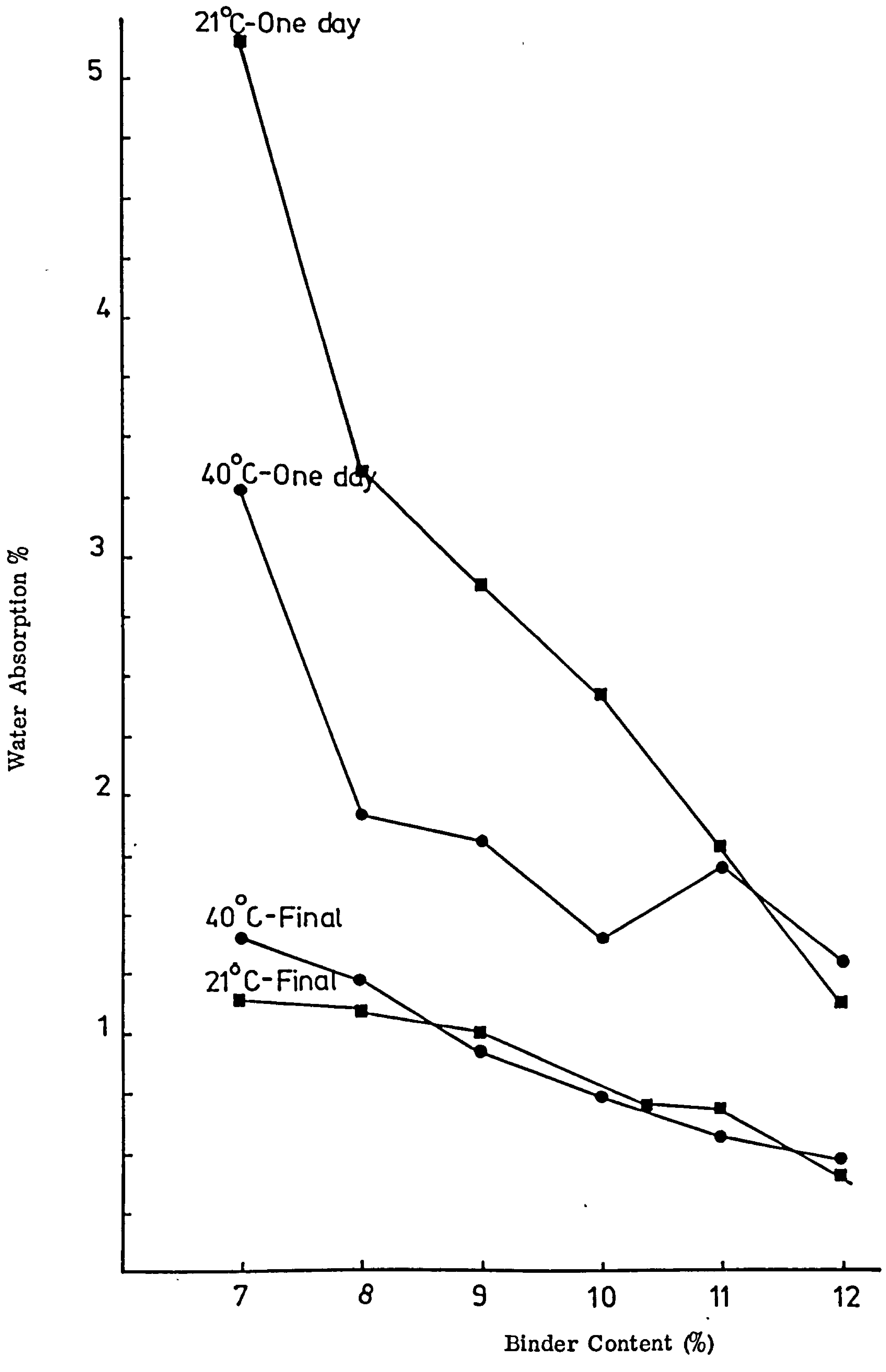


Fig. 8. 52 WATER ABSORPTION AFTER 96h SOAKING vs BINDER CONTENT

(Two curing conditions, two compaction temperatures 21°C and 40°C).

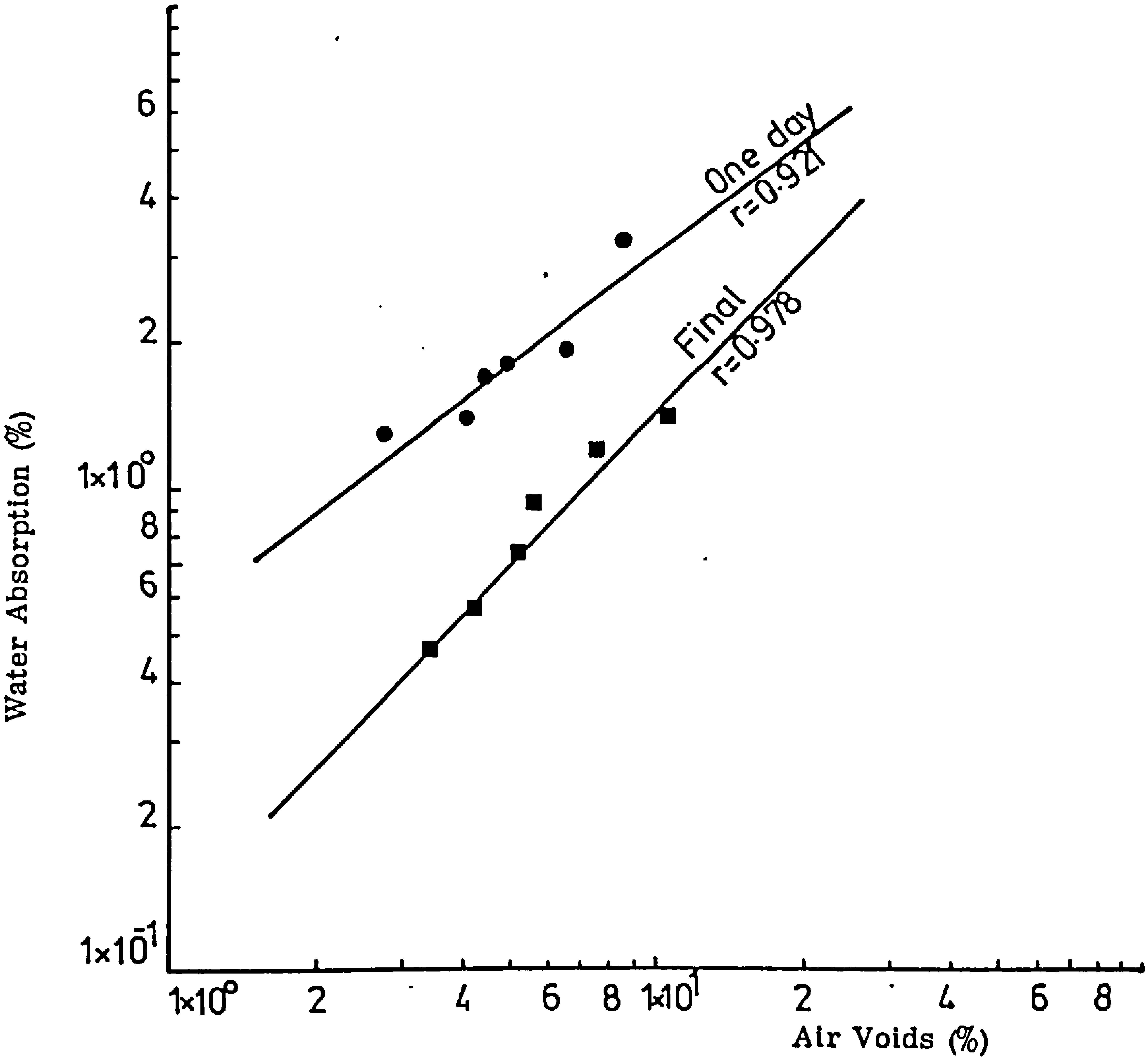


Fig. 8.53 WATER ABSORPTION vs AIR VOIDS
(Compaction at 40°C)

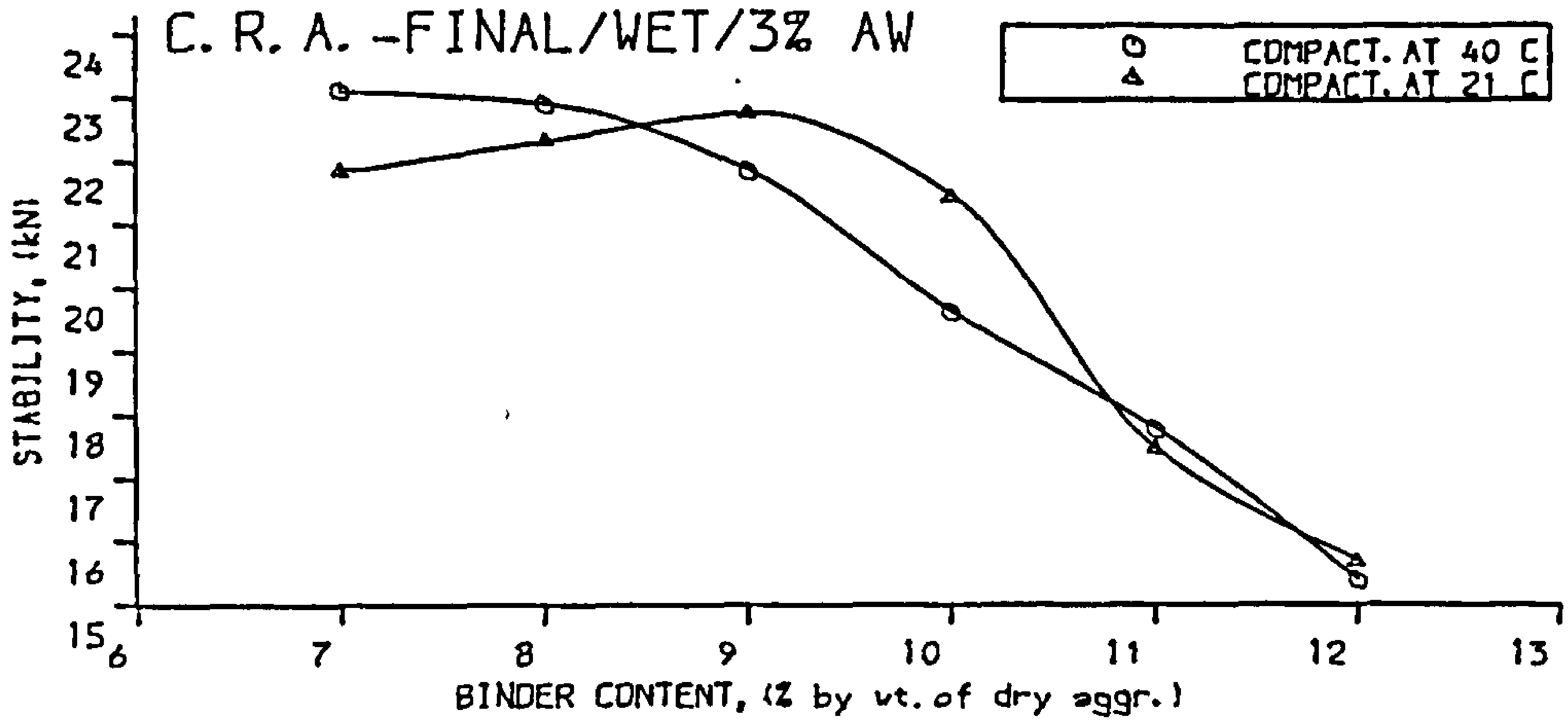


Fig. 8. 54 MARSH. STABILITY v BINDER CONT.

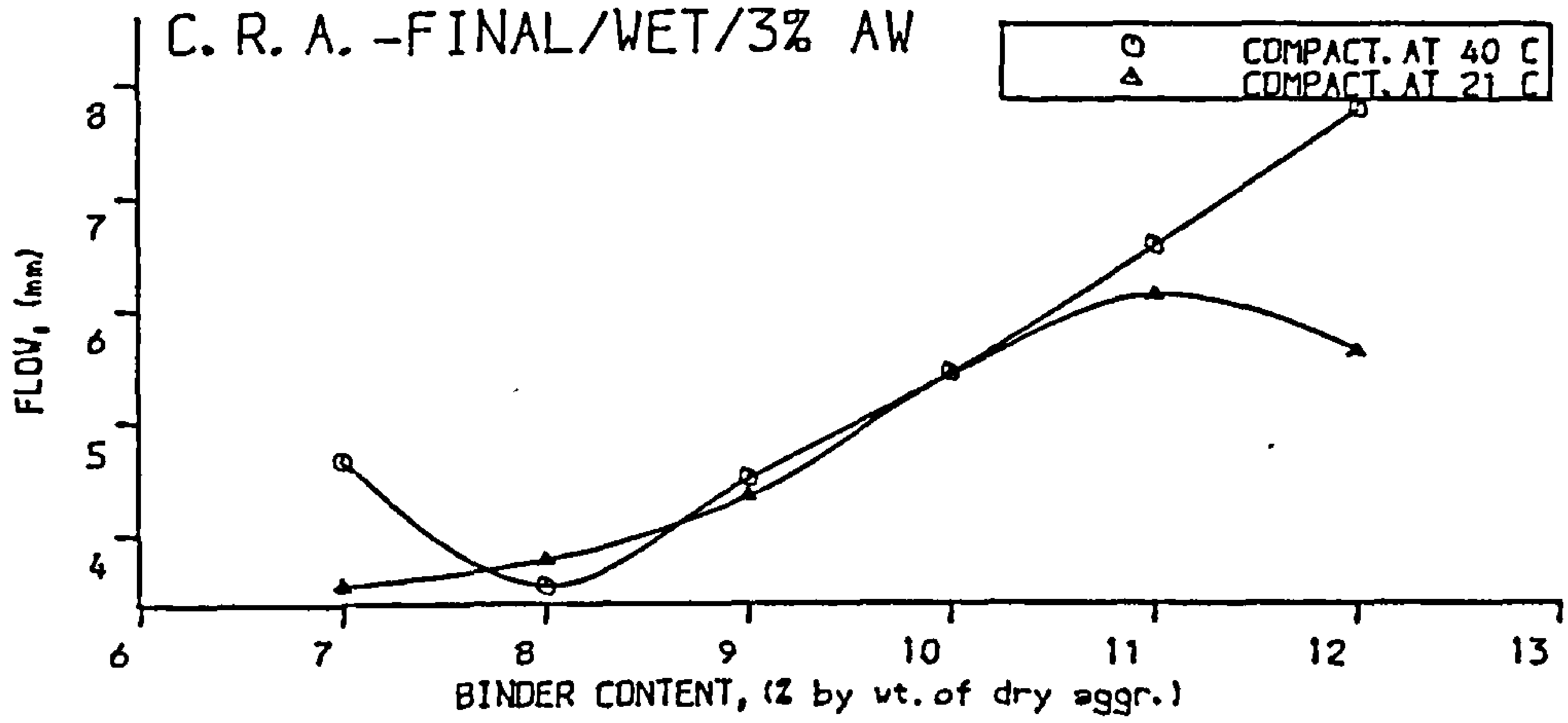


Fig. 8. 55 MARSHALL FLOW v BINDER CONT.

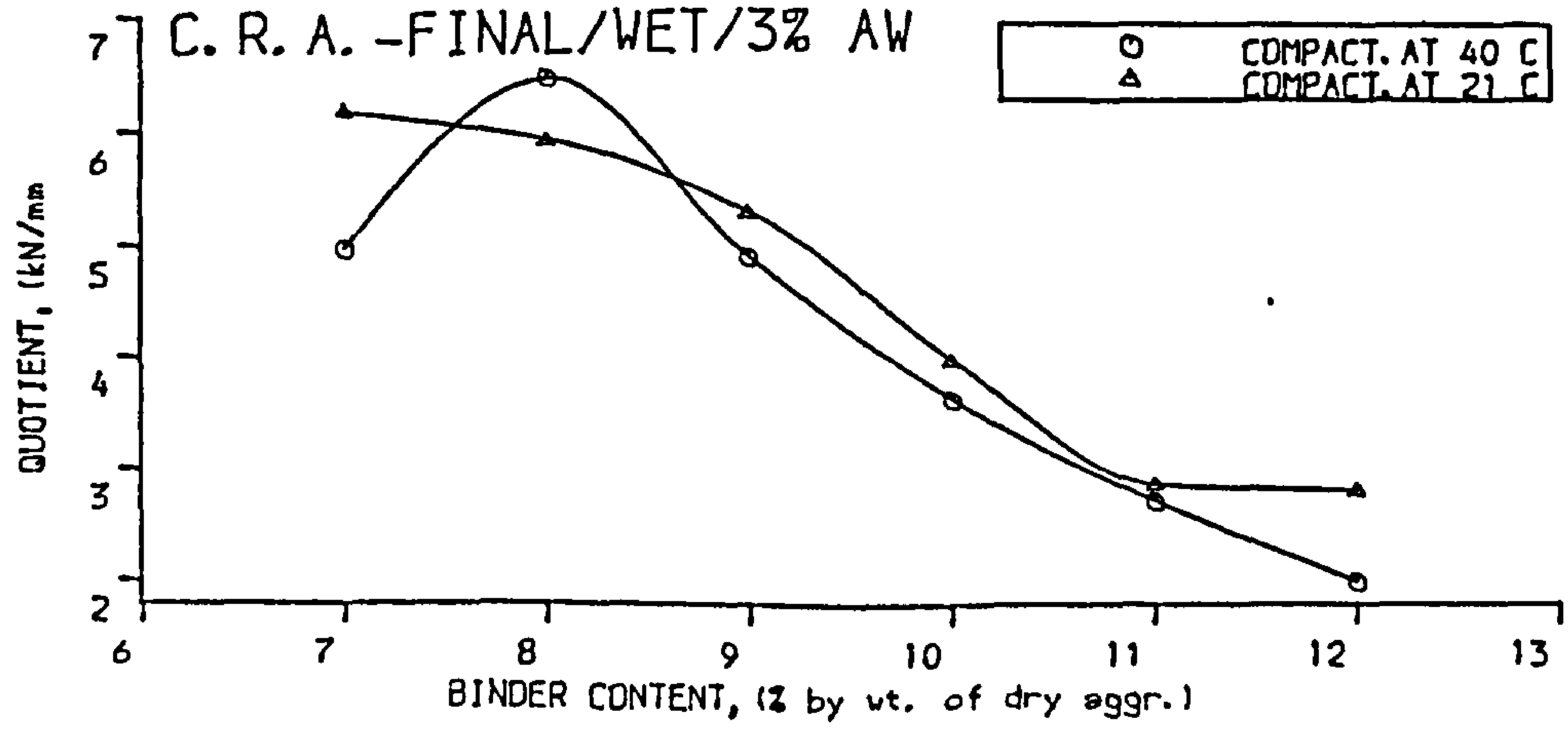


Fig. 8. 56 MARSH. QUOTIENT v BINDER CONT.

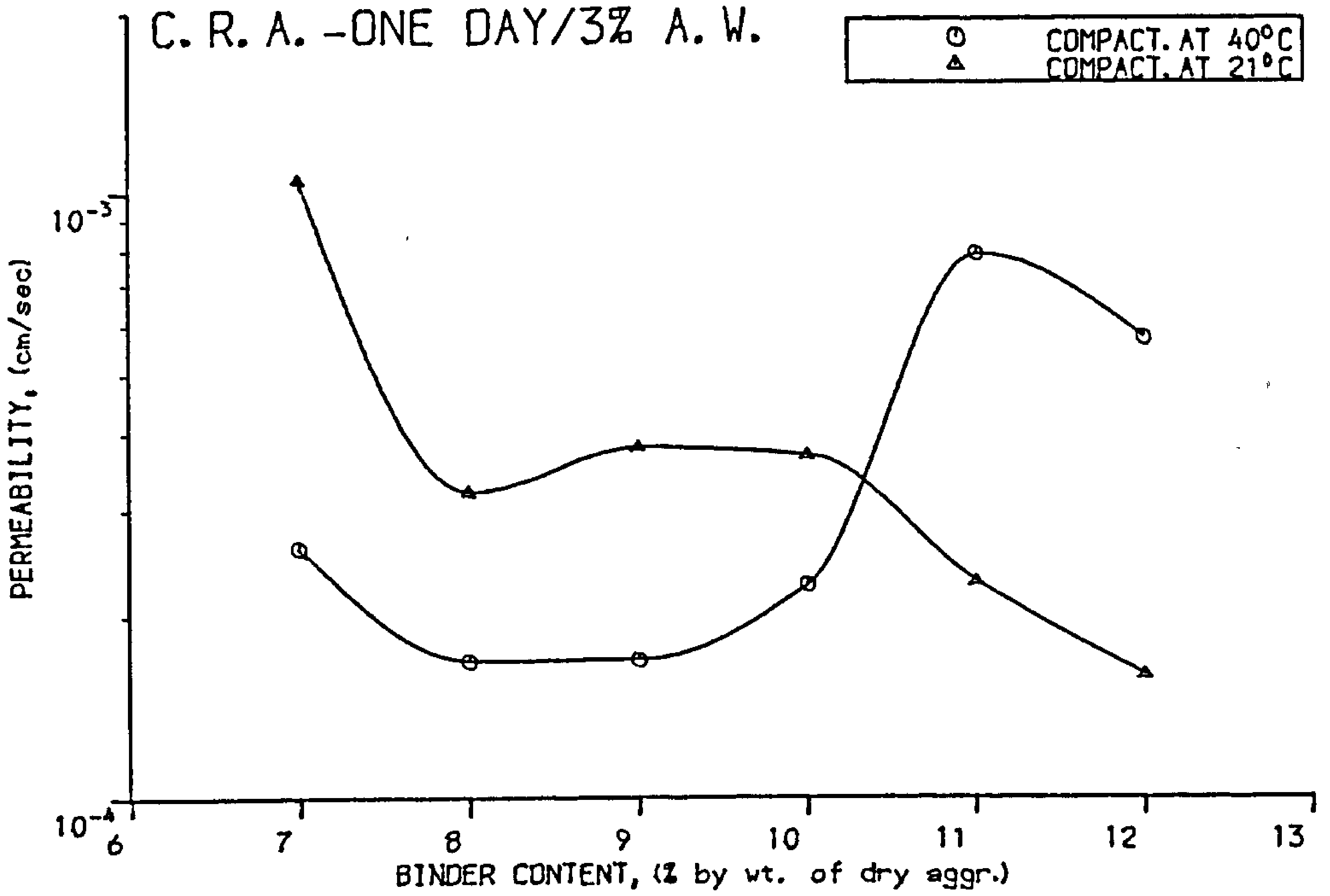


Fig. 8.57 PERMEABILITY v BINDER CONTENT

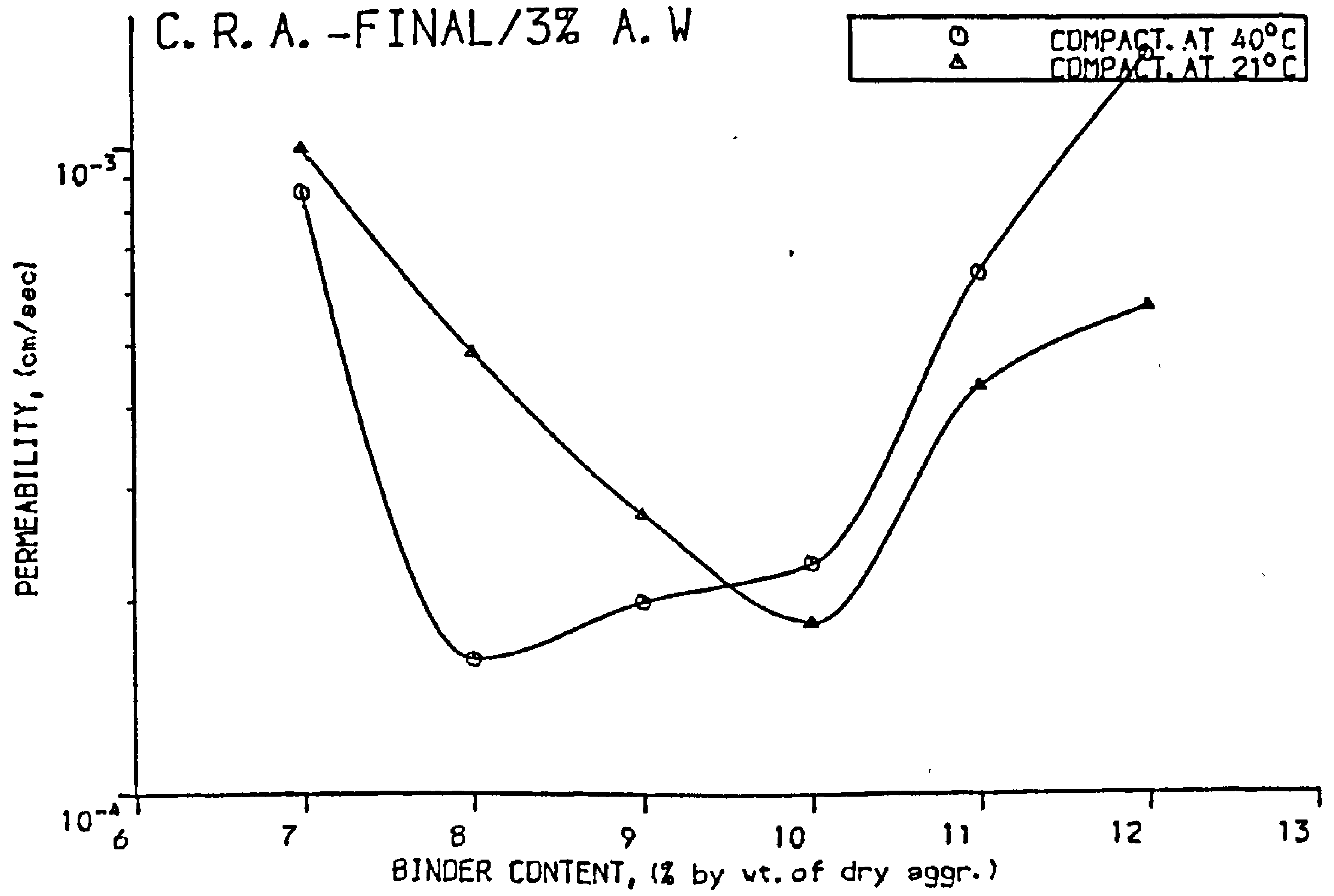


Fig. 8.58 PERMEABILITY v BINDER CONTENT

change in pore size distribution caused by the excessive hydrostatic pressures developed in the low voids matrix.

8.5 Determination of the optimum binder content

The determination of the optimum binder content of any emulsion treated bituminous mixture, is not as straight forward as that of hot mixtures because the strength of the mixture does not develop within a few hours after compaction. To overcome this problem the existing design methods (112) recommend the curing of the specimens for a short period of time (normally three days) before testing. The optimum binder content can then be determined, almost exclusively, from the peaked curve of "wet" stability vs binder content. The bulk density vs binder content curve may or may not show a peak, which then can be taken into consideration for the determination of optimum binder content (60, 61).

It must be emphasised that all the proposed design methods cater for continuously graded mixtures and not for gap graded mixtures. Gap graded mixtures differ from the continuously graded mixtures and therefore they are expected to behave differently. The peaked curves obtained by the continuously graded mixture may also be obtained by the gap graded, in addition to some others.

This investigation revealed that characteristic peaked curves appear in the relation between wet stability (after final curing) versus binder content, and bulk density versus binder content.

The most interesting finding was that an optimum binder content for the C.R.A. mixtures could be chosen from the V.M.A. or permeability versus binder content curves. Additionally, in the case of compacting the specimens at 40°C, from the rate of compaction versus binder content curve.

The V.M.A. versus binder content curves have shown a characteristic flat portion, at the initial stage of binder content increase which is followed by a sudden increase in V.M.A., after a certain binder content. Duthie (197, 198) working on Hot Rolled Asphalt mixtures suggested that this binder content produces a mixture with good durability and stability and he proposed that this should be used as the optimum value of binder content for HRA mixtures. This suggestion can be equally applied to Cold Rolled Asphalt mixtures.

The air permeability versus binder content curves, especially after "final" curing, produced a characteristic minimum at a certain binder content. This can be used as an optimum binder content for minimum permeability.

In cases where compaction is to be carried out at 40°C, an optimum binder content may be determined from the rate of compaction versus binder content. This optimum binder content is related to the effectiveness of compaction of the C.R.A. mixtures.

It is, therefore, suggested that the optimum binder content of C.R.A. mixture should be determined by the above relationships as an average value. The properties of the mixture with the optimum binder content should always be checked to make sure that they satisfy the required limiting criteria. In the absence of any other criteria, these may be the ones proposed by the American Asphalt Institute (49).

8.6 Comparison of optimum C.R.A. mixture with the limiting criteria

The optimum binder content calculated as suggested in the previous section was found to be 9.2 percent by total weight of dry aggregate (8.4% by total weight) and the mixture with 3.0% by weight of dry aggregate added water gave the best results. The properties of the above optimum mixture compared with the limiting values criteria and as shown in Table 8.7. It can be seen that C.R.A. mixtures satisfy all the requirements apart from the stability loss i.e.(100% - retained stability). This is not necessarily a drawback, because the 59% loss in stability was due to the relatively high value of one-day dry stability (13kN). Since the one-day wet stability was much higher than the minimum required, it is reasonable to assume that, if one day stability values are used, the 50% stability loss is too high, and a lower value should be used. This value should be drawn from full scale experiments using C.R.A. mixtures.

Table 8.7 also shows the laboratory results of two typical continuously graded mixtures used in America and reported by Darter et al (66). The mixture No.1 was used by Bond County, Illinois, and after one year of service showed no distress. The mixture No.2, very similar to No.1, has been used successfully for the past ten years by Clark County, Illinois, for low volume roads. Both counties used gravel and HFE-300 type of emulsion. It can be seen that the C.R.A. mixture gave far superior results, even after one day of testing.

It can, therefore, be said that the Cold Rolled Asphalt mixtures, using the same material used in this study will perform much better than the continuously graded mixtures, under the same traffic and environmental conditions.

8.7 Summary of results

The evaluation of the properties of Cold Rolled Asphalt (C.R.A) mixtures revealed a number of interesting results with regard to the binder content, the addition of water to the aggregate before mixing and warm compaction (40°C).

1. The addition of water, which is directly related to the degree of coating, has no significant effect on the air voids, total voids and

CRITERIA	C.R.A. Mixtures after one day curing	Limiting criteria after 3 days of curing	Mixture No. 1 (after 1 day)	Mixture No.2 (after 1 day)
			(Continuously graded mixtures)	
Stability Loss (%)	-59	-50 max	-57	+ 25
Total Voids (%)	7.6	8 max	6.7	6.8
Moisture Absorption (%)	2.8	4 max	3.6	2.5
Modified (wet) Marshall Stability (kN)	5.0	2.3	2.4	2.6
Aggr.Coating(%)	90-95	50 min	60-70	60-75

*After Ref. (66), Mixture No. 1 had 5.3 percent binder (by total weight of dry aggregate) and Mixture No. 2 had 3.5 percent binder (by total weight of dry aggregate)

TABLE 8.7 COMPARISON BETWEEN CRA MIXTURES AND CONTINUOUSLY GRADED MIXTURES WITH RESPECT TO LIMITING VALUES PROPOSED BY THE ASPHALT INSTITUTE (49)

VMA, at both the early and the final stage of curing. All the above dependent variables are only affected by the binder content.

2. The addition of water together with the binder content have a significant effect on the bulk density of the mixtures.

3. All the Marshall properties, apart from the flow, are affected significantly by both the binder content and the added water. The Marshall flow appears to be significantly affected only by the binder content.

4. The retained stability, after one-day of curing is related to air voids and permeability of the mixture.

5. Air permeability is significantly affected by both the binder and added water, and it correlates well with air voids and percentage water absorption, at the early stage of curing. Water absorption also correlates with air voids and binder content at both curing conditions.

6. Warm compaction improves the compactability of C.R.A. mixtures, reduces the volume of voids and improves the "wet" stability of the mixtures at the early stage of curing.

7. The optimum binder content of the C.R.A. is suggested to be determined as the average binder content (a) for maximum wet stability after final curing, (b) for maximum degree of packing (bulk density or compacted aggr. density curve), (c) for most durable and stable mixture (VMA curve) and (d) for lowest permeability. In case of warm compaction an optimum binder content can be determined from the compaction slope vs binder content curve which may be averaged in addition to the other optimum values, given above.

CHAPTER NINE

DESIGN AND PROPERTIES OF DENSE EMULSION MACADAM MIXTURES (D.E.Mc)

9.1 Introduction

Coated Macadams are one of the most widely used bituminous mixtures in highway construction. They consist of a continuously graded aggregate matrix and a relatively soft bituminous binder. The amount of fine aggregate is very small, which results in mixtures with relative high porosity. Coated macadams derive their strength from the mechanical interlocking of the aggregates rather than from the mortar of sand, filler and binder. These mixtures possess a high percentage of voids, they are more permeable than Rolled asphalt mixtures and they are susceptible to secondary compaction under the action of traffic. Macadam mixtures are normally manufactured to a recipe specification which has been developed over years of field experience.

This chapter evaluates the properties of cold dense graded Macadam mixtures when bituminous emulsion is used as a binder. It also examines the effect of the main design variables on the properties of the mixtures, by using the statistical analysis of variance method.

The parameters measured for the evaluation of the properties of the Dense Emulsion Macadam mixtures are the same parameters used to evaluate the Cold Rolled Asphalt mixtures.

This chapter also includes a comparison and critical discussion of the laboratory performance of C.R.A. and D.E.Mc mixtures.

9.2 Design of the experiment and statistical analysis of the data

The study of the effect of binder content, addition of water to the aggregate prior to mixing, curing and liquid content at compaction was carried out by the factorial design shown in Table 9.1.

All the material, the preparation, the mixing, the compaction and the testing were the same as in C.R.A. mixtures and are described in Chapters 4 and 5. It must be noted that although softer bitumen could have been used with these mixtures, it was avoided in order to eliminate the effect of binder grade on the performance of D.E.Mc in comparison to C.R.A. mixtures.

Air permeability tests were not carried out due to the limitations of the apparatus. The apparatus used previously was not sensitive enough to measure permeability values greater than 5.0×10^{-8} cm^2, and the permeable D.E.Mc. mixtures were found to have a minimum permeability value of approximately 11.7×10^{-8}cm^2.

The determination of the effect of the design variables on the properties of the mixture was carried out using the analysis of variance method. The mathematical model was similar to the one used in the previous chapter (equation 8.1), with the only difference that the levels of the independent variables (binder and added water) changed to the ones shown in Table 9.1. The results of the statistical analysis are shown in Tables 9.2 to 9.5 and they will be discussed in the subsequent sections, together with the physical trend of the appropriate variable.

9.3 Results and discussion

9.3.1. The effect of binder and added water on the properties of D.E.Mc at the early stage of curing

9.3.1.1. The effect on bulk density and compacted aggregate density

Statistical analysis has shown that the binder content does not affect significantly the bulk density of the mixture, at the early stage of curing. The only factor which did significantly affect the bulk density

Conditions at Compaction	Curing Time	Binder Content (Percentage)	Added Water		
			1.0	2.0	3.0
Temp = 20°C Water cont. fixed (3.0%)	One day (early stage)	4.5	x	x	x
		5.0	x	x	x
		5.5	x	x	x
		6.0	x	x	x
		6.5	x	x	x
	Five days (final stage)	4.5	-	x	x
		5.0	-	x	x
		5.5	-	x	x
		6.0	-	x	x
		6.5	-	x	x
Temp = 20°C Water cont. varied	One day (early stage)	4.5	-	x*	-
		5.0	-	x*	-
		5.5	-	x*	-
		6.0	-	x*	-
		6.5	-	x*	-
	Five days (final stage)	4.5	-	-	x*
		5.0	-	-	x*
		5.5	-	-	x*
		6.0	-	-	x*
		6.5	-	-	x*

* Wet stability tests only

TABLE 9.1 FACTORIAL DESIGN FOR STUDYING THE EFFECT OF BINDER, ADDITION OF WATER AND TOTAL LIQUID AT COMPACTION, ON THE PROPERTIES OF DEMc MIXTURES.

ONE DAY CURING - D.E.Mc.				
Dependent factors / Independent	Bulk Density	Air Voids	Total Voids	V.M.A.
Binder Content	NS	S**	S**	NS
Added Water	S**	S**	S**	S**
Binder and Added Water	NS	NS	NS	NS

S** = Significant at 1% level of significance

NS = Not significant at 5% level of significance

TABLE 9.2 SUMMARY OF STATISTICAL ANALYSIS OF BULK DENSITY, VOIDS AND VMA AFTER ONE DAY OF CURING

ONE DAY CURING - D.E.Mc.						
Dependent factors	Stability		Flow		Quotient	
Independent	Dry	Wet	Dry	Wet	Dry	Wet
Binder Content	NS	S**	S**	S**	S*	S**
Added Water	S**	S**	NS	NS	S**	S**
Binder and Added Water	NS	S**	S*	NS	NS	S*

S* = Significant at 5.0% level of significance

S** = Significant at 1.0% level of significance

NS = Not significant at 5.0% level of significance

TABLE 9.3 SUMMARY OF STATISTICAL ANALYSIS OF MARSHALL STABILITY FLOW AND QUOTIENT AT DRY AND WET CONDITION, AFTER ONE DAY OF CURING

FINAL CURING - D.E.Mc

Dependent Independent	Bulk Density	Air Voids	Total Voids	V.M.A.	Water at Testing
Binder Content	NS	S**	S**	NS	S**
Added Water	S**	S**	S**	S**	S**
Binder and Added Water	NS	NS	NS	NS	NS

S** = Significant at 1% level of significance

NS = Not significant at 5.0% level of significance

TABLE 9.4 SUMMARY OF STATISTICAL ANALYSIS OF BULK DENSITY, VOIDS, V.M.A., AND WATER AT TESTING AFTER FIVE DAYS OF CURING

FINAL CURING - D.E.Mc

Dependent Independent	Stability		Flow		Quotient	
	Dry	Wet	Dry	Wet	Dry	Wet
Binder Content	S**	S**	S**	S**	S**	NS
Added Water	S**	S**	S**	NS	S**	S**
Binder and Added Water	S**	S*	S**	S**	S**	S**

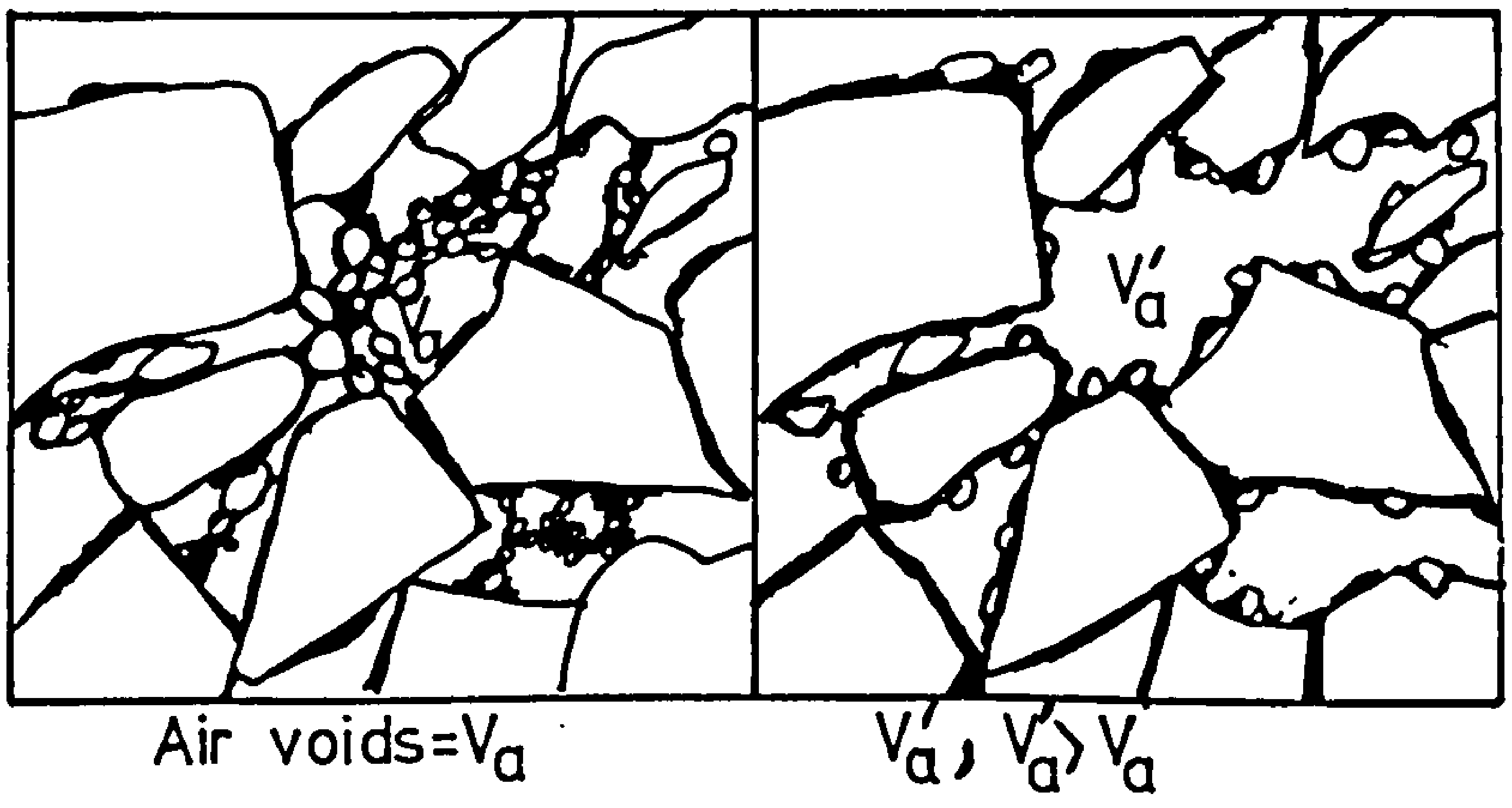
S* = Significant at 5% level of significance

S** = Significant at 1% level of significance

NS = Not significant at 5% level of significance

TABLE 9.5 SUMMARY OF STATISTICAL ANALYSIS OF STABILITY FLOW AND QUOTIENT AT DRY AND WET CONDITIONS AFTER FINAL CURING (five days + two in the oven) was the addition of water to the aggregate in order to obtain better coating.

The above finding is important and must be interpreted with care, by taking into account the conditions at compaction. Compaction took place at a fixed total moisture content of 3.0% and this was obtained by drying the mixture at 60°C in a ventilated oven. During this period not only did moisture evaporate, but also the emulsion broke further. It may be assumed that the binder quantity did not affect the bulk density due to high viscosity (compaction at 21°C) but it was the actual spreading of the binder due to addition of more water prior to mixing. This is explained by the fact that at low percentage of added water, the binder agglomerates the fine particles without spreading evenly around the coarse aggregate, Figure 9.1a. This agglomeration fills part of the voids. At high percentage of added water the binder spreads around the coarse aggregate, agglomeration does not occur, the percentage of voids is slightly increased and there is a limited but significant decrease in bulk density.



a) Low % of added water   b) High % of added water

FIG 9.1a SCHEMATIC REPRESENTATION OF ADDED WATER ON THE DISTRIBUTION OF THE SAND-FILLER-BINDER MORTAR

The results of bulk density have been plotted in Figure 9.1 and as it can be seen they support the above argument. The mixtures with 1.0% added water exhibit slightly greater bulk densities than the other two mixtures with higher percentage of added water i.e. 2% and 3%. Similar results were observed for the compacted aggregate density, Figure 9.2 . However, from the trends shown in the above figures it is clear that an optimum binder content for maximum density can not be determined.

9.3.1.2. The effect on voids and voids in the mineral aggregate (V.M.A.)

Statistical analysis has shown that both main factors - binder and added water - significantly affect the air voids and total voids of the mixture, Table 9.2. As the binder content increased the air voids and total voids decreased, and mixtures with a different percentage of added water possessed a different voids content, for reasons explained in previous section, Figures 9.3 and 9.4.

Although the binder content affects the voids of the mixture, it has no significant effect of the voids in the mineral aggregate (V.M.A.). This is because any increase in binder can easily be accommodated in the high percentage of air voids and therefore the overall V.M.A. remains the same. The factor which significantly affects the V.M.A. was the added water. As it can be seen from Figure 9.5, the V.M.A. does not change appreciably with the binder content, but its level depends on the percentage of added water.

It is interesting, however, to notice that the percentage of V.M.A. and total voids ranged from 28 to 30 percent and 21 to 16 percent respectively, both of which are higher than the values obtained for C.R.A. mixtures.

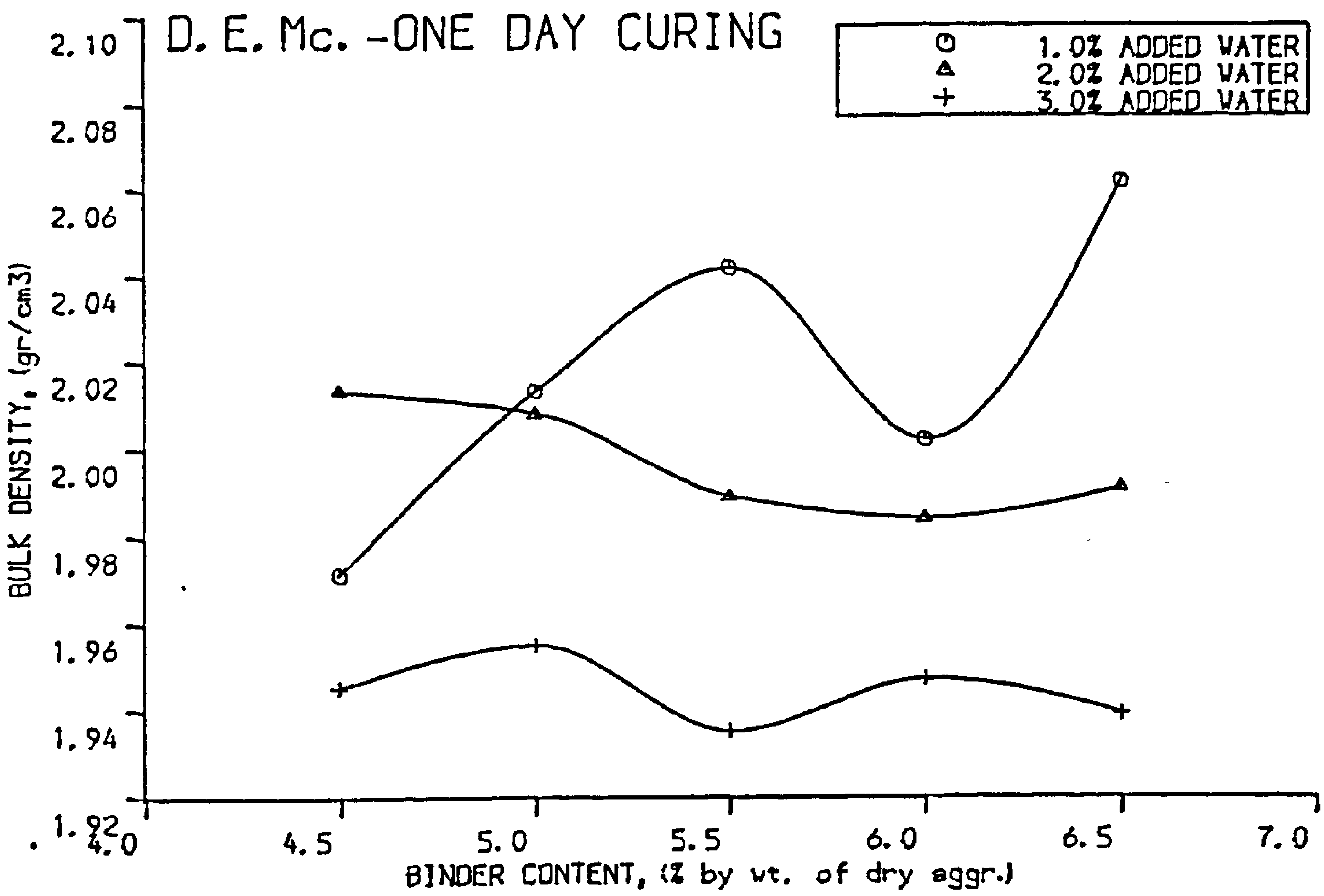


Fig. 9. 1 BULK DENSITY v BINDER CONTENT

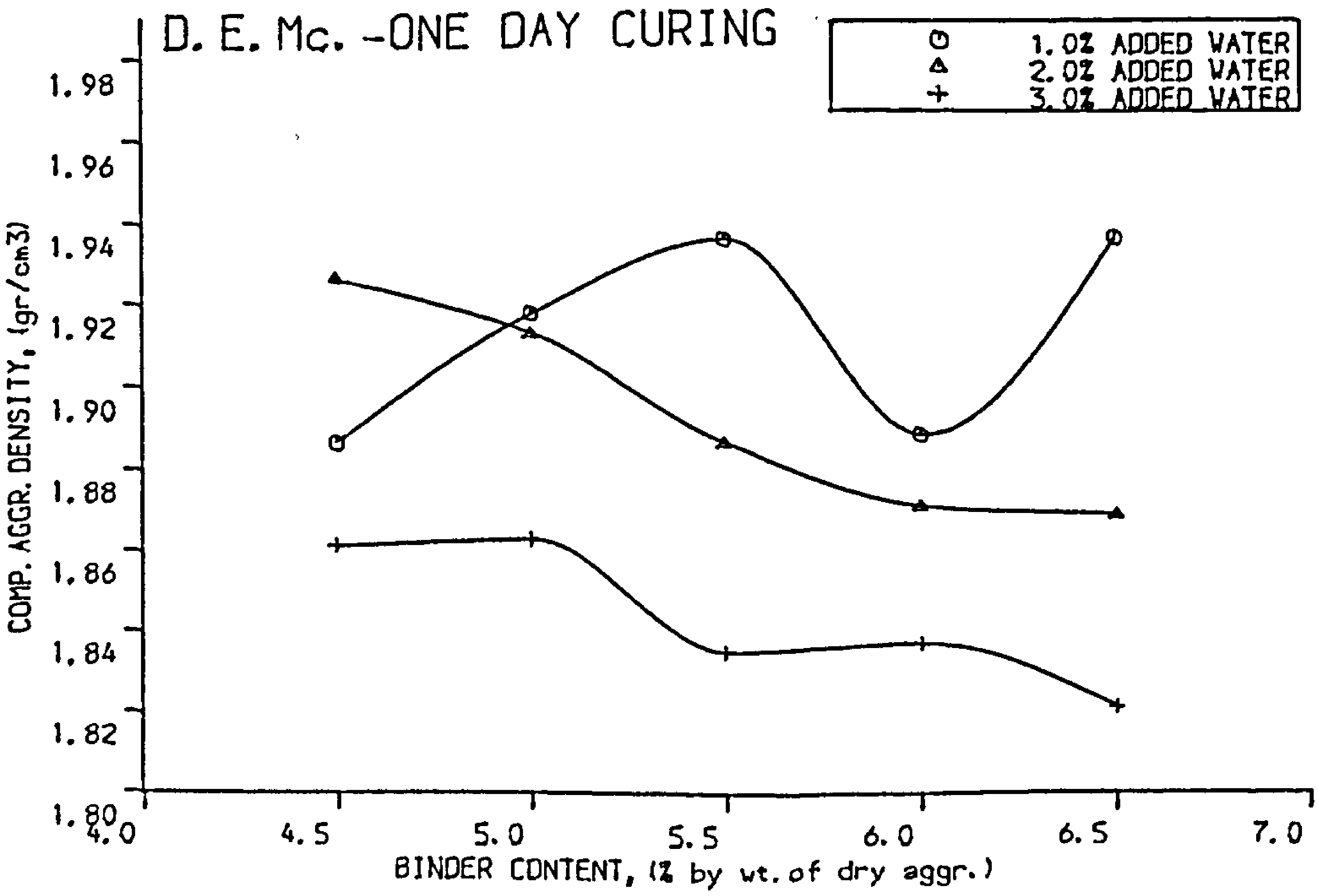


Fig. 9. 2 COMP. AGGR. DENSITY v BINDER CONT.

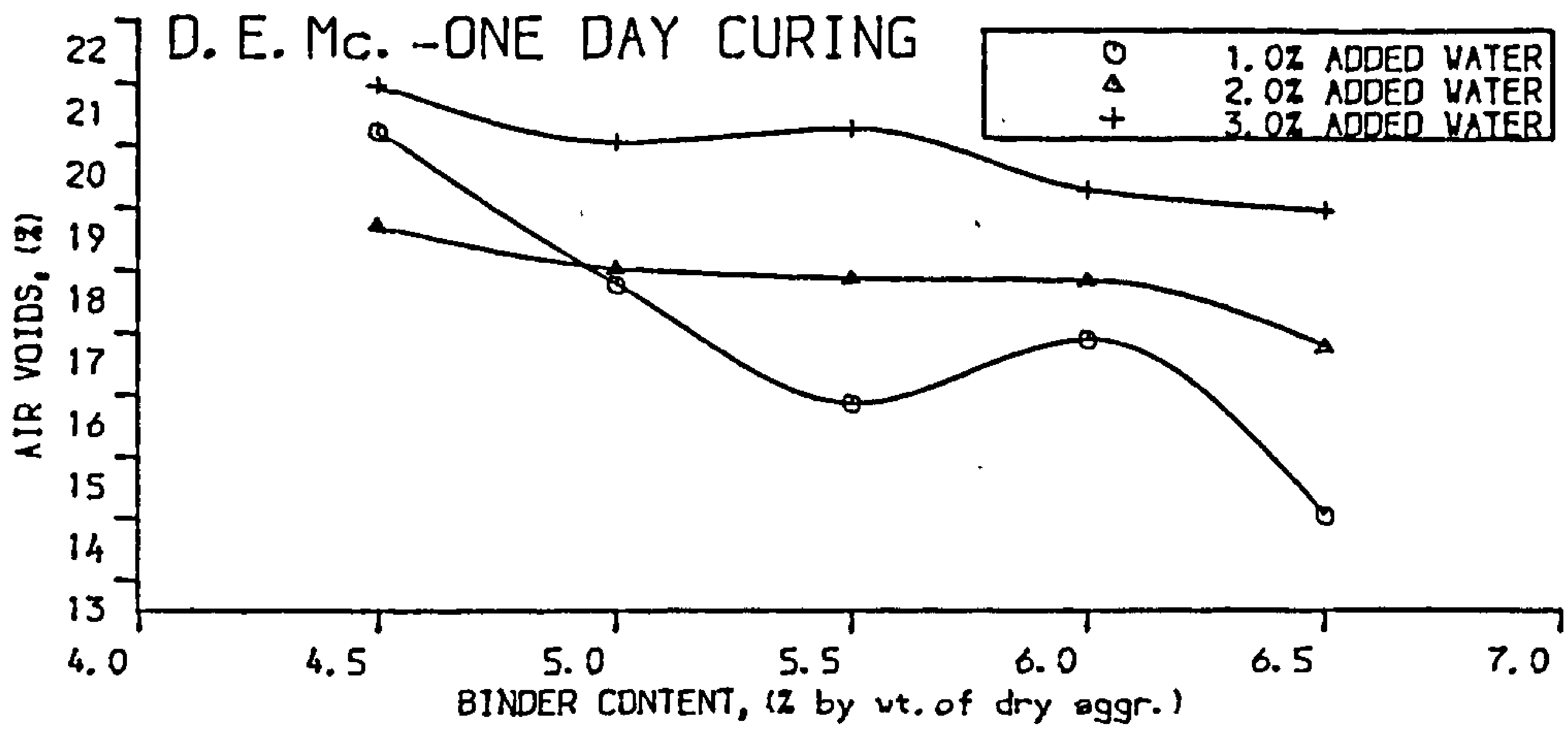


Fig. 9. 3 AIR VOIDS v BINDER CONTENT

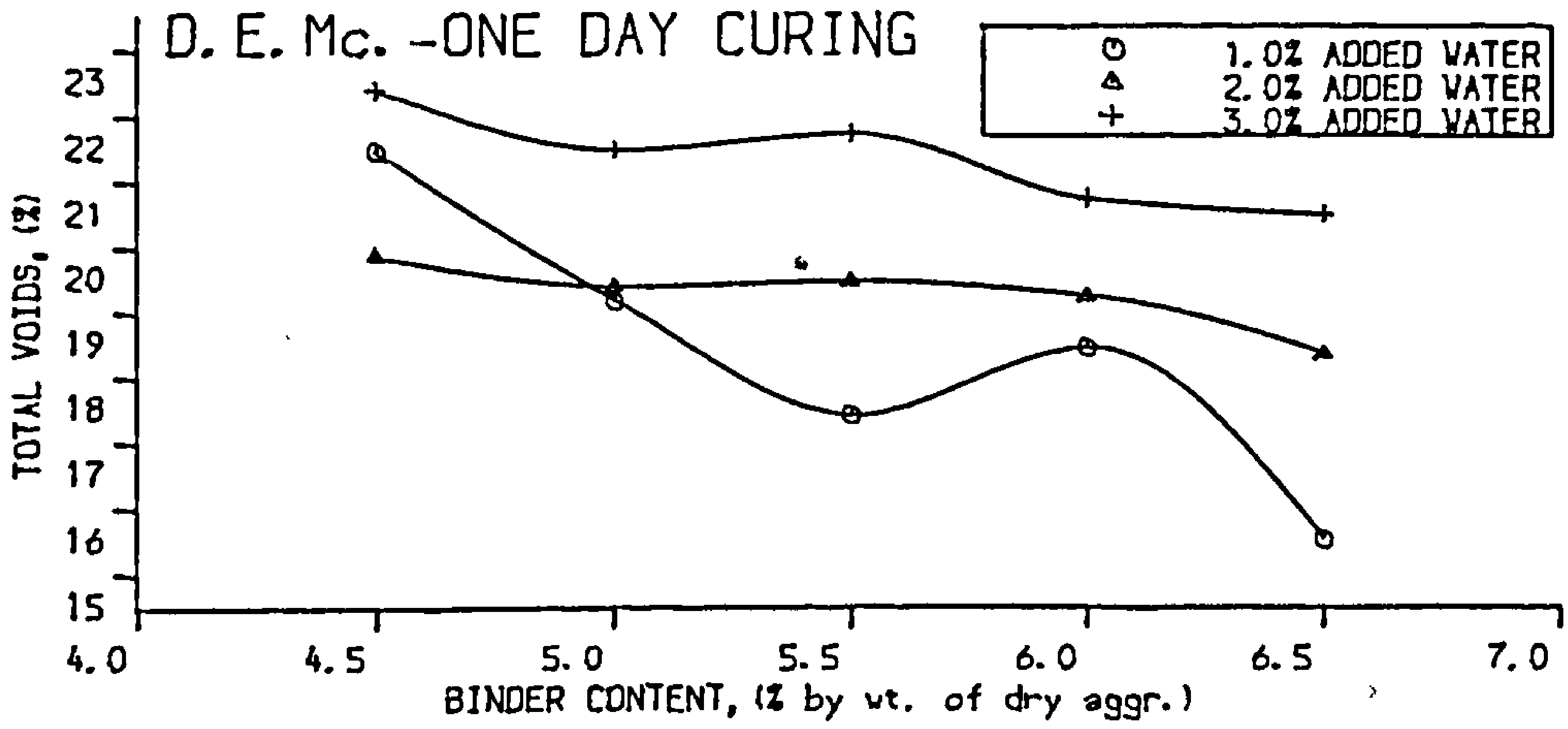


Fig. 9. 4 TOTAL VOIDS v BINDER CONTENT

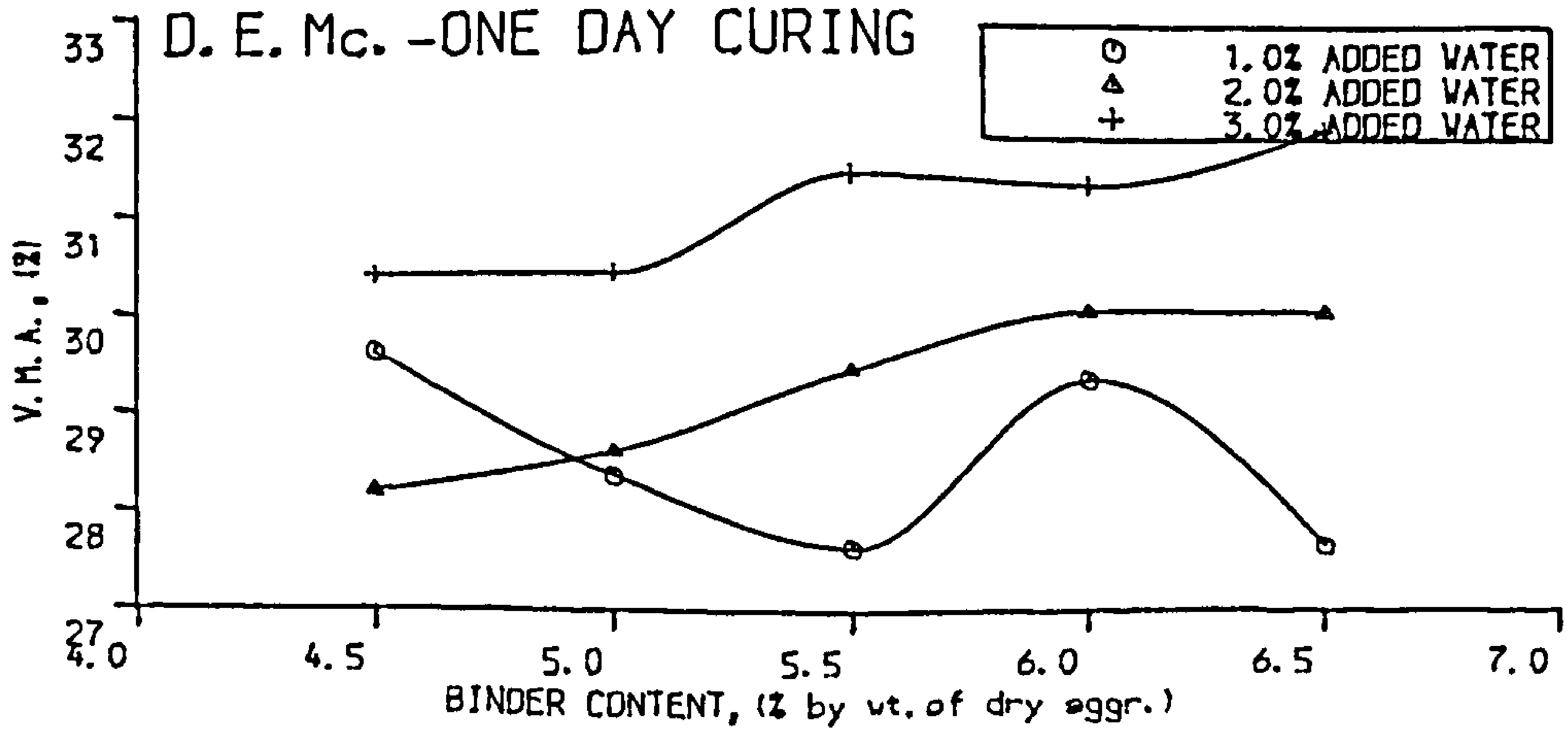


Fig. 9. 5 V. M. A v BINDER CONTENT

9.3.1.3. The effect on modified dry Marshall stability flow and Marshall Quotient

The effect of binder content on the dry stability after one day of curing was found not to be significant, Table 9.3. The dry stability, at this curing stage, was only significantly affected by the percentage of added water. This result is in agreement with research carried out by Gadallah (61) on emulsion treated asphaltic concrete mixtures. During the early stage of curing, the emulsion has not broken completely and thus the binder has not reached its own consistency. Therefore, at this stage of curing, the dry stability is only affected by the added water which is associated with the degree of coating. The better the degree of coating the better the dry stability.

The dry flow, however, is found to be significantly affected only by the binder content, Table 9.3, the degree, of which depends on the level of added water (interaction effect). In general, the flow increased as the binder content increased, Figure 9.7, but the rate of increase differed from one mixture to another (with respect to added water).

Finally, the dry Marshall Quotient was significantly affected by both the binder and added water. Generally, the dry quotient decreased as the binder content increased. The mixture with the highest dry stability values (2.0% added water) also possessed the highest dry quotient values. Overall, the quotient values ranged between 1.3 to 1.9 kN/mm.

9.3.1.4. The effect on the wet stability, flow and quotient

As it was explained, in Chapter 5, the cured specimens underwent 48 hours of capillary soaking, in order to determine the damage done by water on the stability of the mixtures. It was found, using the analysis of variance, that unlike the dry stability, wet stability was significantly affected by both the binder and the added water, as well as their interaction, Table 9.3. Figure 9.9 shows that the wet stability increased as the binder content increased and mixture with different percentages of added water exhibited different wet stability. This is

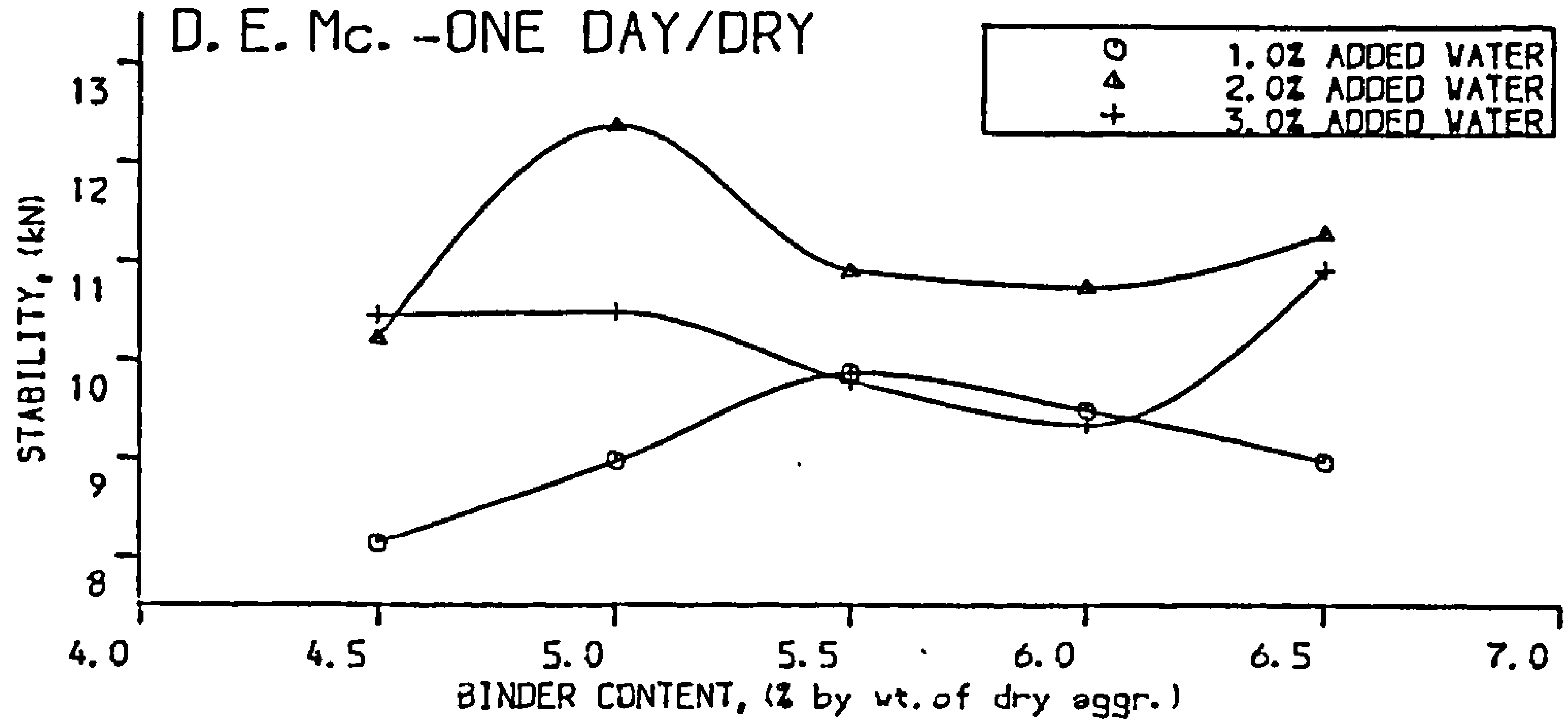


Fig. 9.6 MARSH. STABILITY v BINDER CONT.

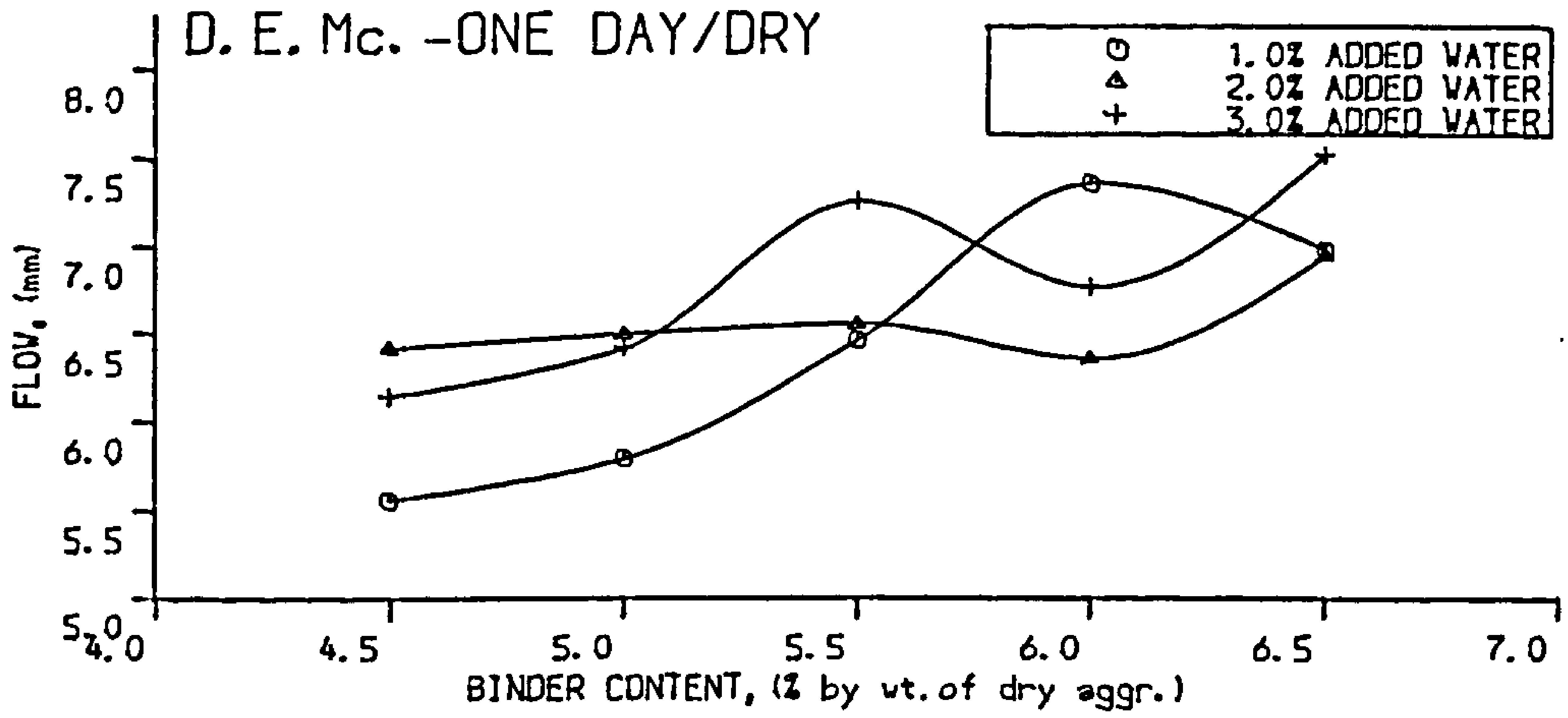


Fig. 9.7 MARSHALL FLOW v BINDER CONT.

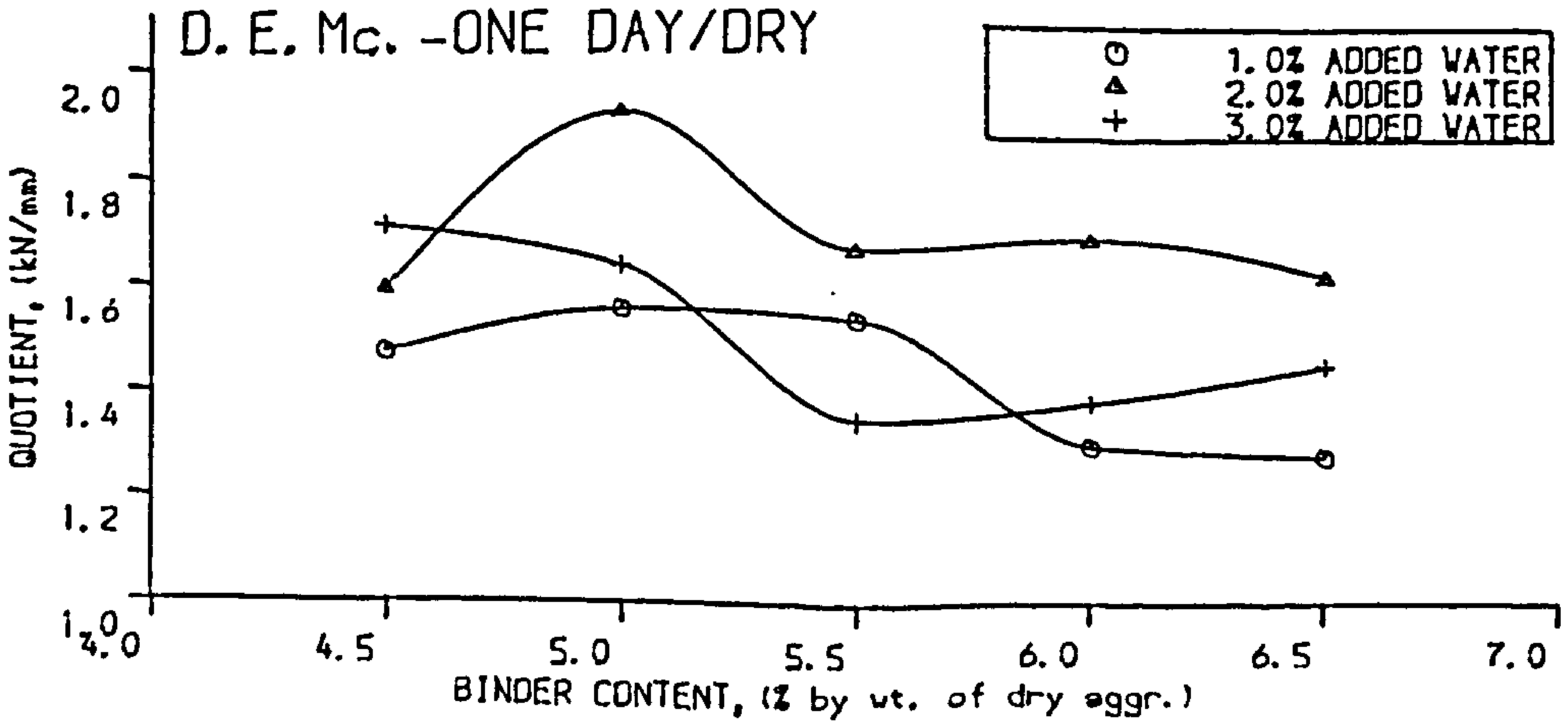


Fig. 9.8 MARSH. QUOTIENT v BINDER CONT.

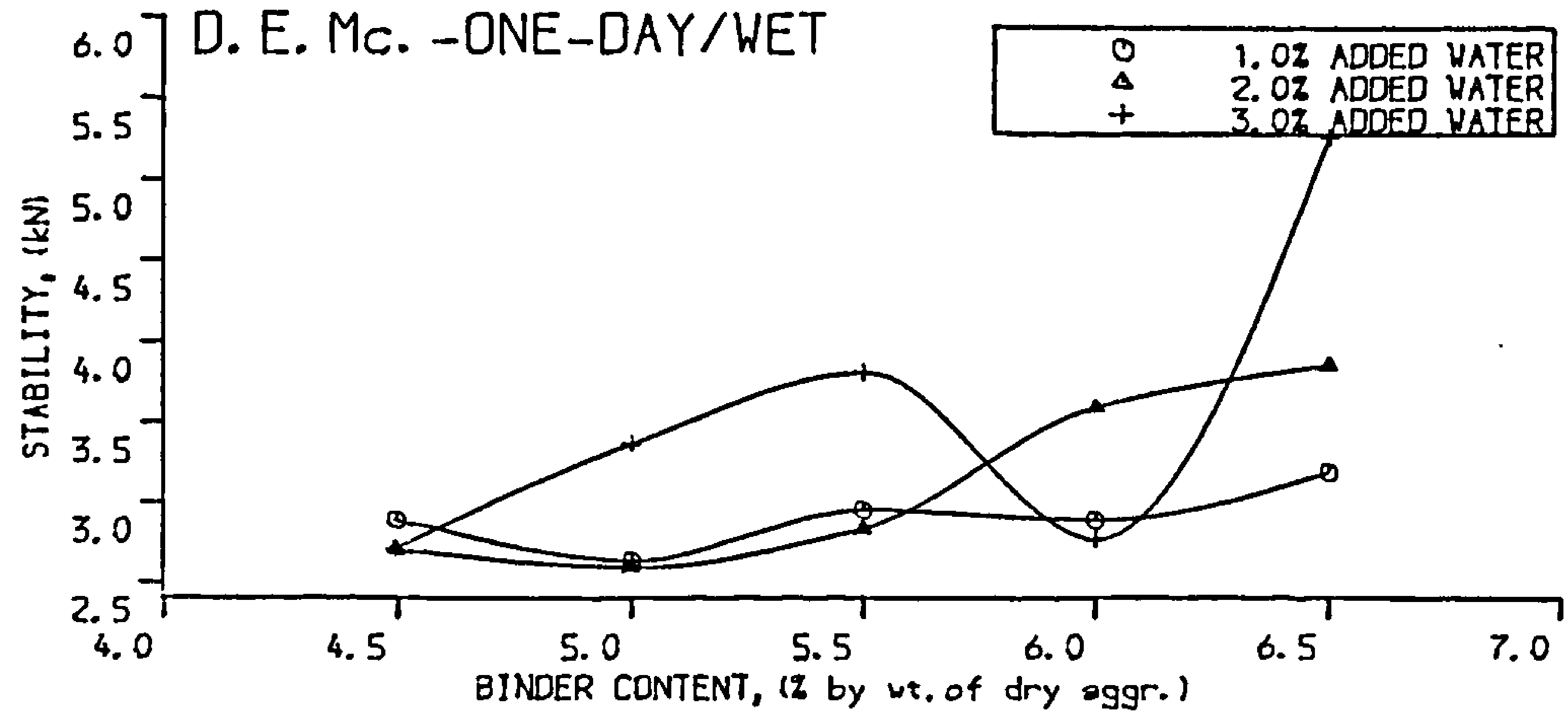


Fig. 9.9 MARSHALL STABILITY v BINDER CONT.

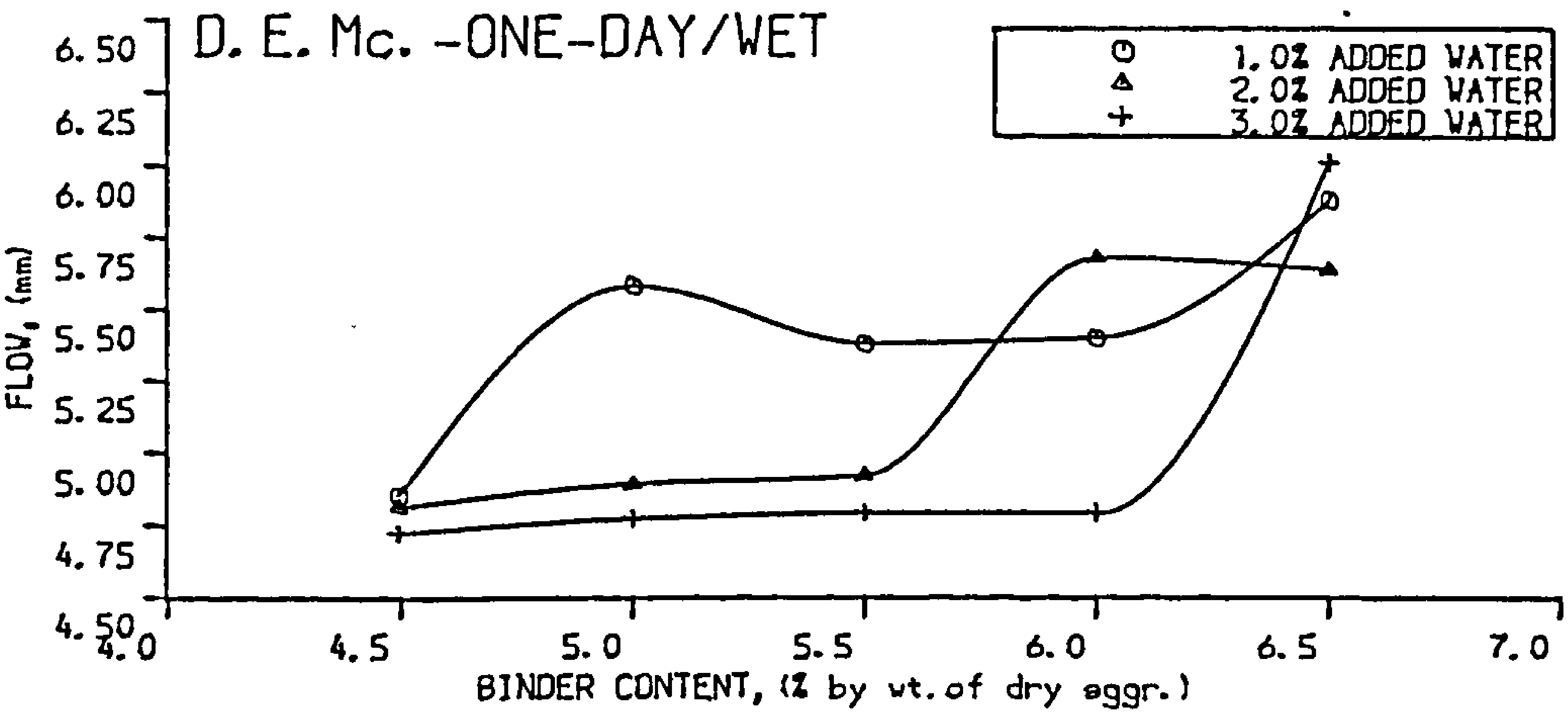


Fig. 9.10 MARSHALL FLOW v BINDER CONT.

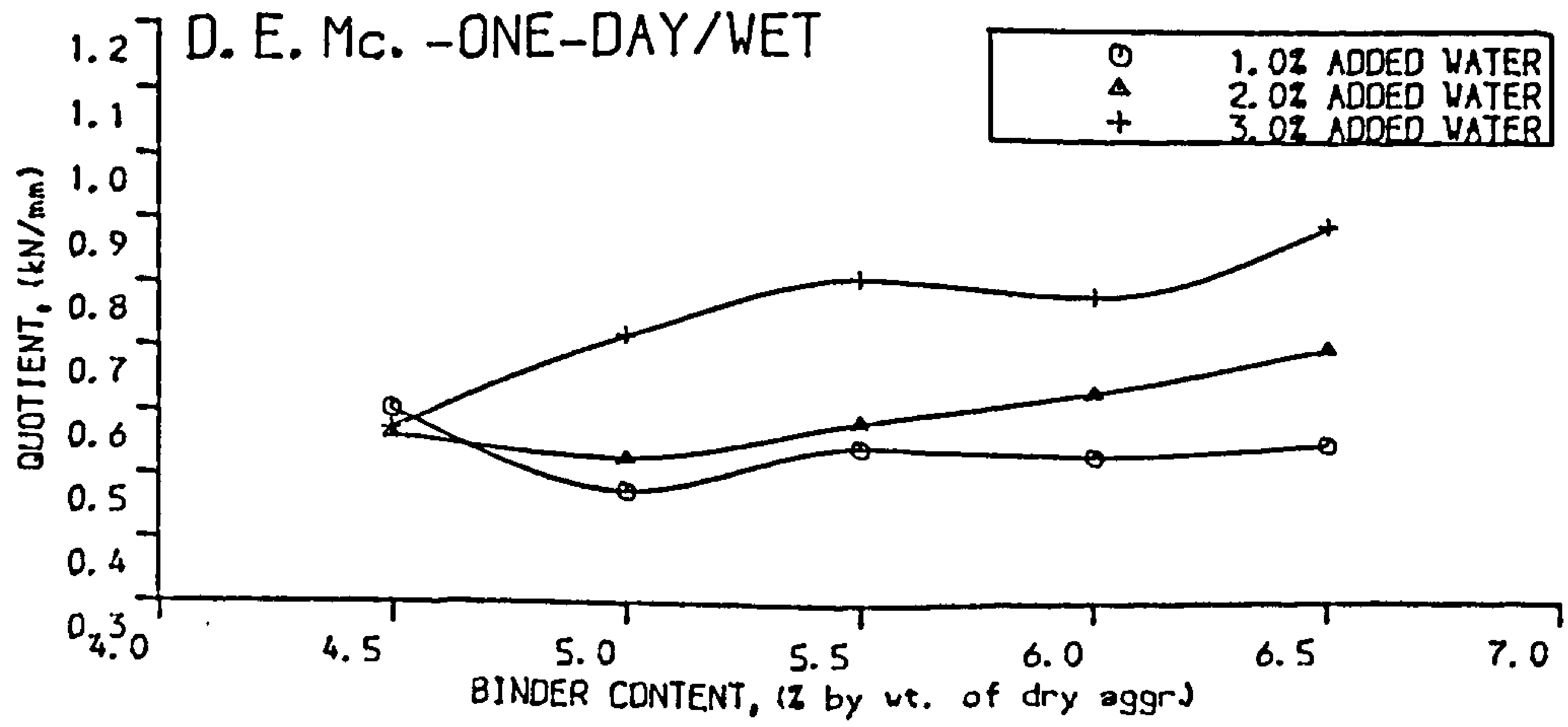


Fig. 9.11 MARSH. QUOTIENT v BINDER CONT.

because better protection of the aggregate-binder bond is obtained as the binder content increases.

Figure 9.11 shows that the wet quotient increases with an increase in binder content. The values of wet quotient are also significantly affected by the percentage of added water.

Figure 9.10 shows that flow values are influenced by the binder content. However, the statistical analysis indicates that the effect of added water is not significant for wet flow.

The water damage on the stability of D.E.Mc mixtures can be seen more clearly when the retained stability is examined. It can be seen, Figure 9.12, that retained stability increases with binder content and that this depends on the added water content to the aggregate. The mixtures with 3% added water possessed higher retained stability values than the other two mixtures. These values ranged from 25.5 to 48.5%.

The loss in stability at the early stage of curing is related to the quantity of water absorbed during the capillary test. The mixture with the highest retained stability (mixture with 3.0% added water) absorbed the lowest amount of water, Figures 9.12 and 9.13.

The amount of water absorbed during capillary test appearsto be related to the air voids and the trend of the relationship is shown in Figure 9.14. However, a general equation for all types of mixtures is not justifiable because the air voids are significantly affected by the percentage of added water (degree of coating), related to the fact that the emulsion has not completely broken.

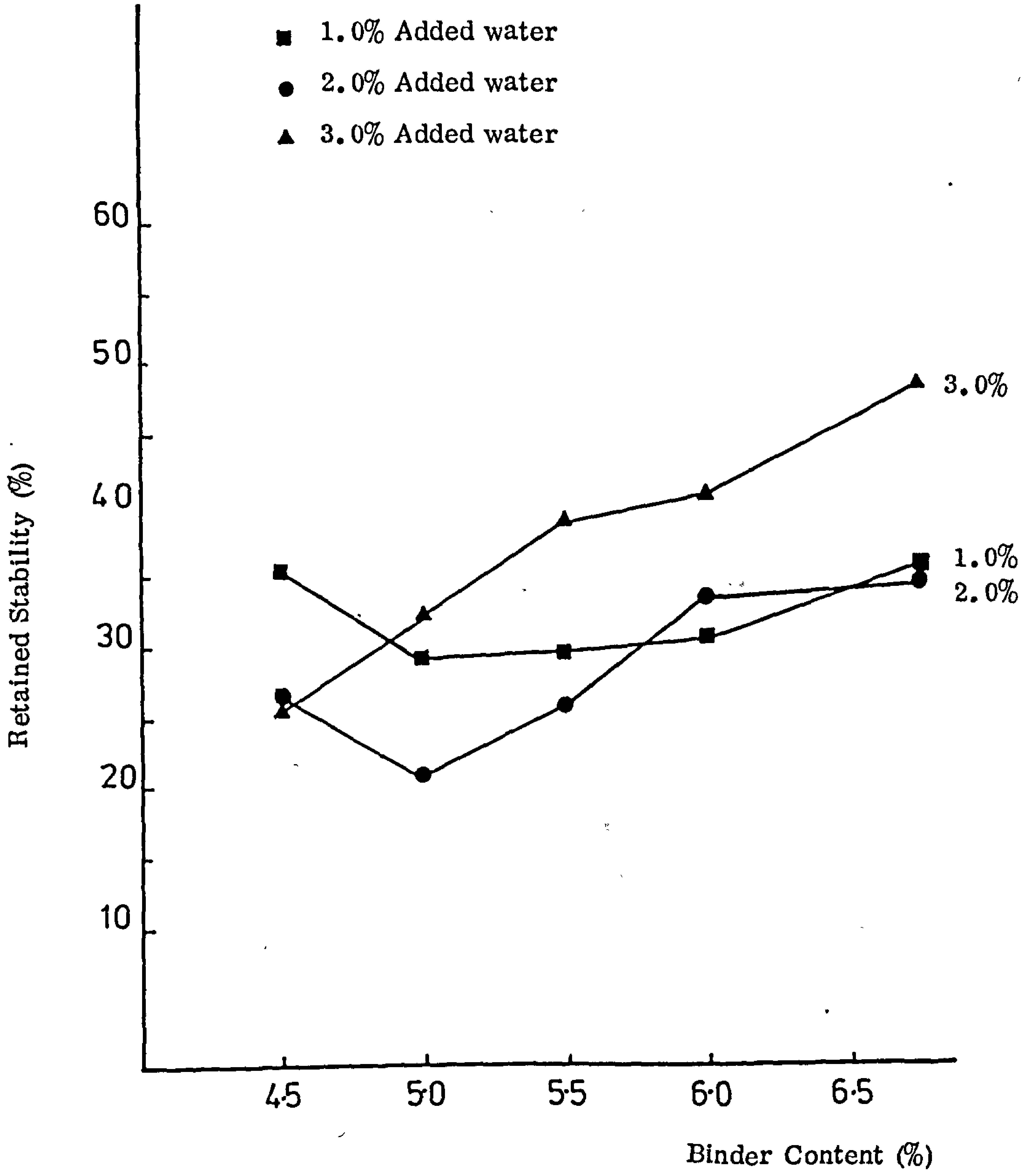


Fig. 9.12 RETAINED STABILITY vs BINDER CONTENT (One day curing)

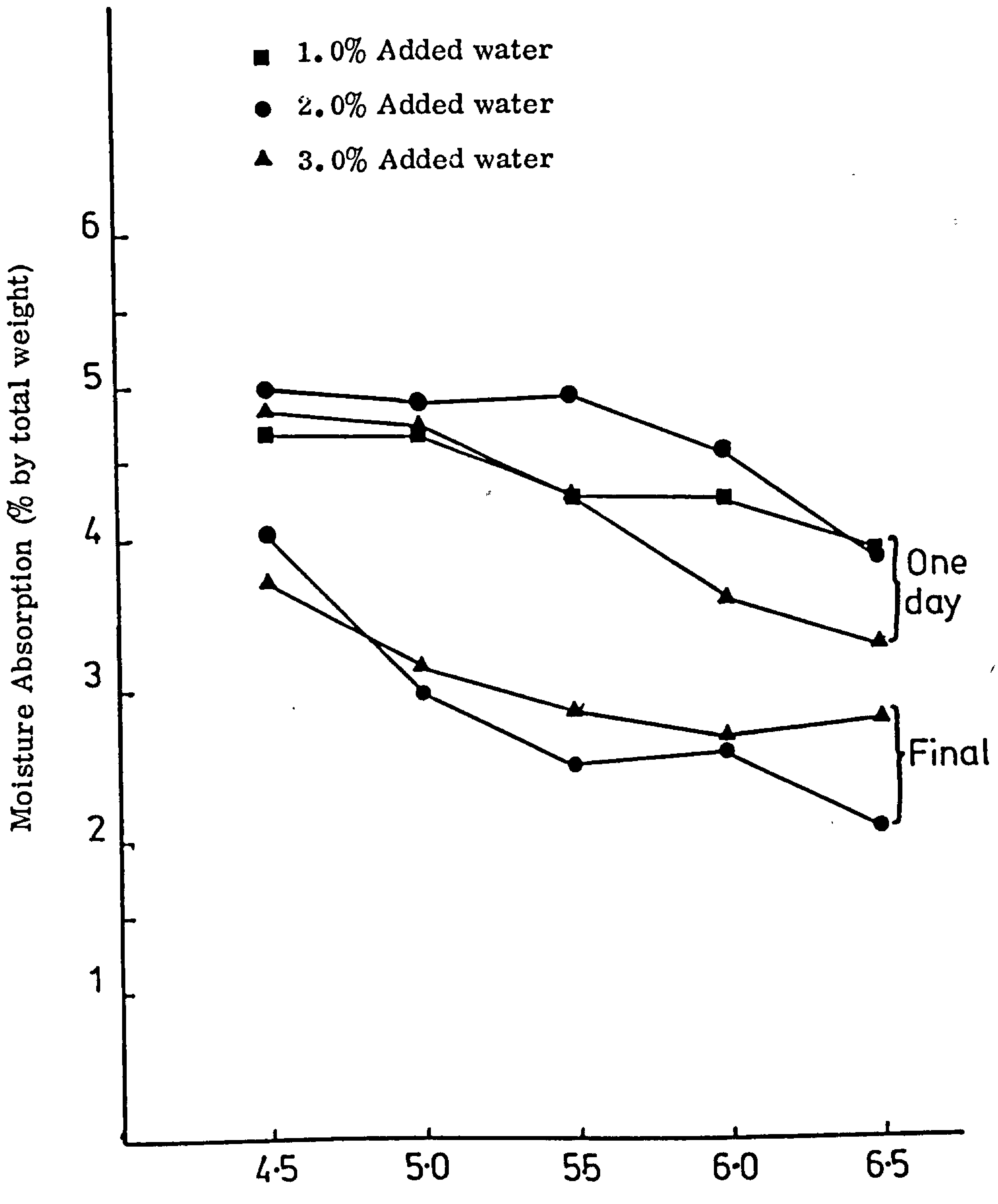


Fig. 9.13 MOISTURE ABSORPTION AFTER 96h SOAKING vs BINDER CONTENT

(Two curing conditions)

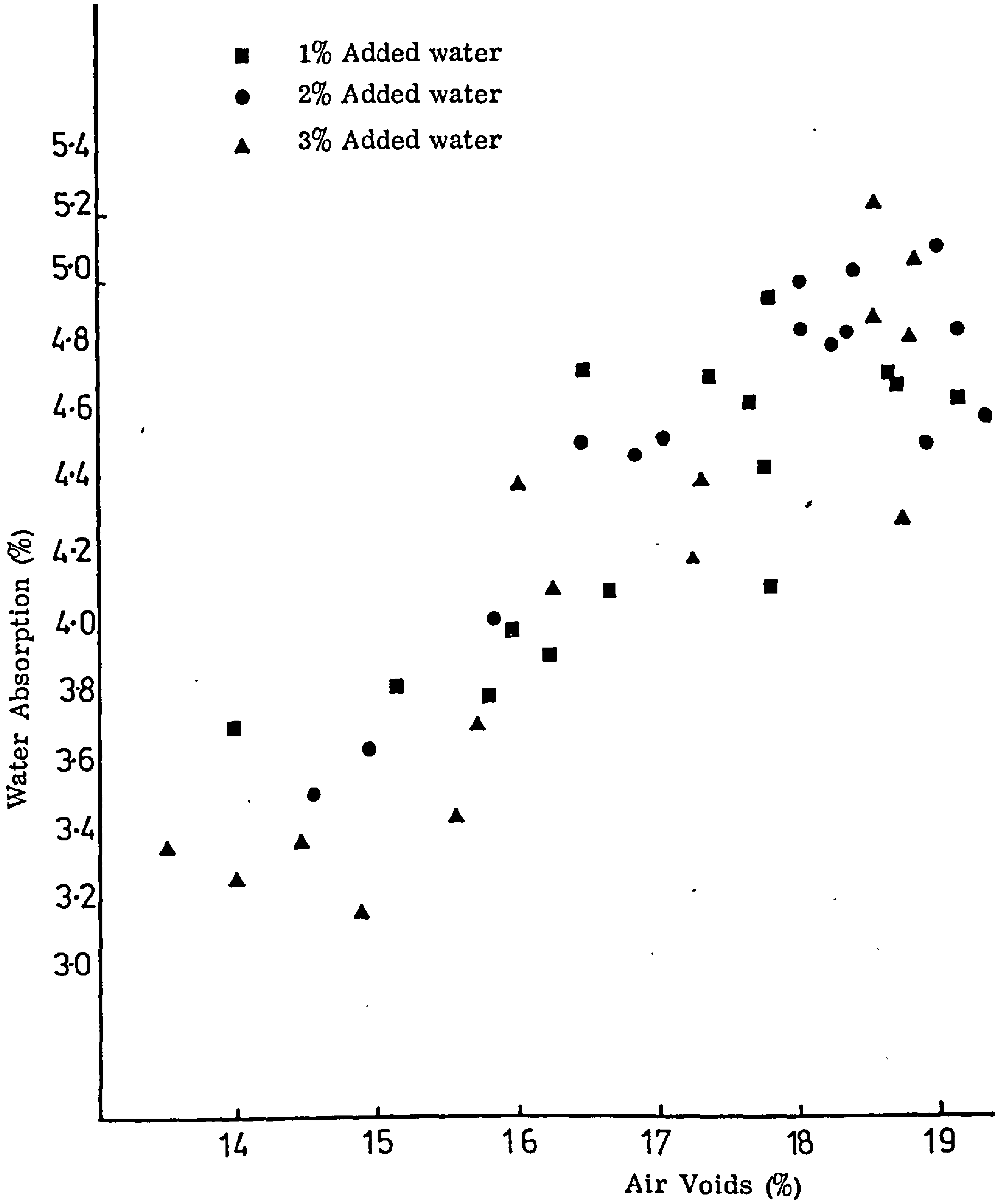


Fig. 14 MOISTURE ABSORPTION vs AIR VOIDS
(One day curing)

9.3.2. The effect of binder and added water on the properties of D.E.Mc mixtures after final curing

9.3.2.1. The effect on bulk density, compacted aggregate density, voids, V.M.A., and water content at testing

The statistical analysis of the data gave results similar to the one day curing results. In other words, the bulk density and V.M.A. were not affected significantly by the changes in binder content. The above two variables were only affected significantly by the added water level. It can be seen from Figures 9.15 and 9.19 that although the changes in bulk densities and V.M.A. with binder content were not significant, mixtures with 2% added water possessed higher bulk densities and V.M.A. values than mixtures with 3% added water.

The fact that the binder content does not affect the bulk density and V.M.A. reinforces the suggestion made in section 8.4.1.1. and 8.4.1.2. .That is, if curing (aeration) takes place before compaction, the only liquid content which can affect the bulk density is the total free water and not the total liquid (i.e. binder + water). This amount of water at compaction was fixed at 3.0 percent which is far less than the optimum total liquid content at compaction (determined in Chapter 5). As a result of compacting at less than the optimum liquid content the bulk densities were lower.

Figure 9.16 shows that the compacted aggregate density values did not show any appreciable change with respect to binder content, but that different values were obtained with different added water levels.

The binder content, and the addition of water to the aggregates, significantly affected the air voids and the total voids of the mixtures. As can be seen from Figures 9.17 and 9.18, air voids and total voids (air + voids filled with water) decreased as the binder content increased and mixtures with a different percentage of added water i.e. a different

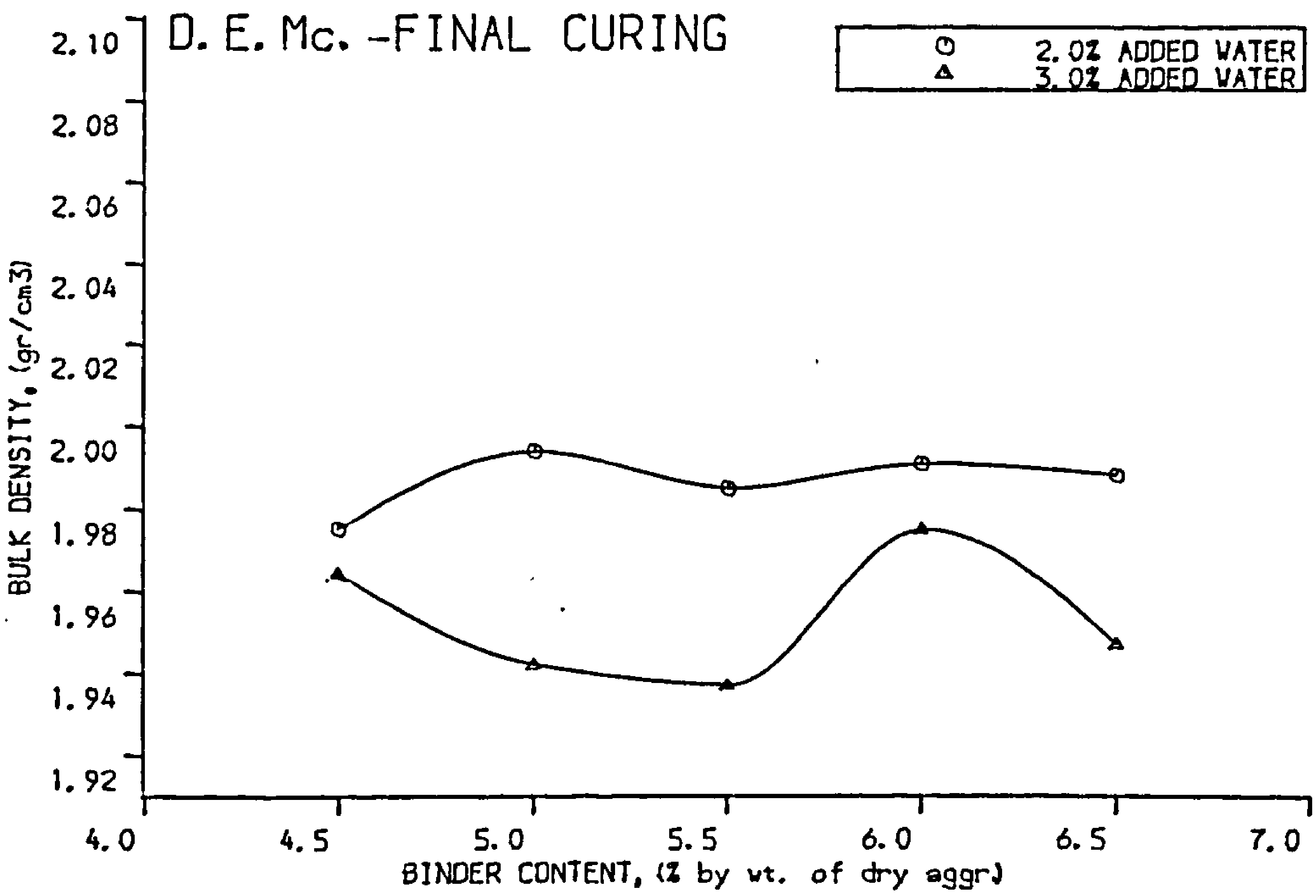


Fig. 9. 15 BULK DENSITY v BINDER CONTENT

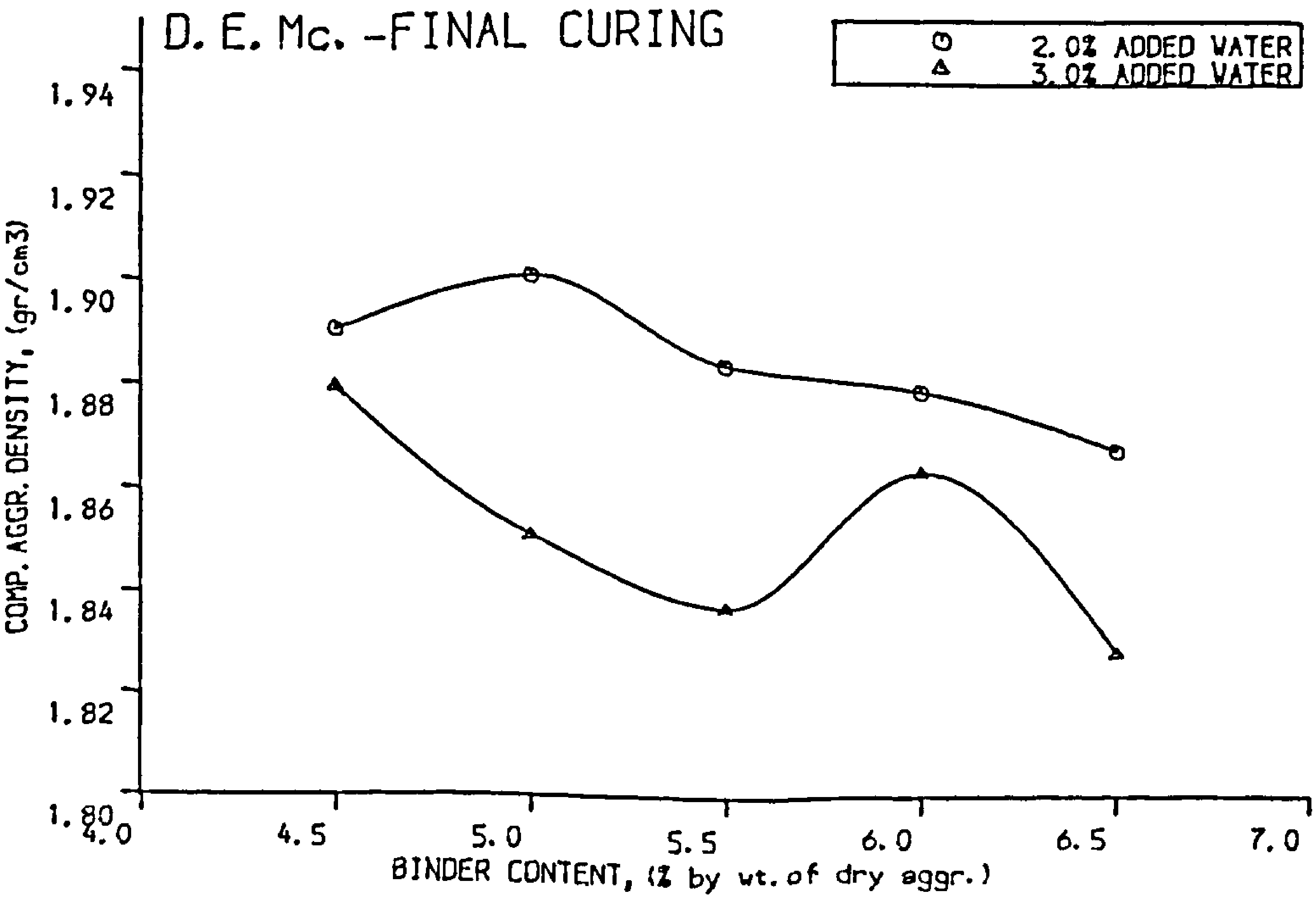


Fig. 9. 16 COMP. AGGR. DENSITY v BINDER CONT.

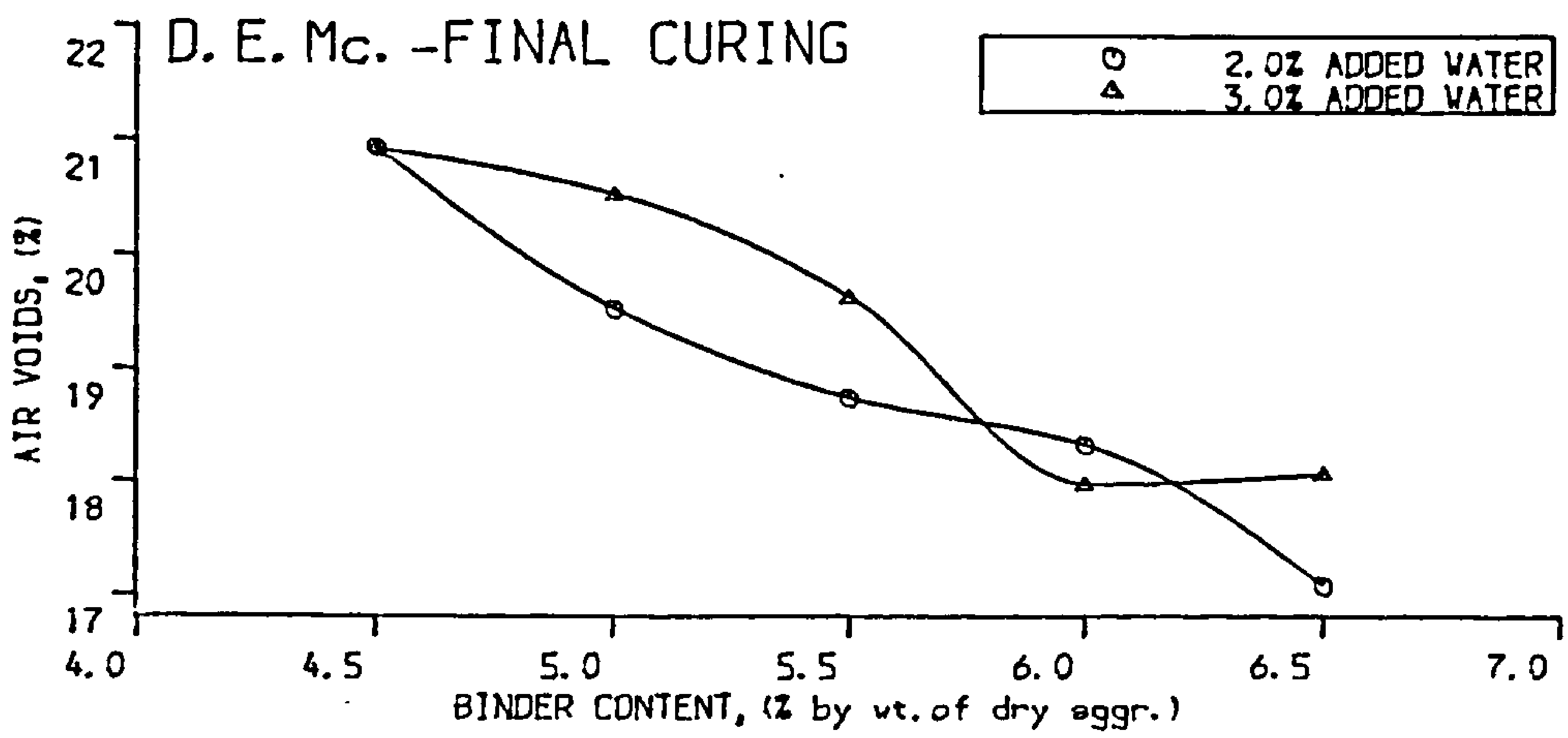


Fig. 9. 17 AIR VOIDS v BINDER CONTENT

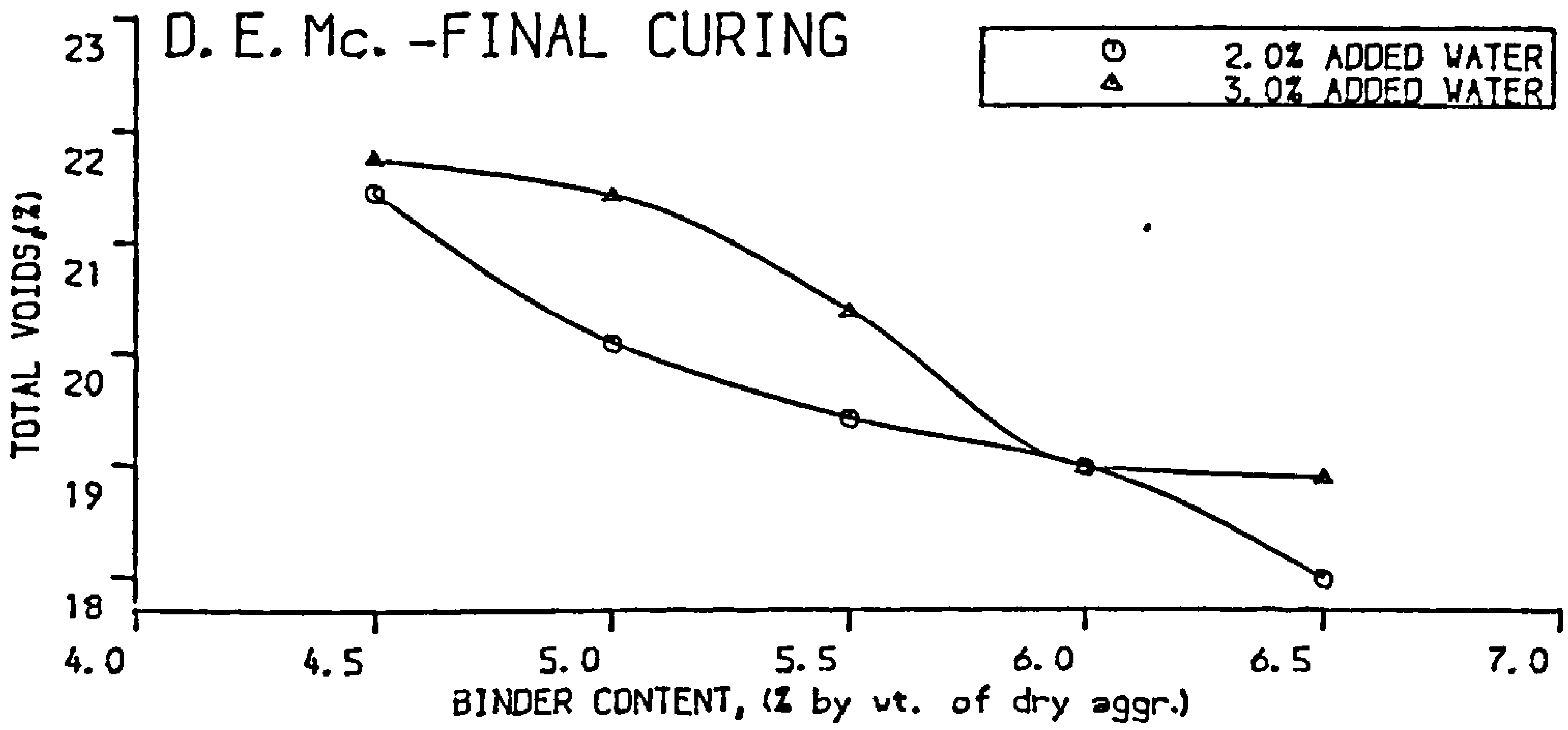


Fig. 9. 18 TOTAL VOIDS v BINDER CONTENT

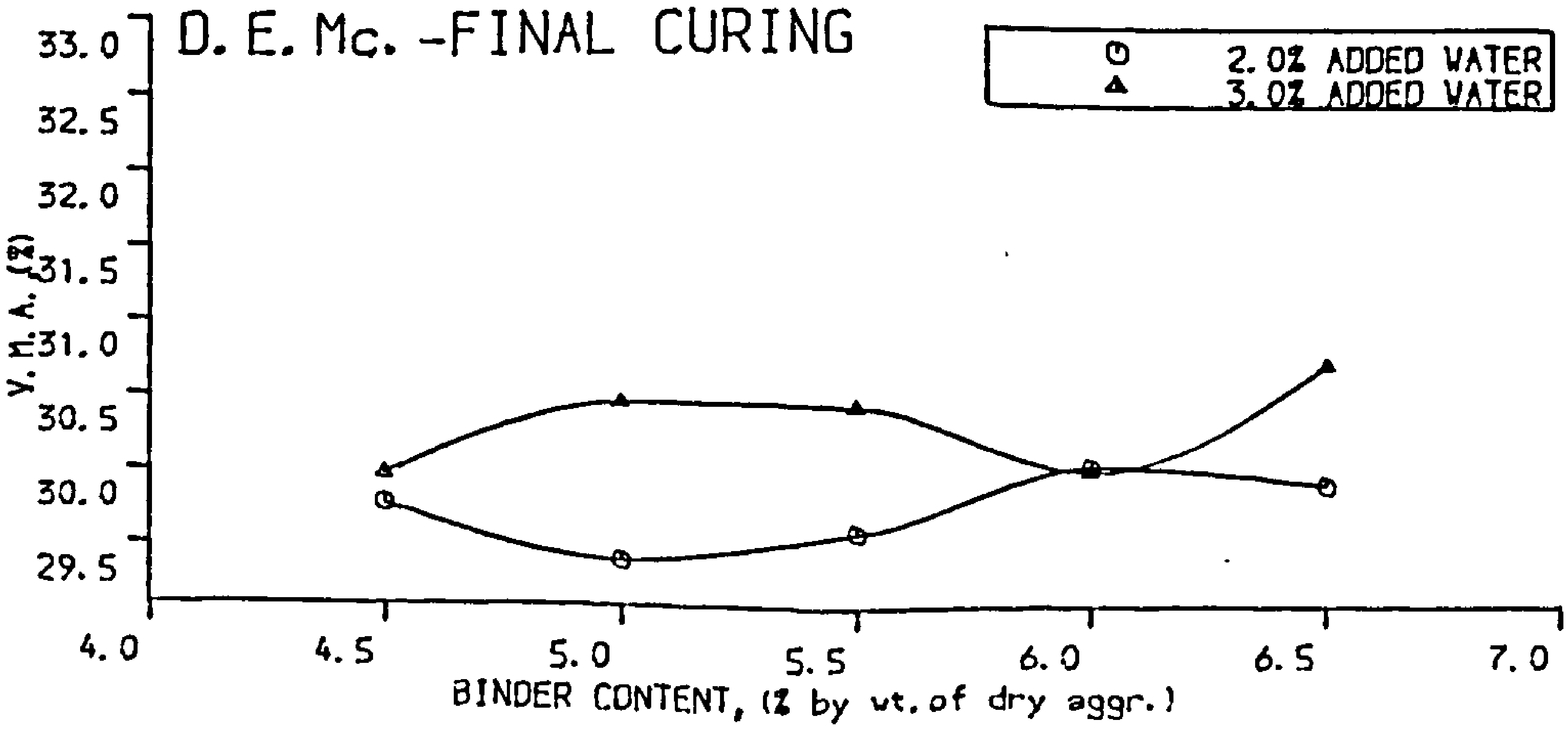


Fig. 9. 19 V. M. A v BINDER CONTENT

degree of coating, possessed different percentage of voids.

In Chapter 5 it was shown that the amount of water lost by the specimens during curing was dependent on the binder content (Figure 5.9). In this chapter, the percentage of water retained in the specimen after curing was found to be significantly affected not only by the binder content but also by the level of added water. Figure 9.20 shows that as the binder content increased the amount of water retained by the specimens increased. Mixtures with 3.0% initial added water retained more water than mixtures with 2.0%. This is because mixtures with 3% added water had originally more water than the 2% mixtures, and this was either absorbed by the aggregates or trapped under the binder film. This water content is extremely difficult to evaporate and it is responsible for the slow development of the properties of the binder. It is therefore necessary to add as much water as is needed for good coating. This will minimize the amount of free water trapped in the system and the risk of producing "wet" mixtures in which "running-off" of the binder is inevitable.

9.3.2.2. The effect on dry and wet Marshall values

When the specimens were cured for five days in the air and two days in the oven (60°C), complete breaking of the emulsion was achieved and the true effect of the binder was observed. The results of the statistical analysis showed that dry stability after final curing, unlike dry stability of one day curing, was significantly affected by the binder content, Table 9.5. Dry stability was also affected by the added water and the interaction between the two main factors. Dry stability values, in general, increased as the binder content increased, and mixtures with a different percentage of added water possessed different dry stability values, Figure 9.21.

In the case of wet stability, after final curing, both the main factors and their interaction affected the values but the wet stability

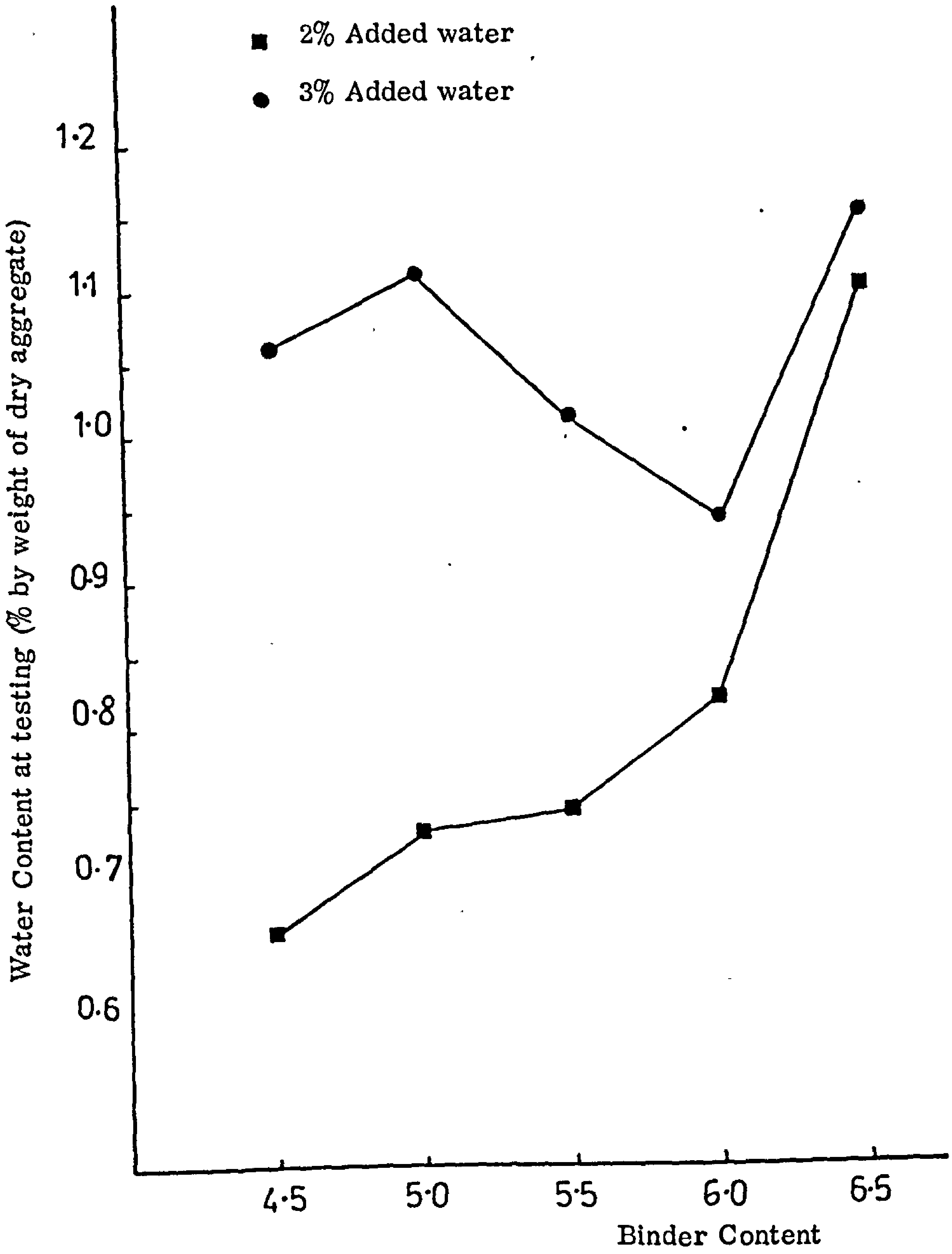


Fig. 9.20 WATER CONTENT AT TESTING vs BINDER CONTENT (Final curing)

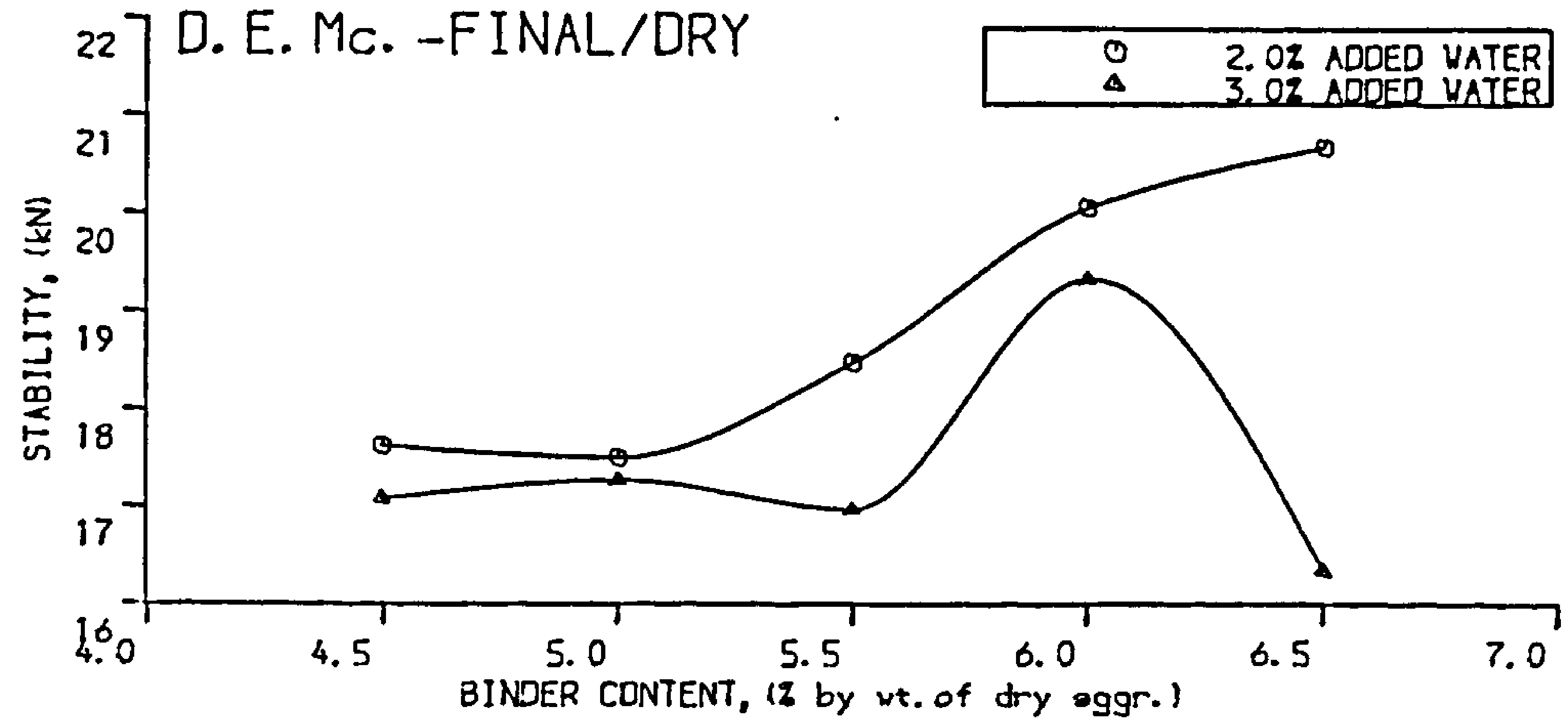


Fig. 9.21 MARSH. STABILITY v BINDER CONT.

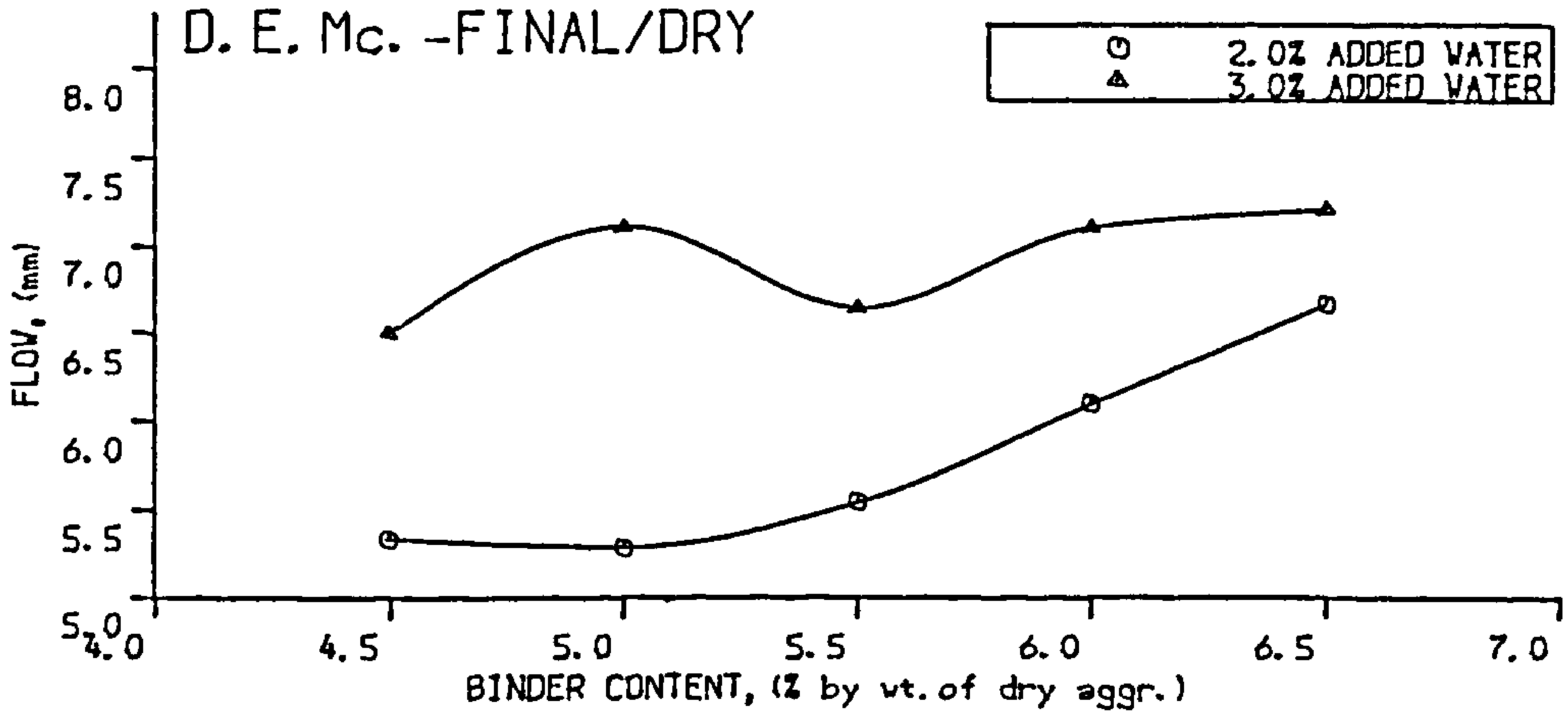


Fig. 9.22 MARSHALL FLOW v BINDER CONT.

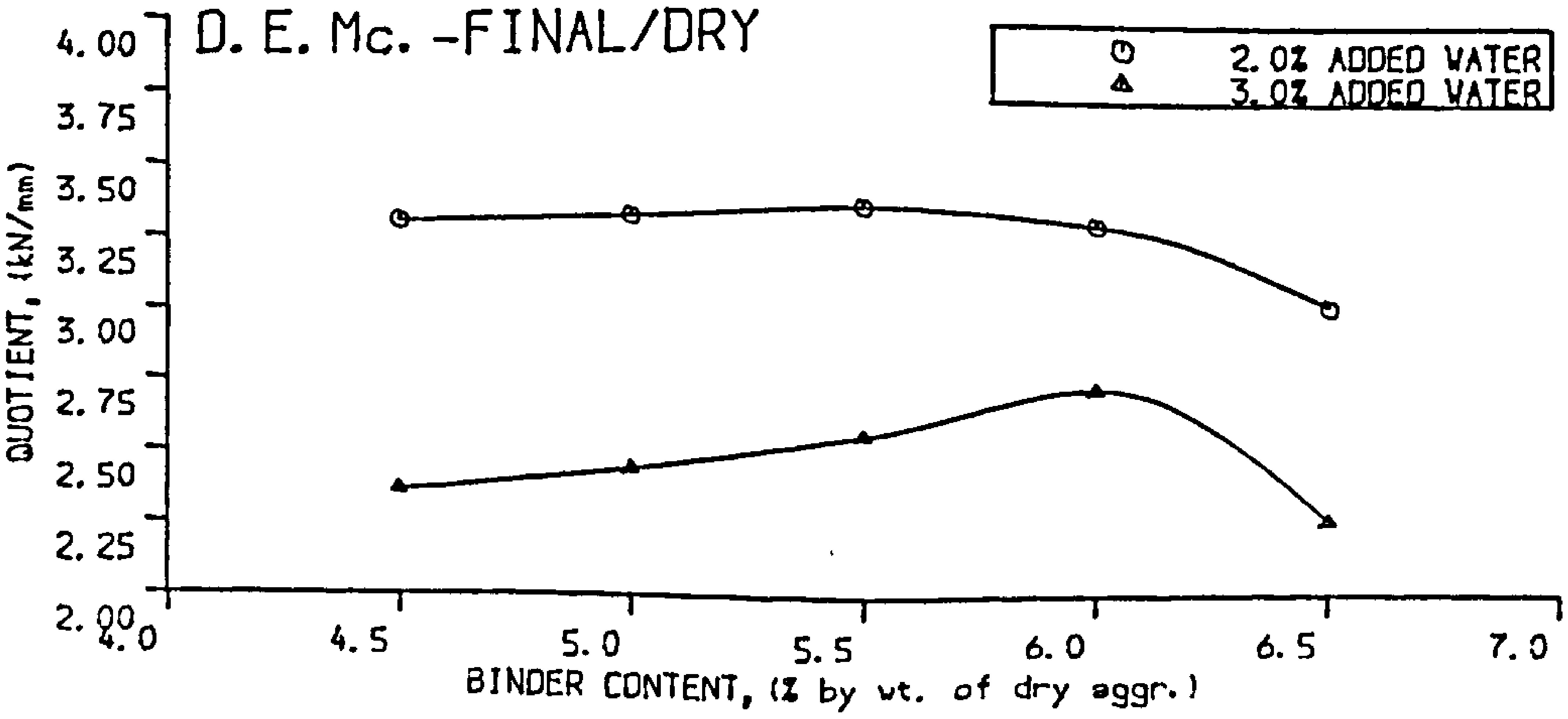


Fig. 9.23 MARSH. QUOTIENT v BINDER CONT.

curves showed a peak, Figure 9.24. This peak corresponds to an optimum binder content of 6% for maximum wet stability.

The wet/dry stability ratio expressed as a percentage of retained stability has been plotted against binder content in Figure 9.27. Mixtures with 6% binder content retained 54% of their stability. It should be noted that mixtures with 2% added water possessed higher retained stability than mixtures with 3% added water. The reason for this can be attributed principally to the degree of coating. In the case, however, of wet mixtures (too much initial added water) "running-off" of the binder can certainly result in lower wet stability values and as a consequence lower retained stability.

Examining the results of retained stability, Figure 9.27 and the amount of water absorbed during capillary test, Figure 9.13, it can be seen that,as after one day curing,mixtures which absorbed more water during soaking exhibited lower retained stability. Water absorption was found to correlate well with air voids, Figure 9.28. Examining the linear relationship it is apparent that mixtures with higher air voids can be expected to absorb more water during the 48 hours capillary soaking. Indeed this was observed in the final cured D.E.Mc mixtures with higher air voids (mixtures with 3% added water) absorbed more moisture than mixtures with lower air voids (2.0% added water) Figures 9.13 and 9.17. This proves that the relationship between air voids and water absorption is valid and the anomaly observed on the one day cured mixtures was entirely due to the unbroken emulsion. Good correlation of water absorption was also found with binder content, Figure 9.29. As was expected, the linear relationship showed that when the binder content increased the water absorption decreased.

A comparison between water absorption and permeability of the mixtures could not be carried out, due to the inability of the permeameter to measure the permeability of the highly permeable D.E.Mc mixtures.

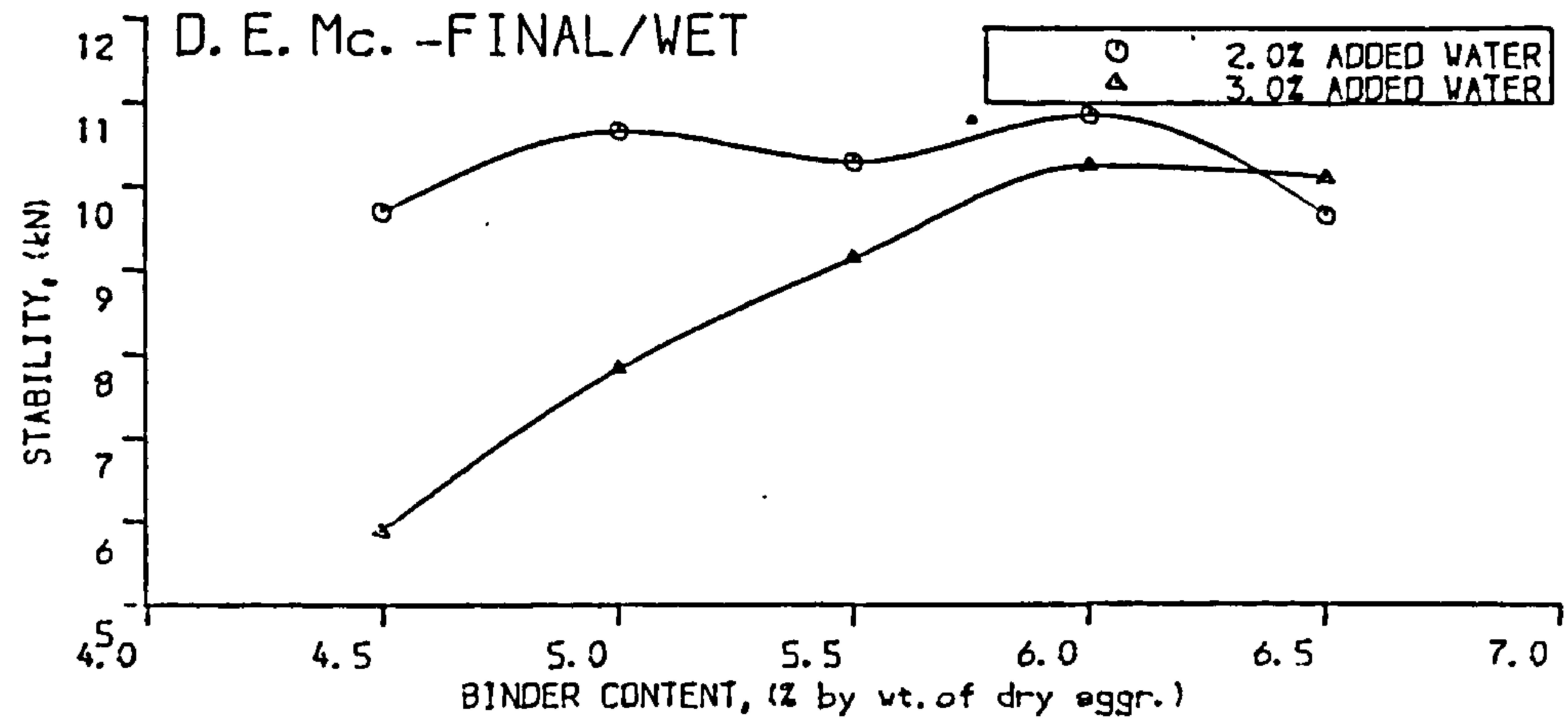


Fig. 9. 24 MARSH. STABILITY v BINDER CONT.

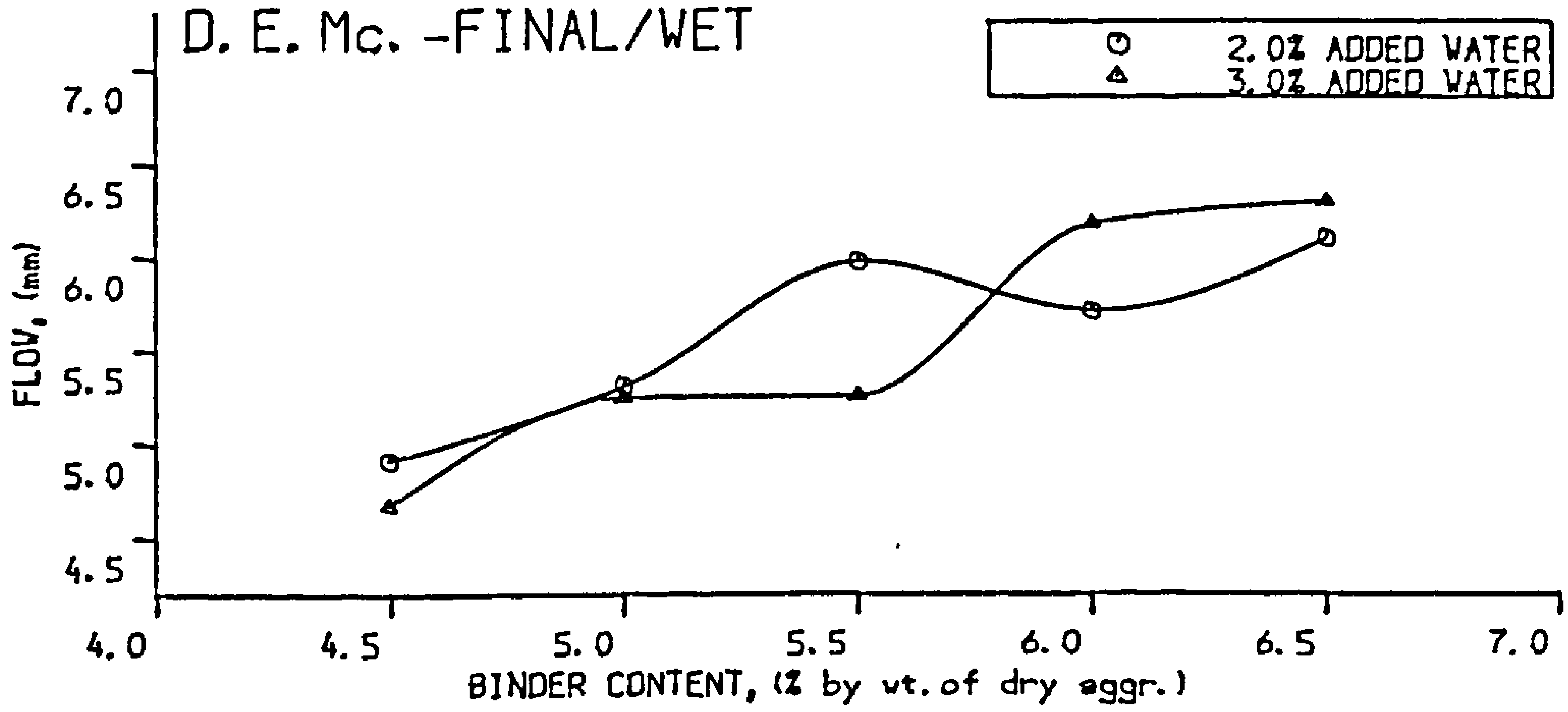


Fig. 9. 25 MARSHALL FLOW v BINDER CONT.

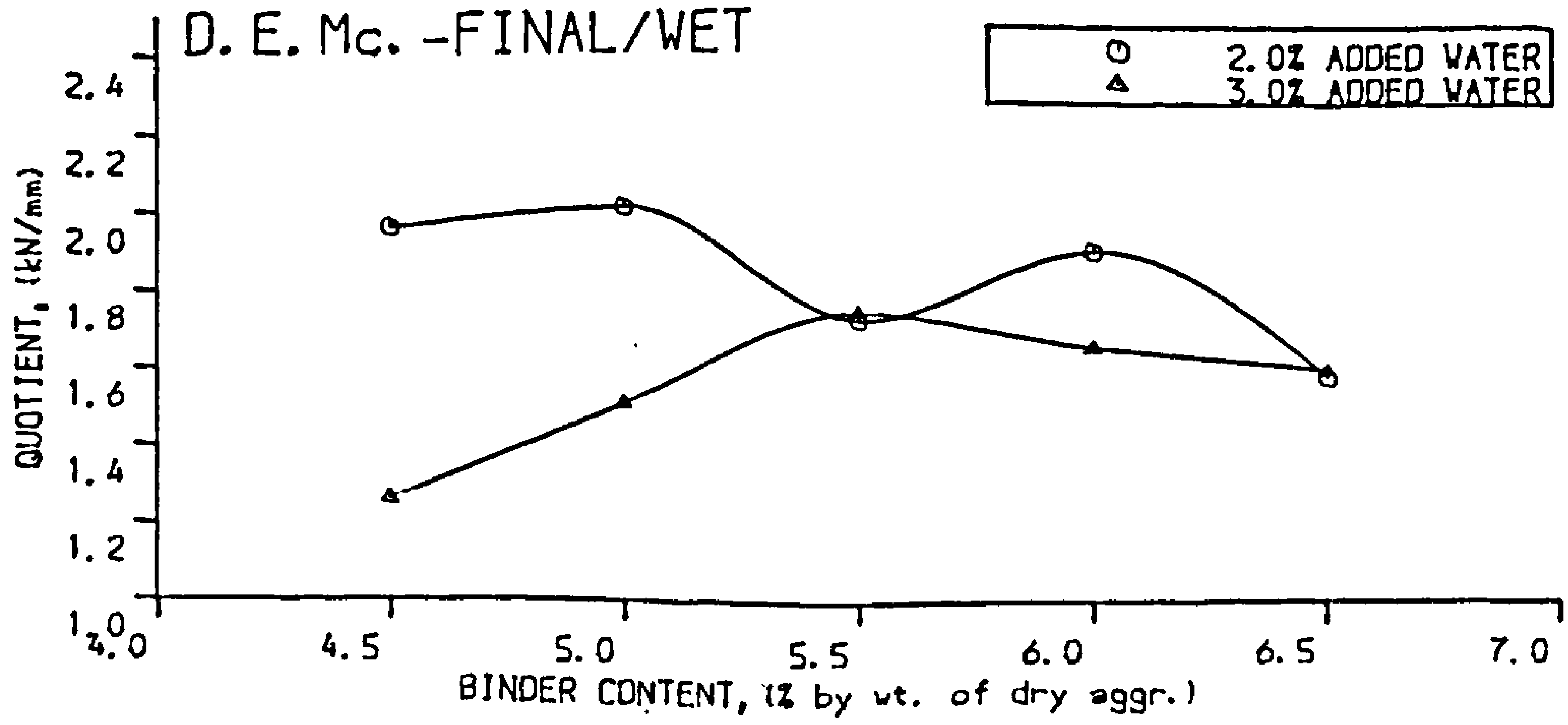


Fig. 9. 26 MARSH. QUOTIENT v BINDER CONT.

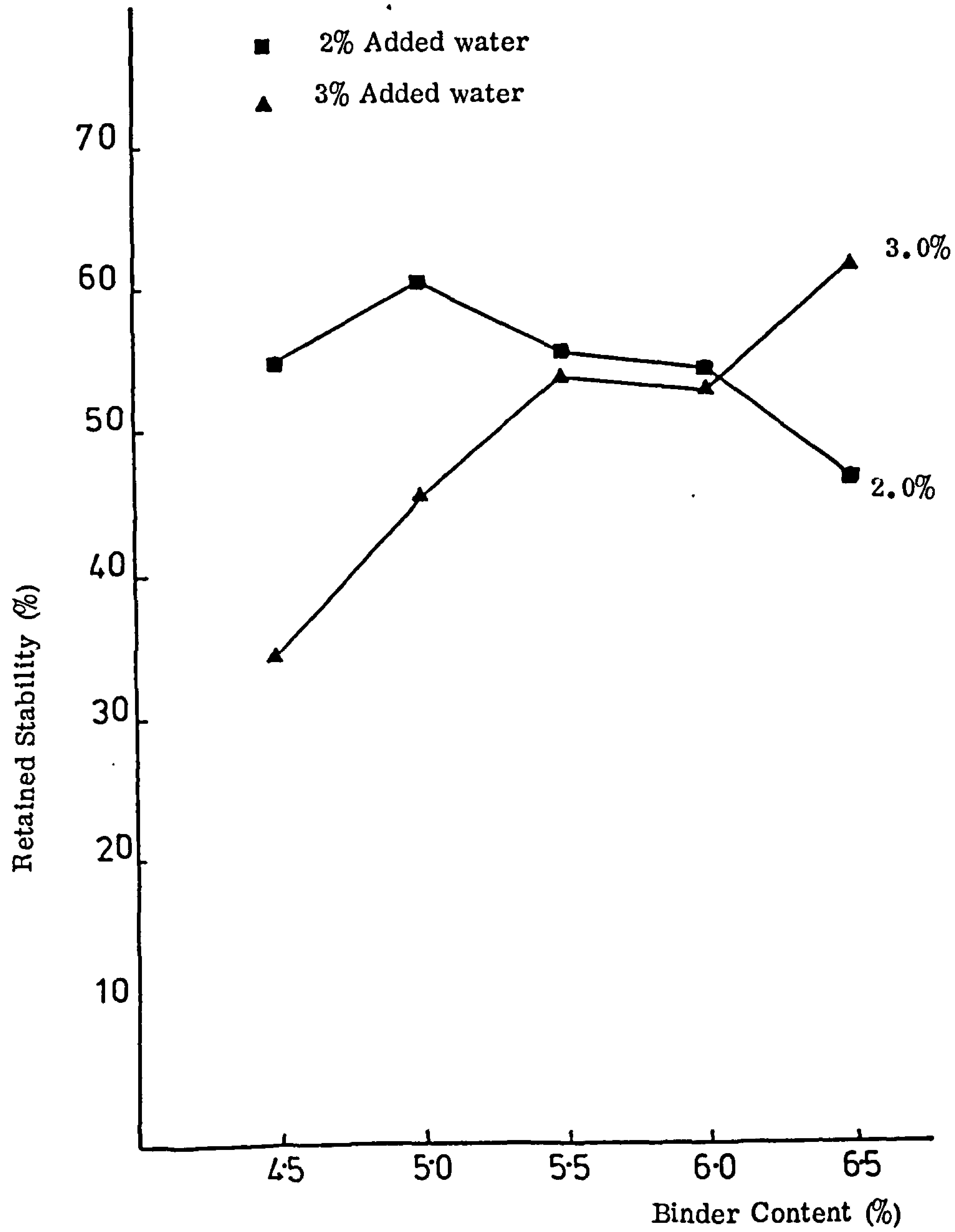


Fig. 9.27 RETAINED STABILITY vs BINDER CONTENT (Final curing)

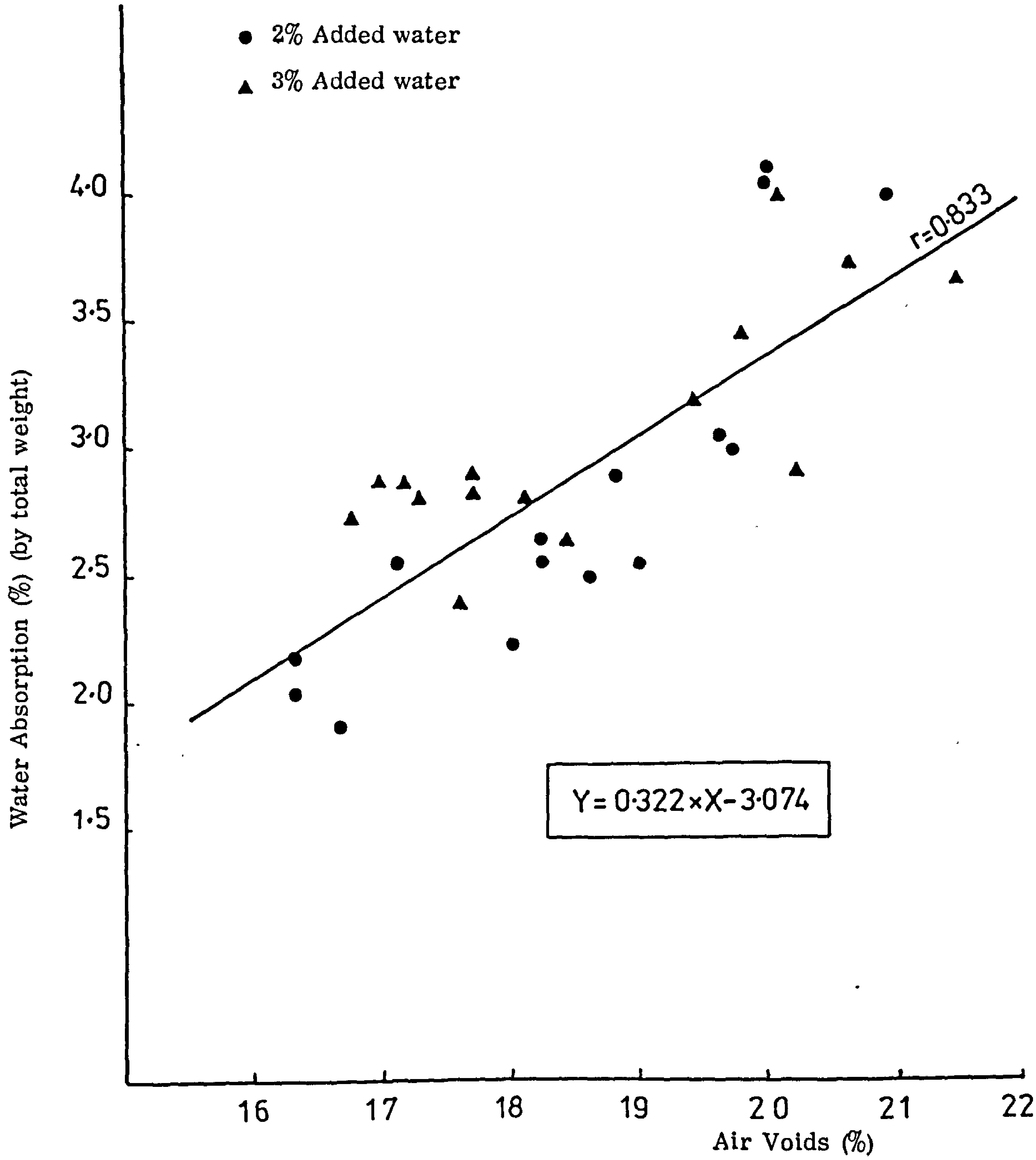


Fig. 9.28 MOISTURE ABSORPTION vs AIR VOIDS
(Final curing)

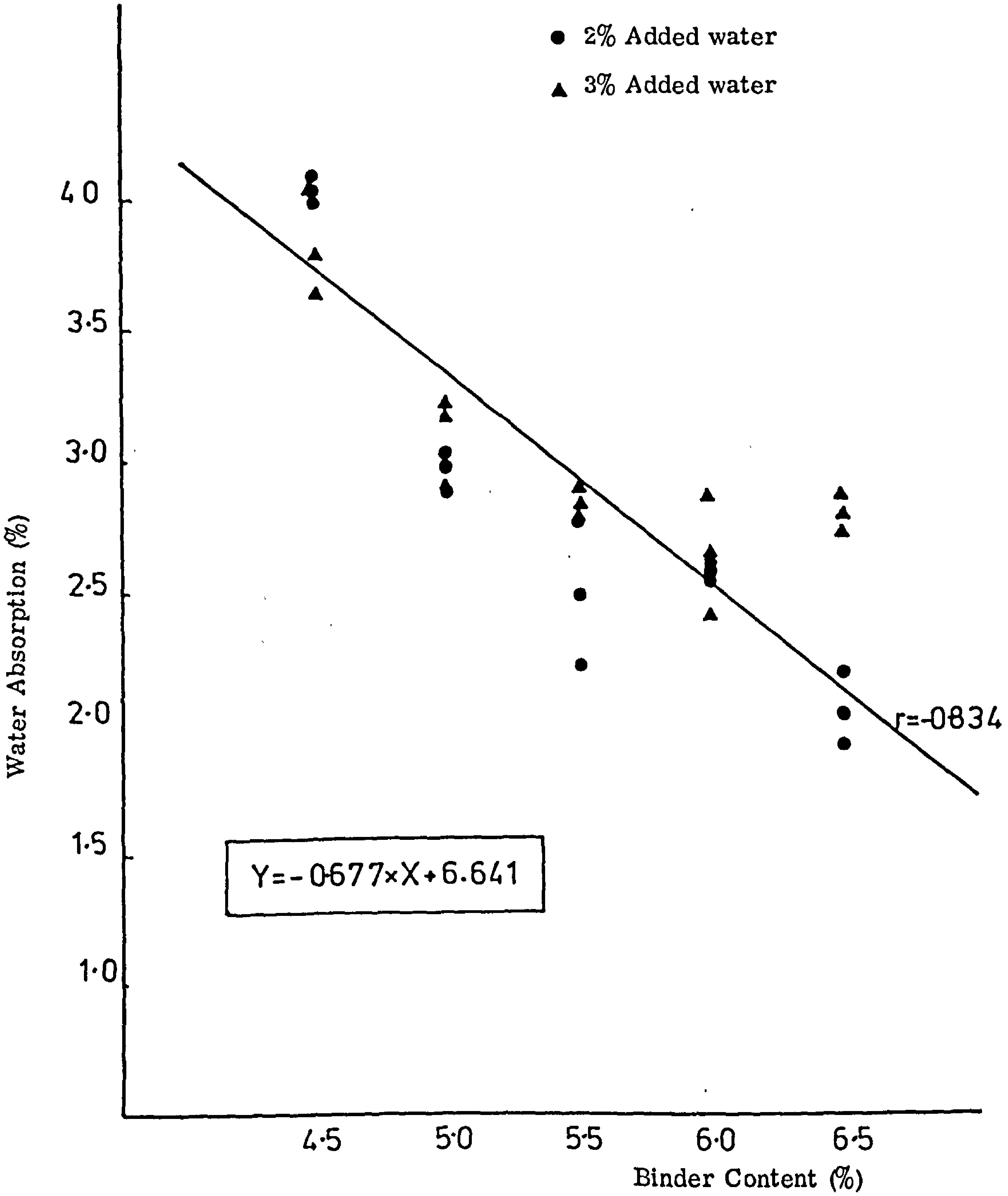


Fig. 9.29 MOISTURE ABSORPTION vs BINDER CONTENT (Final curing)

Finally, as in the one day cured specimens, the flow values were mainly influenced by the binder content, but its effect was dependent on the level of added water (interaction effect), Table 9.5. As Figures 9.22 and 9.25 show, the flow increased as the binder content increased, according to the level of added water. Mixtures with 3% added water gave higher flow values than mixtures with 2.0% added water.

9.3.3. Compactability of the D.E.Mc mixtures

The compaction of D.E.Mc mixtures so far was carried out at fixed moisture content of 3% which enabled the effect of binder content and added water without the effect of moisture content at compaction to be determined. Since it is possible to compact the D.E.Mc mixtures immediately after mixing, i.e. at varied moisture content, it was decided to examine the effect of varied moisture content on the compactability and properties of the D.E.Mc mixtures.

The compactability of the mixtures was determined, as in the previous mixtures (C.R.A.) in terms of volume of voids, (see Section 8.4.3.1.). Figures 9.30 and 9.31 show the compaction curves of D.E.Mc mixtures with 2% and 3% added water, compacted at a fixed moisture content of 3%. Figures 9.32 and 9.33 show the compaction curves of similar mixtures, but compacted immediately after mixing at varied moisture content levels which are higher than 3%. It is apparent that for the same binder content and compaction level, the mixtures compacted immediately after mixing exhibited lower volume of total voids. It can therefore be said that when the D.E.Mc are compacted at moisture contents higher than 3% their compactability increases.

The rate of compaction was expressed, as in C.R.A. mixtures, by the slope of the compaction curves. A good linear relationship exists between total voids and number of gyratory revolutions when they are

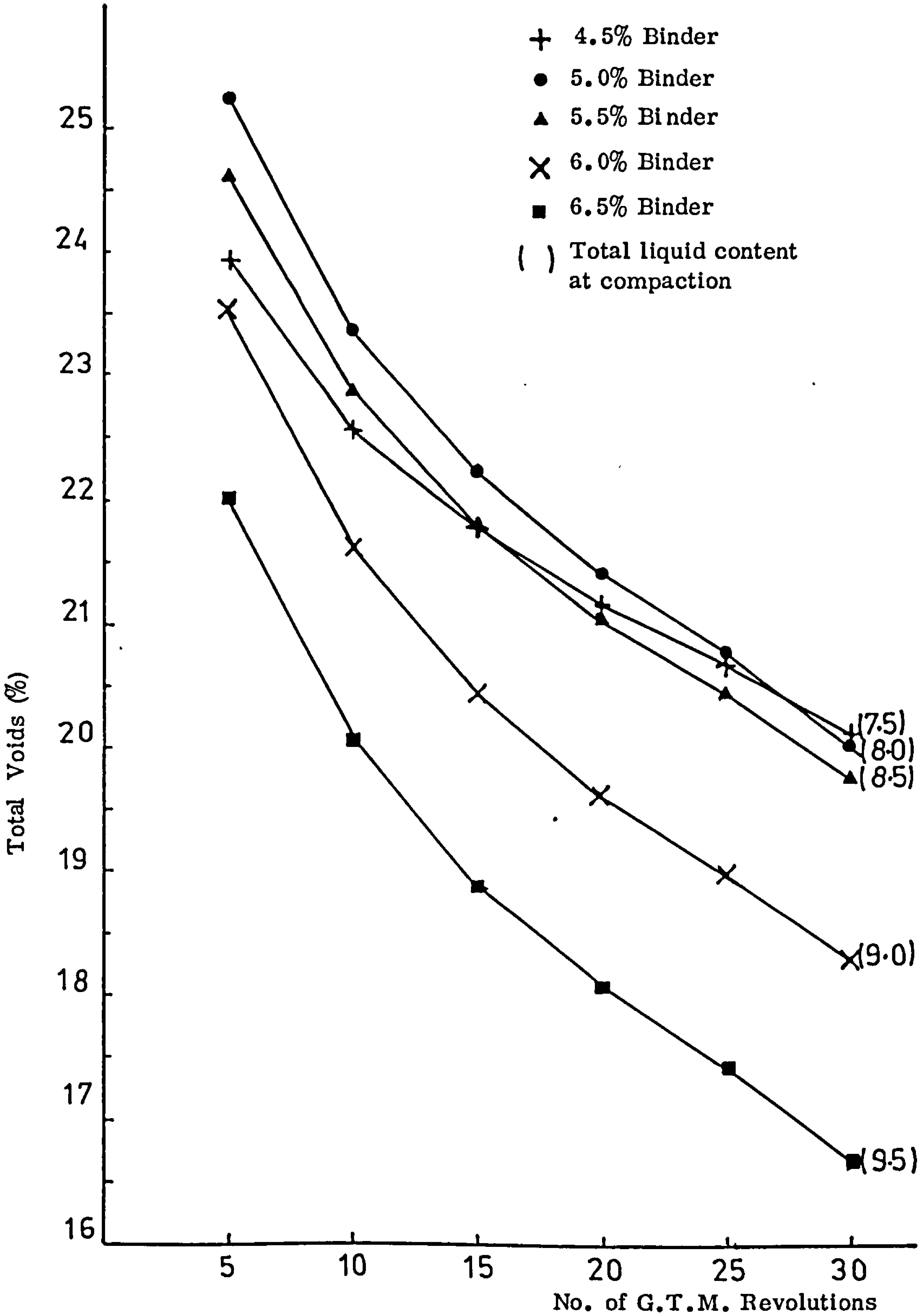


Fig. 9.30 COMPACTION CURVES OF D.C.Mc - FIXED W/C AT COMPACTION 2% WATER ADDED TO THE AGGREGATE

(Average of three specimens)

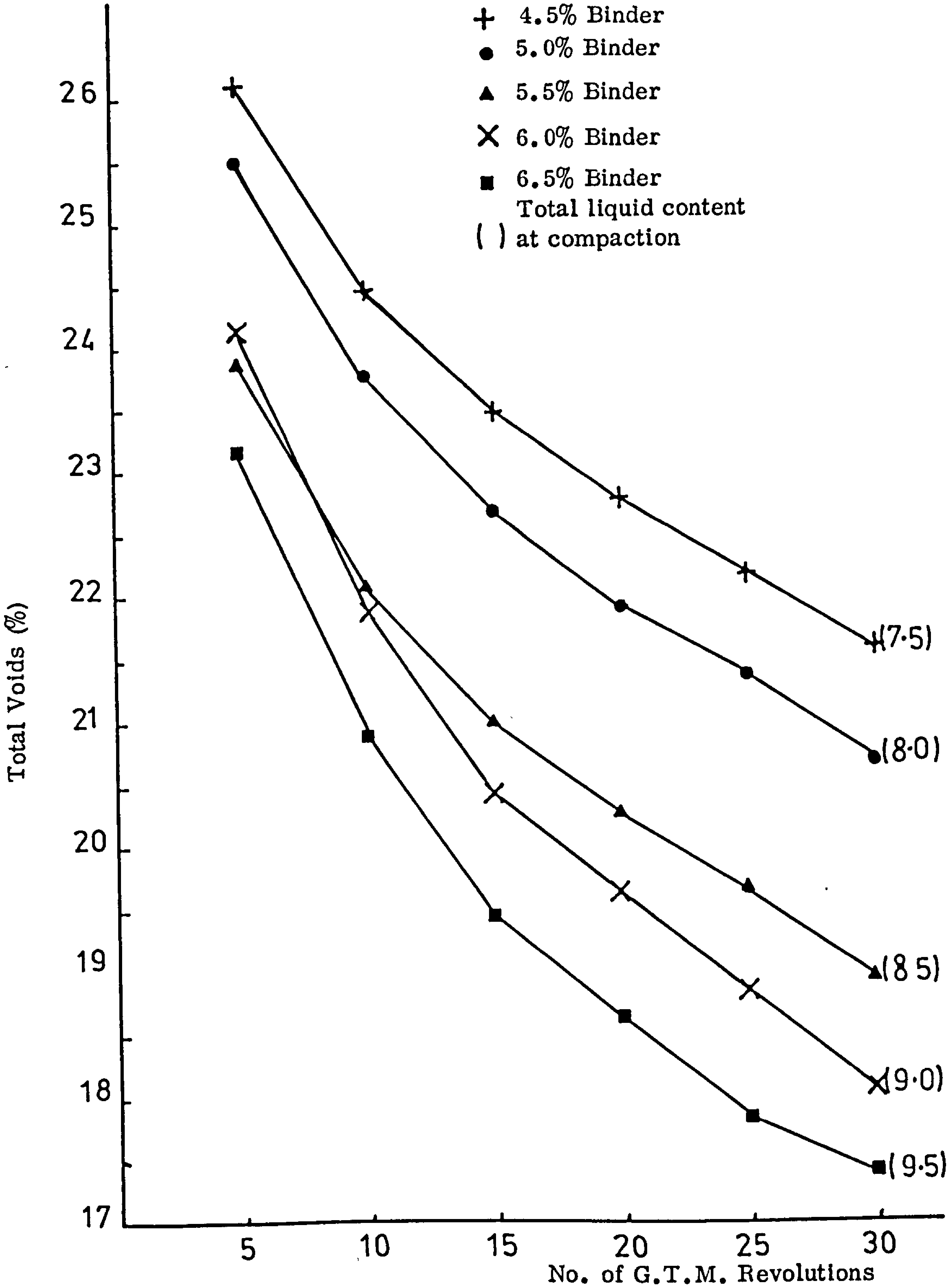


Fig. 9.31 COMPACTION CURVES OF D.E.Mc., FIXED WATER CONTENT AT COMPACTION 3% ADDED WATER TO THE AGGREGATE

(Average of three specimens)

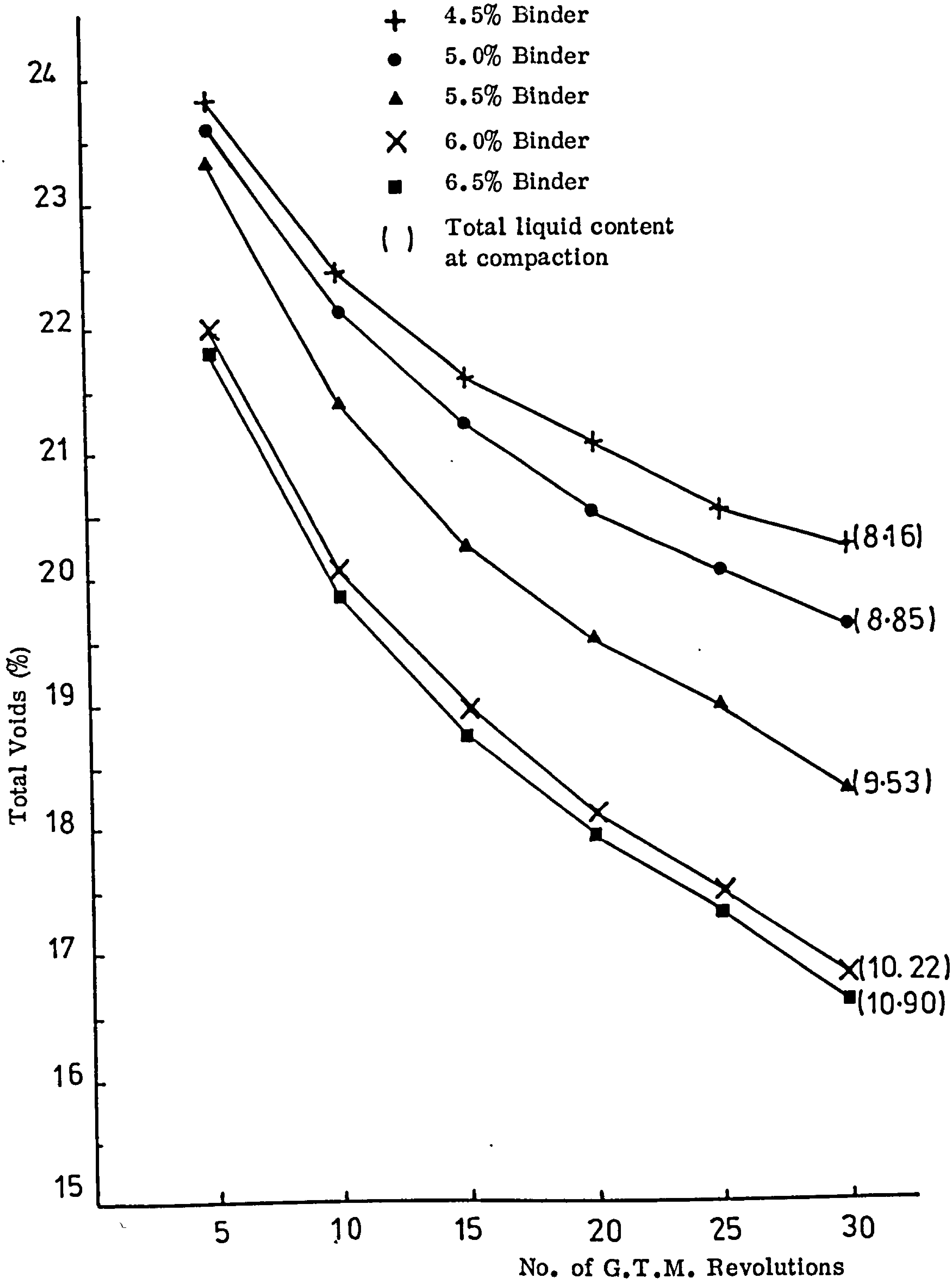


Fig. 9.32 COMPACTION CURVES OF D.E.Mc WITH VARIED W/C AT COMPACTION 2% ADDED WATER

(Average of three specimens)

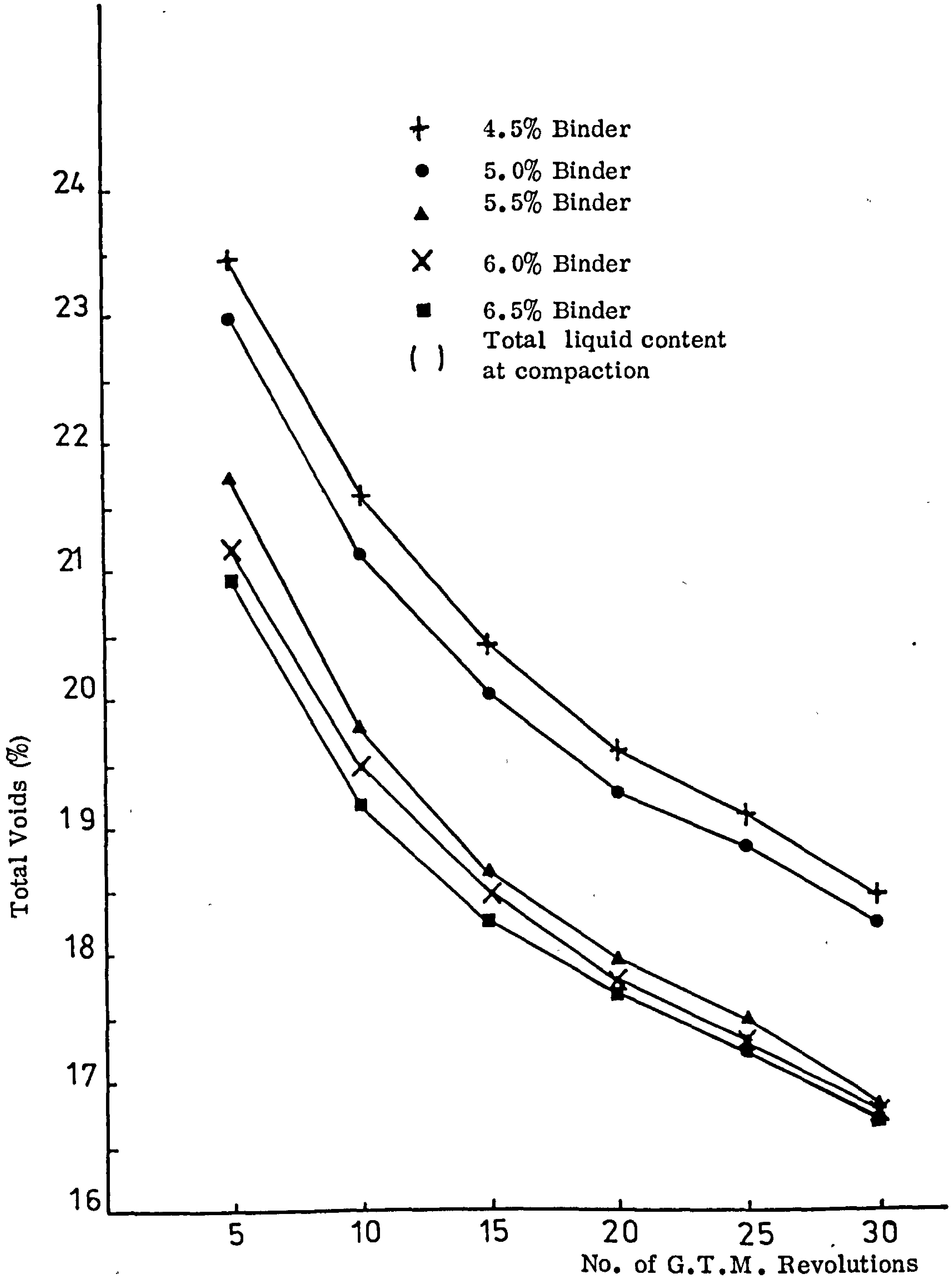


Fig 9.33 COMPACTION CURVES OF D.E.Mc WITH VARIED WATER CONTENT AT COMPACTION 3% ADDED WATER

(Average of three specimens)

plotted in a semi-logarithmic scale, see Table 9.6, column 3. The slopes of these lines were plotted against the total liquid content (water and binder) at the time of compaction and it was revealed that the rate of compaction changes with the total liquid content, Figure 9.34. The rate of compaction increases as the total liquid content increases, until a maximum value is obtained. This suggests that if compaction takes place immediately after mixing, there is an optimum percentage of total liquid content for the most effective compaction. This optimum total liquid content may be used for estimating the optimum binder content, if the initial added water and the binder/water ratio of the emulsion used are known. It must be noted that the optimum total liquid content can only be determined from curve I, (Figure 9.34) which is obtained from mixtures compacted immediately after mixing. This is because when compaction takes place immediately after mixing the binder is still an emulsion so that the effect is one of a liquid with a particular viscosity. When compaction takes place at 3% moisture content, the effect is mainly due to binder content (since moisture content remains constant). Part of the bitumen develops its properties during the necessary drying period, and the resultant viscosity of the system is higher than the viscosity of the mixtures compacted immediately after mixing.

Therefore, it can be said that when D.E.Mc mixtures are compacted immediately after mixing, their compactability is improved, which results in a significant reduction of total voids. It is then possible to determine the amount of total liquid content at compaction for most effective compaction, which may be used for the estimation of optimum binder content of the mixture.

9.3.4. The effect of varied moisture content at compaction on the properties of D.E.Mc mixtures

It has been shown in the previous section, that compacting at higher than 3.0% of total water content improved the compactability and reduced

COMPACTION AT FIXED WATER CONTENT (3.0% by wt.aggr)				COMPACTION AT VARIED WATER CONTENT			
$Y = 10^{(aX + b)}$							
Total liquid Content	a (1)	b (2)	Correlation r (3)	Total liquid Content	a (4)	b (5)	Correlation r (6)
7.50	-0.0957	1.448	-0.997	8.16	-0.0996	1.443	-0.999
8.00	-0.1292	1.497	-0.997	8.85	-0.1045	1.448	-0.999
8.50	-0.1211	1.478	-0.997	9.53	-0.1340	1.463	-0.999
9.00	-0.1383	1.471	-0.997	10.22	-0.1488	1.449	-0.997
9.50	-0.1591	1.456	-0.980	10.90	-0.1500	1.446	-0.997
7.50	-0.1050	1.492	-0.997	9.16	-0.1330	1.465	-0.999
8.00	-0.1154	1.489	-0.997	9.85	-0.1282	1.452	-0.999
8.50	-0.1272	1.469	-0.98	10.53	-0.1409	1.436	-0.999
9.00	-0.1472	1.480	-0.99	11.22	-0.1226	1.418	-0.999
9.50	-0.1630	1.481	-0.999	11.90	-0.1228	1.407	-0.999

X = No of G.T.M. Revolutions, Y = total voids (%), a = slope

TABLE 9.6 COEFFICIENTS OF LINEAR RELATIONSHIP BETWEEN TOTAL VOIDS AND NO. OF G.T.M. REVOLUTIONS FOR D.E.Mc (THE ABOVE OBTAINED FROM THE AVERAGE OF THREE SPECIMENS)

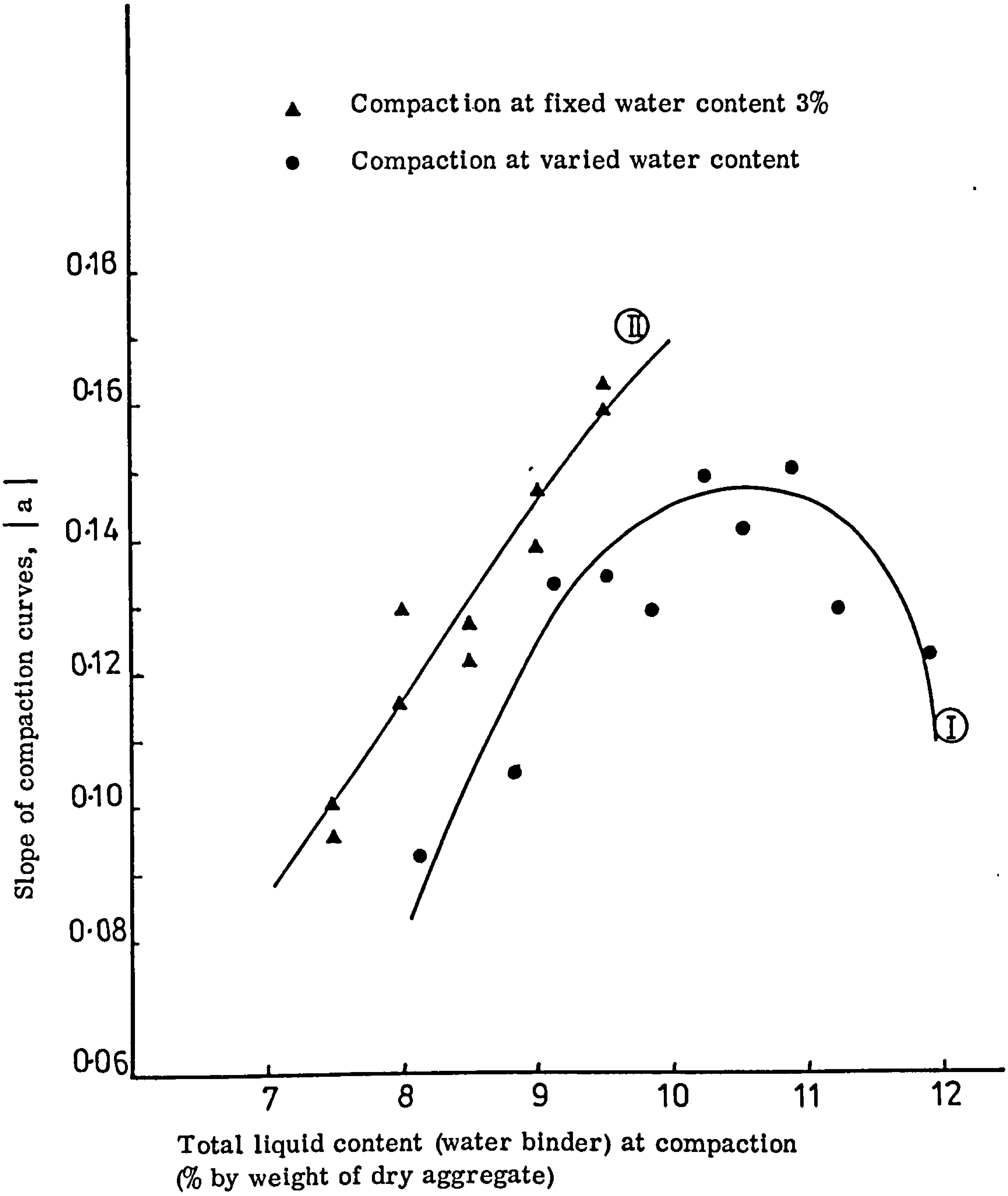


Fig. 9.34 SLOPE OF COMPACTION CURVES vs TOTAL LIQUID CONTENT

significantly the volume of total voids of the mixtures. As a result, the bulk densities of the mixtures were increased, with the maximum obtained at the optimum total liquid content of 10.5%, see Figure 9.35.

To examine whether or not the improvement in bulk density and the reduction of total voids improved the stability of the mixtures, and in particular the wet stability, the compacted specimens were cured for one, and five days and then tested after 48 hours of capillary soaking. The results were plotted in Figures 9.36 and 9.37, respectively. It can be seen that mixtures compacted immediately after mixing, although they possessed better bulk densities and lower voids, they exhibited lower wet stability values, specially at higher binder contents. This was not due to the fact that mixtures absorbed more water during capillary test (both mixtures absorbed almost the same amount of water, Figure 9.38) but due to the different amount of water present in the system before soaking started. Figure 9.36 shows (the number in parenthesis) that all mixtures compacted immediately after mixing possessed higher water content after one day of curing, due to the excessive amount of water trapped in the matrix during compaction. This is believed to cause slower development of the binder properties, which resulted in lower wet stability values than mixtures compacted at much lower water content (3%).

Both mixtures after final curing, during which complete breaking of the emulsion took place, exhibited almost the same wet stability values regardless of the amount of water present in the matrix before soaking, and the amount of water absorbed during soaking, Figure 9.37 and 9.38.

It can, therefore, be concluded that compacting the D.E.Mc mixtures at higher than 3% water content improved the compacted density of the mixtures, reduced the volume of voids but the wet stability at the early stage of curing was slightly deteriorated. However, the ability to compact at higher than 3% added water, i.e. immediately after mixing

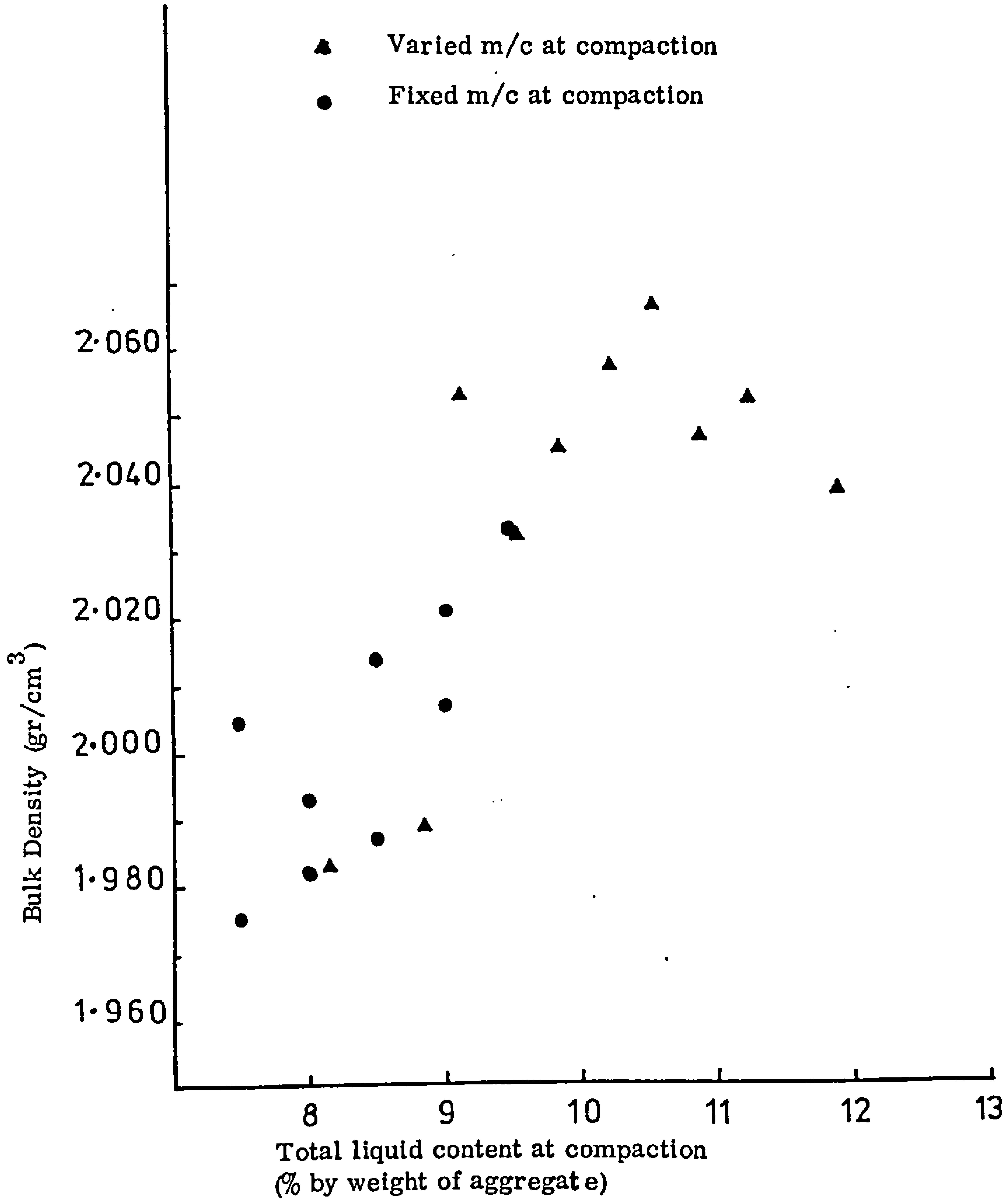


Fig. 9.35 BULK DENSITY vs TOTAL LIQUID CONTENT AT COMPACTION

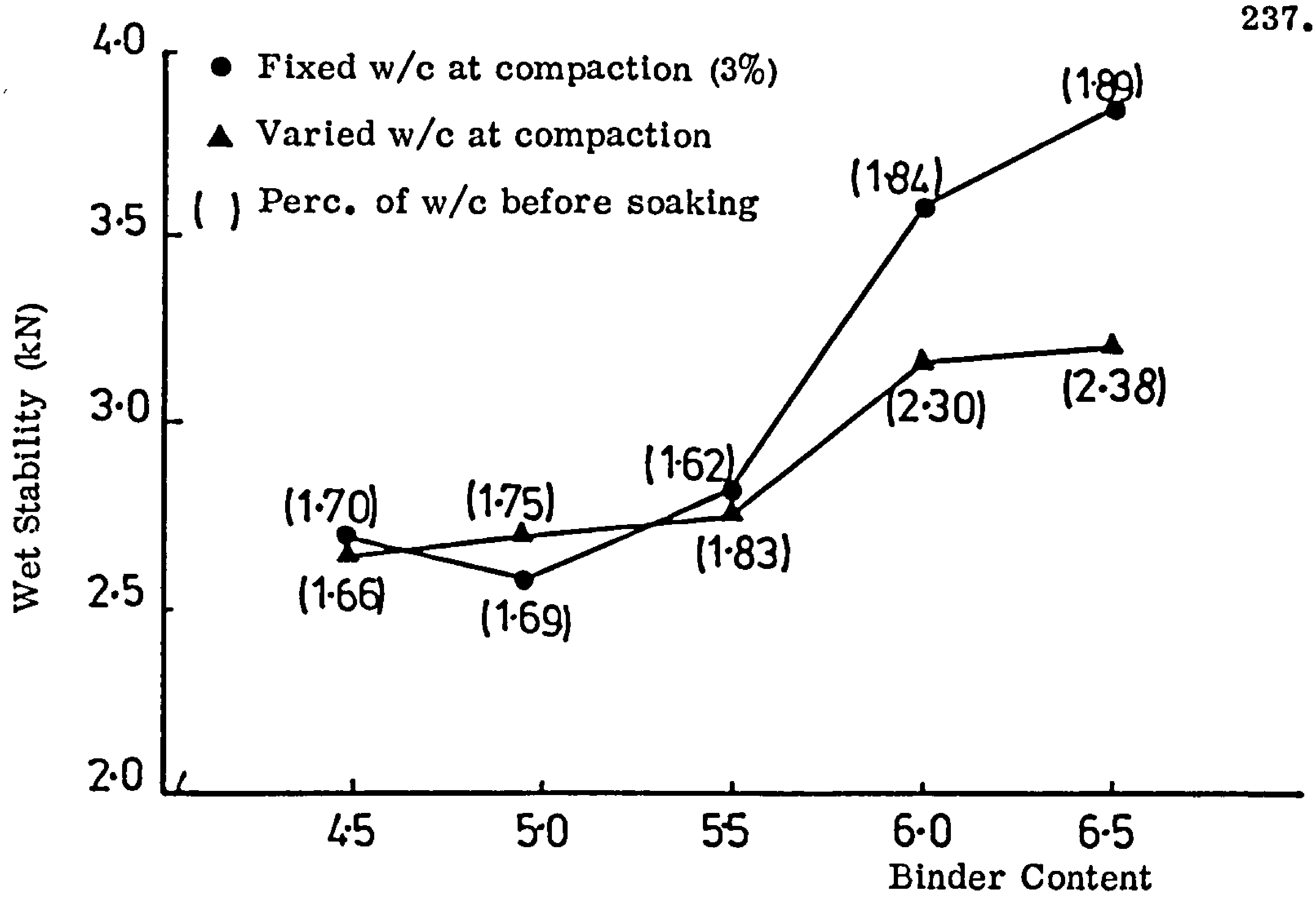


Fig. 9.36 WET STABILITY AFTER ONE DAY CURING

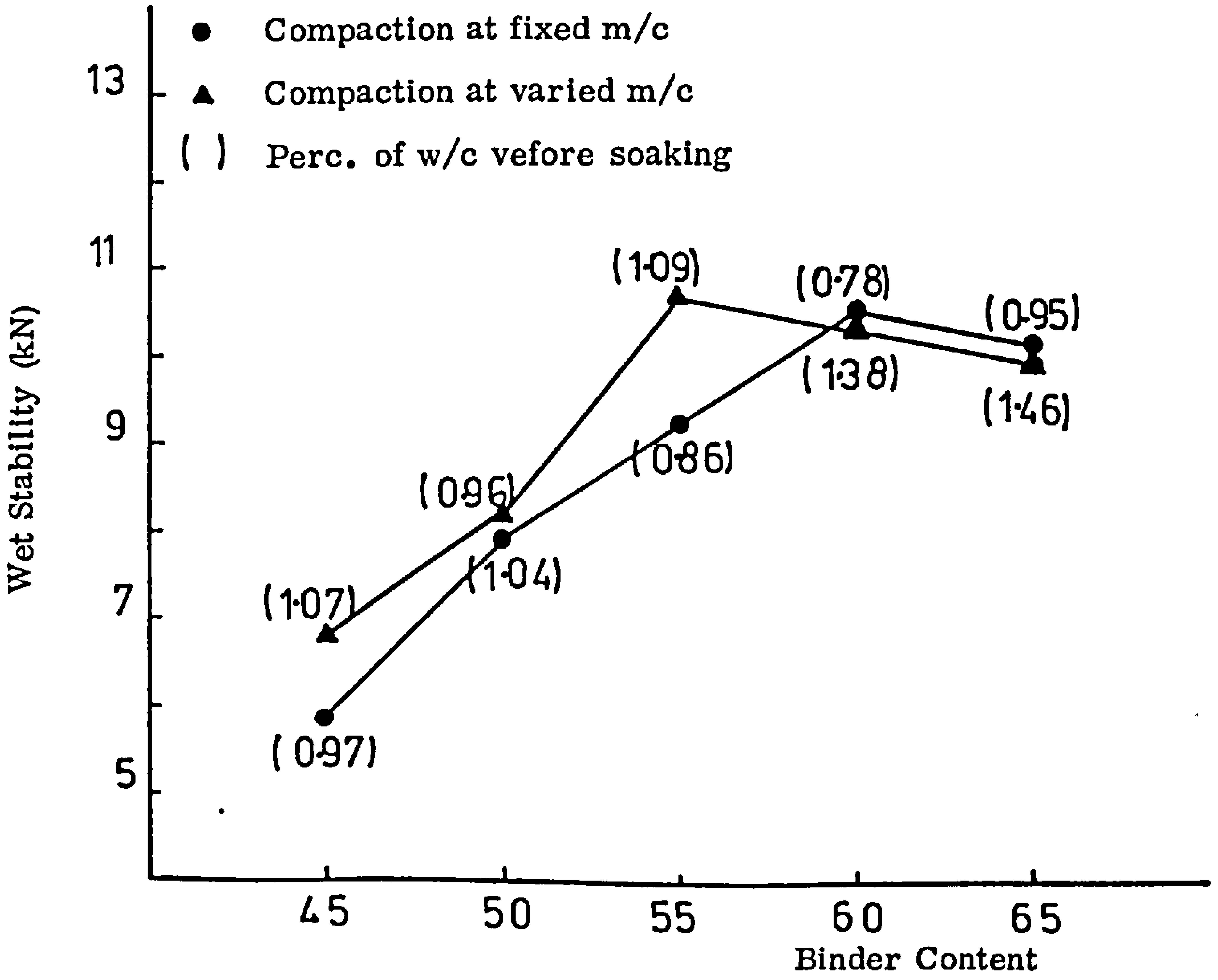


Fig. 9.37 WET STABILITY AFTER FINAL CURING

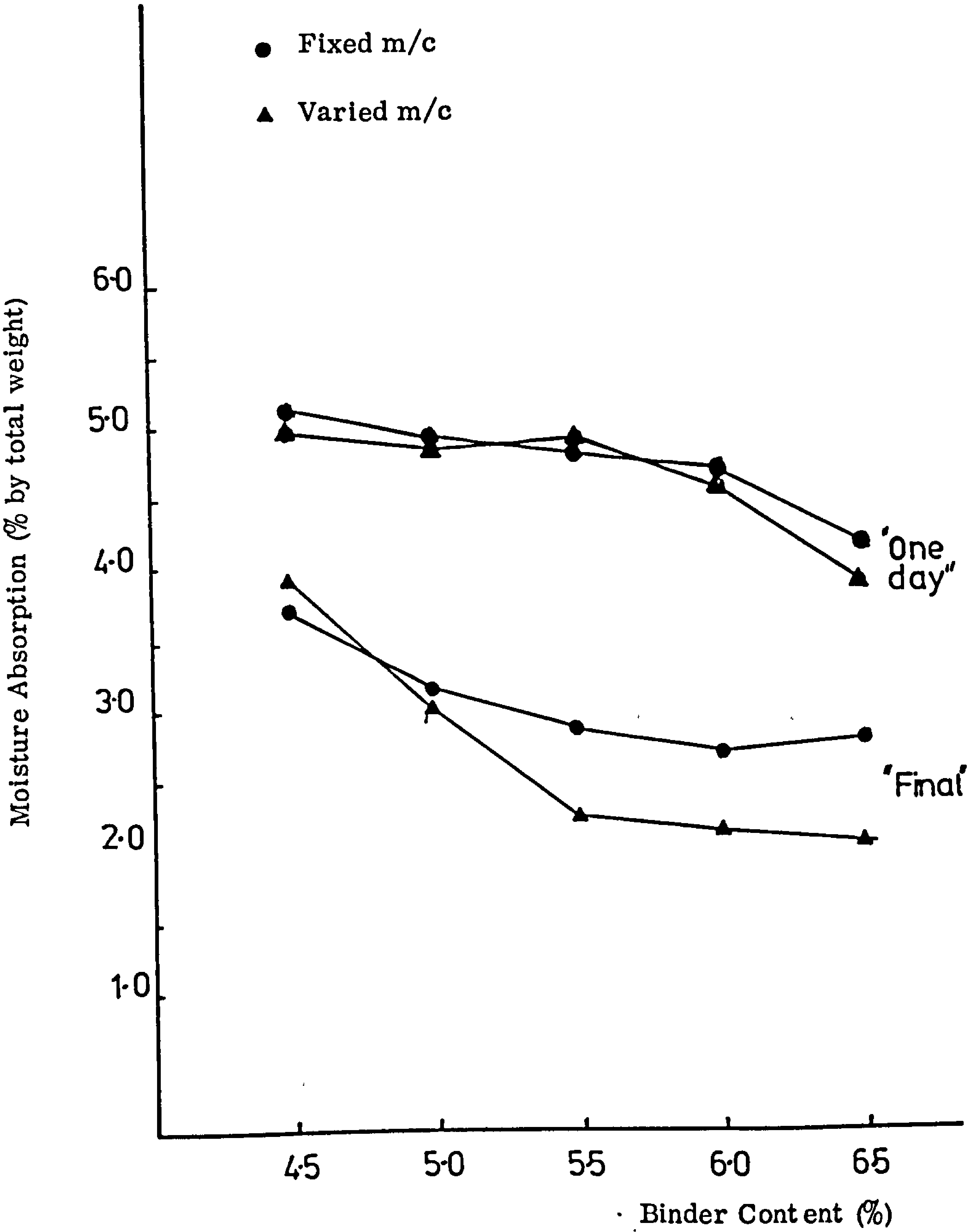


Fig. 9.38 MOISTURE ABSORPTION vs BINDER CONTENT FOR MIXTURES COMPACTED AT FIXED AND VARIED MOISTURE CONTENTS

(Two curing conditions)

is of a great advantage and makes the D.E.Mc mixtures very versatile.

9.4. Determination of the optimum binder content and added water of the D.E.Mc mixtures

The analysis of the results has shown that the binder content does not affect the majority of the physical properties of the D.E.Mc mixtures. This is believed to be due to the nature of the mixtures i.e. due to the continuous gradation of the aggregates resulting in the mechanical interlocking of the aggregates. Out of all the possible relations for the determination of the optimum binder content only one could be used. This is the wet stability (after final curing) versus binder content curve, Figure 9.37. This curve showed a distinct peak at a certain binder content, depending on the initial percentage of added water. It can therefore be used for the determination of optimum binder content as well as optimum percentage of added water.

An estimation, however, of the optimum values of the two parameters i.e. binder and added water, may be obtained from the slope of the compaction curves versus total liquid content curve, provided that compaction takes place at varied moisture contents. These optimum values should only be treated as estimates because they are based on the effective compaction, and the optimum binder content and added water for effective compaction may not be necessary optimum values for maximum stability. As an example, the optimum liquid content from Figure 9.34 was 10.8 which corresponds to approximately 6.5% or 5.5% binder content depending on the amount of initial added water used. In comparison the optimum binder content from the wet stability curve was found to be 6.0% with 2% added water.

It can therefore be concluded that the optimum binder content and optimum percentage of added water for D.E.Mc mixtures can be determined exclusively from the wet stability vs binder content curve, after final curing. However, the optimum binder content may be estimated from the slope of the compaction curves vs binder content curve, provided that compaction takes place immediately after mixing. It must be emphasised that the properties of the final mixture must be checked to see whether they satisfy a certain limiting criteria, based on field experience.

9.9 Comparison between D.E.Mc and C.R.A. mixtures

The two emulsion treated mixtures examined in this study represent the two most widely used bituminous mixtures in the UK, the Macadam coated and the Rolled Asphalt mixtures. Their aggregate gradations are entirely different and hence their behaviour and properties were found to be different.

The D.E.Mc, due to small amount of fine aggregate in the matrix required less binder content for maximum stability than C.R.A., i.e. 6% instead of 9.2%, by weight of dry aggregate. The stability values, however, of the C.R.A. were much higher than D.E.Mc at any curing stage. Table 9.7 shows some of the properties of the two mixtures, and the limiting criteria proposed by the Asphalt Institute for emulsion treated mixtures.

The most distinct difference between the two mixtures is the amount of total voids. D. E.Mc mixtures possess very high volume of voids compared to C.R.A.mixture, which allow them to be compacted immediately after compaction. For C.R.A. mixtures, however, any moisture content greater than 3.0% could not be accommodated and due to the fact that moisture content at mixing was much higher than 3% aeration of the mixtures was necessary. The fact that D.E.Mc can be compacted immediately after mixing, is a great advantage despite the fact that there is a small reduction of the stability.

Comparing the slopes of the compaction curves, when compaction took place at 21°C and at a fixed moisture content, it was found that the

Mixture Properties	D.E.Mc		C.R.A.		Limiting (*) criteria proposed by the Asphalt Institute (49)
	Early stage of curing	Final stage of curing	Early stage of curing	Final stage of curing	
Retained stability (%)	33.5	54.5	59.0	100.0	50 min
Modified (wet) stability (kN)	3.5	10.8	5.0	22.8	2.2 min
Total voids (%)	18.8	19.0	7.6	8.5	8.0 max
Moisture absorption (%)	4.5	2.5	2.8	0.9	4.0 max
Aggregate coating (%)	90-98	90-98	90-95	90-95	50 min

(*)Based on three days cured specimens in the laboratory (room temperature)

TABLE 9.7 COMPARISON BETWEEN D.E.Mc AND C.R.A. (D.E.Mc OBTAINED WITH 6% BINDER AND 2% INITIAL ADDED WATER, C.R.A. OBTAINED WITH 9.2% BINDER AND 3% ADDED WATER, ALL PERCENTAGES BY WEIGHT OF DRY AGGREGRATE) values for the D.E.Mc were on average ten times higher than the C.R.A. This indicates that under the above conditions D.E.Mc. will compact quicker than C.R.A.

Finally, when the optimum properties of the mixtures were compared with the limiting criteria proposed by the Asphalt Institute (49) it was found that only C.R.A. mixtures satisfied most of the criteria, even after one day of curing. This shows the superiority of C.R.A. over the D.E.Mc mixtures.

9.6 Conclusions

The study of the properties of Dense Emulsion Macadam (D.E.Mc) mixtures under the testing conditions and materials used revealed the following results:

1. The binder content has no significant effect on the bulk density and voids of the mineral aggregate, but it affects significantly any other property of the mixture.
2. The added water, which is associated with the degree of coating of the aggregates, affects all the properties of the mixtures apart from the flow. Marshall flow appears to be affected only by the binder content. The fact that the added water affects most of the mixture properties reveals that, greater emphasis should be given to this parameter. The limiting criteria of 50% minimum coating is too broad, since it has been demonstrated that significant changes can be obtained within the narrow margin of 90 to 98 percent coating.
3. From the results it is suggested that the optimum binder content should be obtained from the wet stability vs binder content curve, after final curing.
4. The retained stability after one day of curing i.e. at the early curing stage, is affected mainly by the amount of added water and the binder content.

5. When compaction takes place at higher than 3% water content i.e. immediately after mixing, the wet stability at the early stage of curing slightly deteriorates despite the improvement in bulk density and reduction of the volume of voids.
6. There are distinct differences between the properties of D.E.Mc and C.R.A., these are:

   D.E.Mc possess higher voids, lower wet stability, absorb more water during capillary soaking and the retained stability is comparatively low even after final curing.

   D.E.Mc, however, require less binder content than C.R.A. for optimum performance, they compact easier than C.R.A. at 21°C and they can be compacted immediately after mixing.

CHAPTER TEN

PERMANENT DEFORMATION CHARACTERISTICS OF COLD ROLLED ASPHALT (C.R.A.) AND DENSE EMULSION MACADAM (DEMc) MIXTURES

10.1 Introduction

Although rutting failure is the most common type of pavement failure in most European countries (116, 117, 118),existing mixture design methods for emulsified bituminous mixtures are based on the determination of the proportions of the constituents of the mixture, mainly by attainment of a minimum value of stability, but no consideration is given to the long term permanent deformation performance of the mixture.

The resistance to permanent deformation of emulsion treated mixtures, like any other bituminous mixtures, is affected by the type of binder and aggregate, the type of aggregate gradation and the type and level of compaction. Emulsion treated mixtures develop their strength with time and therefore it is logical to assume that their resistance to deformation is also affected by the time of curing.

This chapter examines the effect of curing time, binder content, degree of coating and compaction, on the resistance to permanent deformation of gap graded (C.R.A.) and continuously graded (D.E.Mc) emulsion treated mixtures.

The assessment of resistance to deformation was carried out by the static creep test and the analysis of data was assisted by the analysis of variance method.

Correlation between the creep and Marshall test is also presented.

10.2 The effect of mix composition on the permanent deformation of bituminous mixtures

The factors which significantly affect the permanent deformation of any bituminous mixture are the type and the gradation of the aggregates, the properties of the bitumen and the compaction of the mixture. Their degree of importance depends on the type of the mixture.

Gap graded mixtures derive their strength from the mortar rather than from the aggregate, and therefore the type of fine aggregates, filler and properties of the binder should influence more than anything else the resistance to permanent deformation. The strength of Macadam, on the other hand, is derived from the mechanical interlocking of the aggregate matrix and since better strength is obtained by better compaction (205, 206), the degree of compaction should be a predominant factor on the resistance to deformation.

The strength or stiffness of the mortar of gap graded mixtures, can be improved by selecting the correct fine aggregate and/or improving the rheological properties of the binder. It is difficult to ascertain which of the above factors is more important, the decision as to which of these factors should be considered for improvement of the stiffness of a mix should be made on economical and practical considerations.

Brien (195) found that resistance to deformation of gap graded mixtures, improved as the dry viscosity of the sand increased. Dry viscosity of sand is associated with the shape and surface texture of the sand particles. Jacobs (199) showed that mixtures with angular and rough textured surface fine aggregates (crushed rock sands) possessed higher resistance to deformation than mixtures with smooth and round particles (natural sand). He pointed out, that the improvement in resistance to deformation was obtained at the expense of flexibility and workability.

The presence of filler also affects the stiffness of the mixture since it effects the stiffness of the binder. Work carried out by Brien (196) showed that mixtures with a high filler content possessed greater stiffness and therefore showed less deformation than mixtures with a low percentage of filler. Szatkowski and Jacobs (200) concluded that increasing the filler content reduces the rate of tracking, providing that the binder content is equal to or less than the optimum binder content. Above optimum binder content an increase in filler content does not have any effect on rate of tracking because the mixture is more sensitive to increases in binder content.

In the case of emulsified bituminous gap graded mixtures, irregular and surface active filler, (limestone, Portland cement or P.F.A.) will affect not only the stiffness of the binder and (hence the stiffness of the mixture), but they will also act as cementitious agents in the presence of free water, which will contribute further to the resistance to deformation.

Cabrera (201) has shown that the susceptibility of hot Rolled asphalt mixes to changes in loading time is reduced by the use of fillers consisting of pulverized fuel ash. Barker (88), Hassan (81) and Lam (202) also examined the effect of Pulverised Fuel Ash (P.F.A.) on the deformability of the gap graded mixtures and found that when mixtures are mixed and compacted at lower than the recommended temperatures, the mixtures with P.F.A. filler have better resistance to deformation. This was primarily due to better compaction obtained.for P.F.A. filler mixtures than limestone filler mixtures, at the lower than recommended mixing and compaction temperature.

The effect of binder, the third component of the mortar, on permanent deformation has been examined by Jacobs (203) and Brien (196) and it was found that the use of harder binders, with higher Penetration Index (PI) reduces the rate of tracking. Since good correlation was found between softening point, penetration index and rut depth, it was shown that an increase of about 11°C in softening point reduces the rate of tracking by a factor of two,at 45°C. Similarly, an increase in P.I. from -0.5 to +2 reduced the relative strain and hence the rate of deformation by 50% (relative deformation measured at 40°C).

The rate of deformation of a gap graded mixture is affected by the stone content only when the percentage of stone is lower than 30% or higher than 60%. In both cases the rate of deformation is increased (195, 196, 199).

The degree and type of compaction, together with the type of coarse aggregate, are the primary factors which affect the deformation of continuously graded Macadams (205, 206, 207, 208). Leech and Selves (205) have shown that gravel bituminous mixtures had less deformation resistance than crushed rock or slag aggregate mixtures. They also found that increasing the compacting effort from 3 roller passes to 25 roller passes decreased the deformation by approximately 43% (after 1000 repetitions of the tracking machine, and when granite was used as aggregate). The same authors, in an earlier paper, (208) reported that better compaction can be obtained by the modified rolling procedure. This uses the ordinary 3 wheel roller with a tandem roller, for compaction of the edges of the pavement. Modified compaction was reported to increase compaction by 3%, which allowed an 8% reduction in design thickness.

Jacobs (209) found that although the resistance to deformation measured by wheel-tracking test (45°C) increased with increasing compaction, the effect on gap-graded mixtures was less marked than with the continuously graded mixtures, particularly at high degree of compaction. Deformation of the continuously graded mixtures increased at a high degree of compaction due to "over-roll" effect.

Finally, the method of compaction can also affect the permanent deformation and a comprehensive study carried out by Hill (141) showed that laboratory rolling compaction gave the lowest stiffness modulus, and hence higher deformation, than any other type of compaction. The highest stiffness moduli was obtained by the gyratory compactor. However, it has been suggested (148) that the method of compaction may not be important if the object is merely to rank a set of mixtures.

Emulsified bituminous mixtures do not develop their strength immediately after compaction but gradually, depending of the rate of breaking of the emulsion. It is therefore necessary to know the factors which influence the creep behaviour of the mixtures at every stage of curing. The factors considered in the subsequent sections are the binder content, the degree of coating, the curing time and in the case of gap graded mixtures, the temperature at compaction.

10.3 Design of the experiment

The study of the factors affecting the permanent deformation of gap graded and continuously graded emulsion treated mixtures was carried out by the factorial design shown in Table 10.1.

The materials used and the procedure for the preparation of specimens for the study of deformation were identical to the ones described in previous chapters. Since the best results were obtained with the specimens containing 3% water content at compaction, the study of deformation was entirely carried out with specimens at this condition.

The evaluation and ranking of the mixtures in terms of resistance to permanent deformation was carried out using the static creep test. The apparatus used was the newly designed CANIK UL creep test

Type of Mixture	Curing Time	Testing Conditions	Binder Content (%)	Added Water 3.0%	 4.5%
C. R. A.	One day and final curing	Compaction Temp =21°C Testing Temp =40°C Stress = 0.1MN/m^2 Duration = 1h	7.0	⊗	x
			8.0	⊗	x
			9.0	⊗	x
			10.0	⊗	x
			11.0	⊗	x
			12.0	⊗	x
		Compaction Temp =40°C Testing Temp =40°C Stress = 0.1MN/m^2 Duration = 1h	7.0	⊗	-
			8.0	⊗	-
			9.0	⊗	-
			10.0	⊗	-
			11.0	⊗	-
			12.0	⊗	-
				2%	3%
D. E. M_c	One day and final curing	Compaction Temp = 21°C Testing Temp =40°C Stress = 0.1MN/m^2 Duration = 1h	4.5	⊗	x
			5.0	⊗	x
			5.5	⊗	x
			6.0	⊗	x
			6.5	⊗	x

x Mixtures tested after one day curing

⊗ Mixtures tested after one day and final curing

TABLE 10.1 FACTORIAL DESIGN FOR STUDYING THE RESISTANCE TO DEFORMATION OF THE EMULSION TREATED GAP GRADED AND CONTINUOUSLY GRADED MIXTURES apparatus and the testing conditions and procedure were similar to the ones arrived at the Symposium in plastic deformability of bituminous mixtures (210) i.e. stress = $0.1 MN/m^2$, temperature = 40^oC, time of duration of test = one hour. Details regarding the apparatus and the testing procedure has been given in Chapter 5.

The study of the effect of the parameters, listed in Table 10.1, on the resistance to deformation was based on the slopes obtained from the logarithmic relation between the stiffness values of the mixture, obtained from the creep test, and the stiffness values of the base bitumen, calculated from the Van der Poel nomograph (127), and the position of the curves with respect to Smix axis i.e. the value of the stiffness of the mixture. The stiffness of the mixtures was also compared at a certain loading time of 3600 sec as recommended in Ref. 151. The comparison between the creep and Marshall tests were made using values of Smix corresponding to Marshall test conditions i.e. Loading time 50.8 mm/min (approx. equal to 330 sec), temperature 21^oC. Under these conditions the value of Sbit is approximately equal to 5×10^3 N/m^2.

10.4 Statistical analysis of the results

The statistical analysis of the results was carried out by analysis of variance method (ANOVA), using a two way model. The mathematical model was as shown below:

$$Y_{ijk} = \mu + A_i + B_j + (A \times B)_{ij} + E_{jk} \qquad \ldots 10.1$$

where Y = the dependent factor

μ = the overall average

A = the effect of independent factor A at ith level

B = the effect of independent factor B at jth level

A x B = the joint influence of A and ith level and B at jth level (interaction effect)

Ejk = the random error

The dependent factor was chosen to be the slope of the creep curves log Smix vs log Sbit.

The independent factor A was always the binder content, hence, i = 1 to 6 for C.R.A. mixtures, or i = 1 to 5 for the D.E.Mc mixtures. The independent factor B was one of the following:

(i) B=added water, hence, j = 1, 2 for all mixtures, corresponding to 3% and 4.5% of added water for C.R.A. and 2% and 3% for D.E.Mc, or

(ii) B=curing time, j = 1, 2 for all mixtures corresponding to "one day" and "final" curing stage, or

(iii) B=compaction temperature, j = 1, 2, corresponding to 21°C and 40°C temperature at compaction.

The results of the statistical analysis have been summarised in Tables 10.2 and 10.9 and they will be discussed in the following section of the chapter.

10.5 Results and discussion

10.5.1. Creep behaviour of the emulsion treated mixtures

For all the design cells shown in Table 10.1 two specimens were tested, the average of which was used to plot all the subsequent creep curves. The measured cumulative deformation at various loading times was divided by the height of the specimen and the resulted strain was plotted against loading time. A representative set of curves, at various binder contents, is shown in Figures 10.1 and 10.2. It is apparent that the rate of creep strain decreases with time, for most of the mixtures. In some of the mixtures, the rate of strain suddenly increases, after a certain loading time, at which the specimen has reached a certain critical strain. The critical strain was reached only by rich bitumen mixtures.

COLD ROLLED ASPHALT MIXTURES (GAP GRADED)											
	The effect of added water and binder content			The effect of curing time and binder content				The effect of compaction temperature and binder content			
	Added Water (A/W)	Binder Content (B/C)	A/W + B/C	Curing Time (C/T)		Binder Content (B/C)	C/T + B/C	Compaction Temp. (C/Temp.)		Binder Content (B/C)	C/Temp. + B/C
Slope of stiffness curve	NS	S**	NS	21°	S*	S**	NS	one day	NS	S*	NS
				40°	S*	S**	NS	final	S**	S**	NS

NS = Not significant at 5% level of significance

S* = Significant at 5% level of significance

S** = Significant at 1% level of significance

TABLE 10.2 STATISTICAL ANALYSIS SUMMARY RESULTS FOR THE PERMANENT DEFORMATION OF C.R.A. MIXTURES

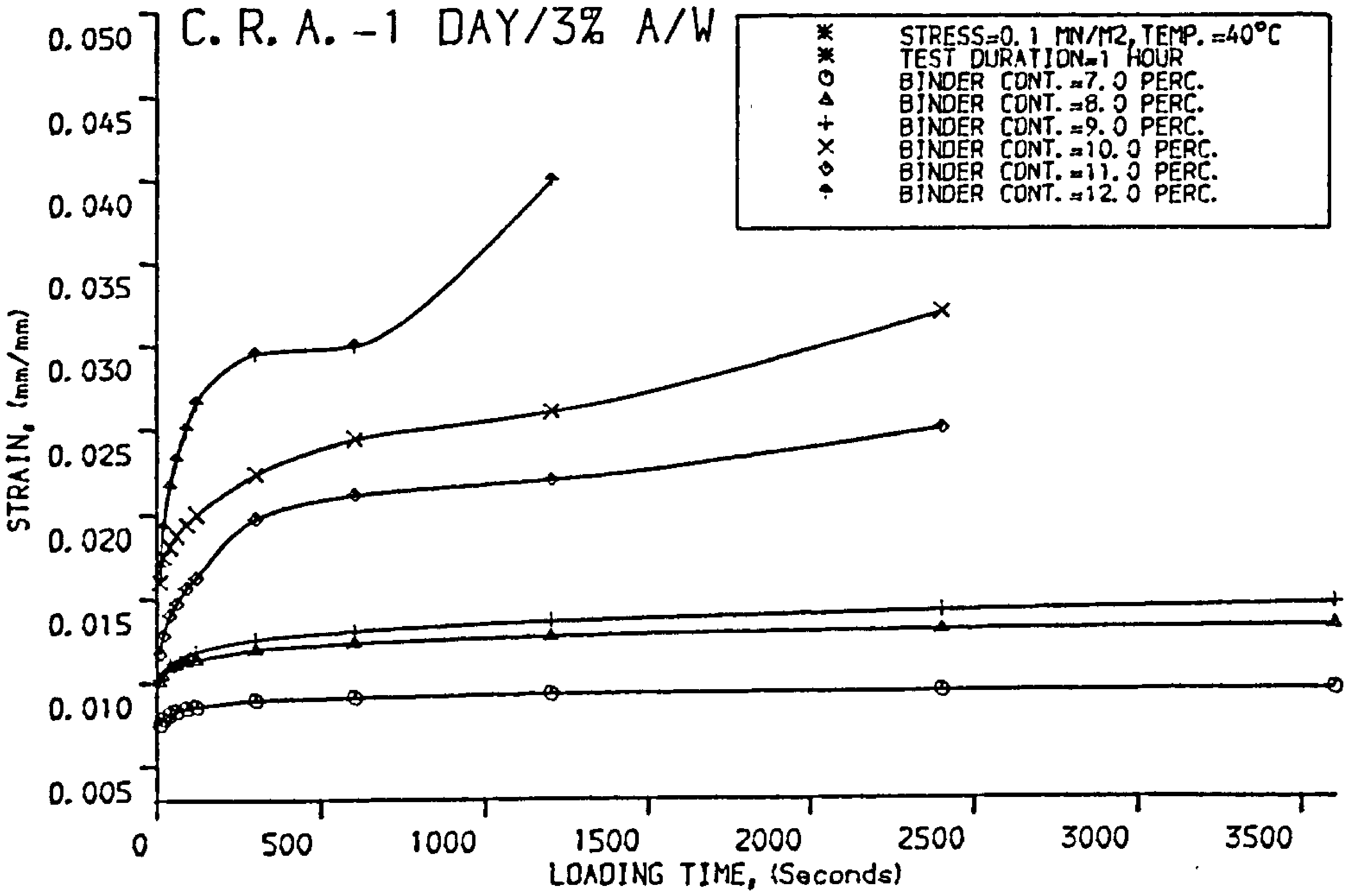


FIG. 10.1 STRAIN vs LOADING TIME

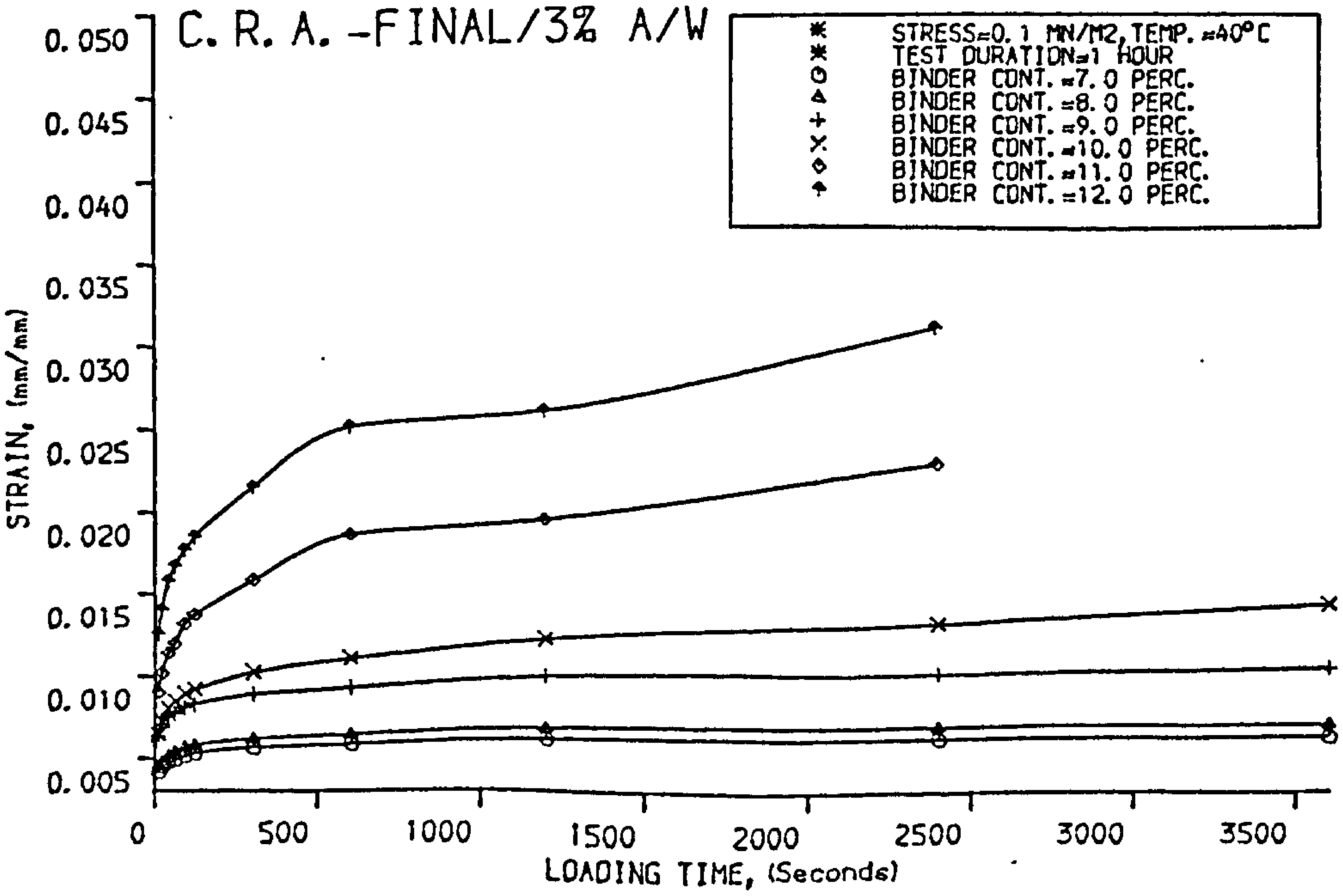


FIG. 10.2 STRAIN vs LOADING TIME

This reveals that critical strain, among other things, is also a function of binder content.

The mixtures arrival at the point of critical strain can be explained by considering the deformation model under static load, developed by Hills (141). In this model the creep deformation is only due to thinning of the binder film between aggregates i.e. shear strains in the bitumen. Under the constant compressive load the speed of relative displacement of a pair of aggregate particles depends on the thickness of the binder between them, and diminishes as the thickness of the binder decreases. The thinning of the binder film is not opposed by any hydrostatic pressure, provided that there is a sufficient amount of air voids. When the percentage of air voids drops below a certain level, the thinning of the binder film is opposed by hydrostatic pressures due to an excessive amount of binder in relation to voids content. The aggregate particles have to ride over one another in order to allow further deformation to take place, and this, due to non-confinement of the specimen, causes volumetric changes. The specimen is in a dilated "failed" state, a critical strain level has been reached after which the rate of strain starts to increase rapidly. The rate and level of strain is also a function of test temperature, stress level and stiffness of the bitumen.

Figures 10.1 and 10.2 show the cumulative strain of gap-graded emulsion treated mixtures, with respect to loading time, after one day of curing and final curing. It can be seen that rich mixtures i.e. with greater than 10% binder content, which are associated with low air voids reached the critical strain during the testing period. The percentage of air voids found to be on average 5%. This can therefore be considered as the minimum percentage of air voids below which C.R.A. mixtures with higher than 10% binder content will reach the state of critical strain during testing.

When considering the effect of hydrostatic pressures on the critical strain, the presence of free water content in the system should not be ignored. This on average was found to be 2% (by dry aggregate) for the "one day" cured mixtures and 1% for the "final" cured mixtures.

In the case of continuously graded mixtures (D.E.Mc) which are associated with a high voids content, the model is slightly different. Figure 10.3 shows that critical strain does occur in rich mixtures, after one day of curing, despite the high percentage of voids (approximately 18%). When the mixtures were cured for sufficient time until final breaking occured, no mixture, regardless of the binder content, reached the state of critical strain during the loading time i.e. one hour, Figure 10.4. Since all the other parameters affecting the deformation of the mixtures were kept constant, it is reasonable to assume that in the case of continuously graded emulsion treated mixtures the critical strain is mainly dependent on the internal stability of the mixtures. After one day of curing only part of the bitumen developed its properties and therefore the cohesive and adhesive forces between aggregates were weak. The introduction of more binder caused a greater retention of water in the system, which is mainly responsible for the final breaking of the emulsion, and hence it caused a further weakness of the cohesive and adhesive forces.

However, the strain vs loading time curve is not a convenient way of expressing the creep characteristics of a bituminous mixture, particularly when the permanent deformation is to be determined from these curves (145, 151). This is because of the large number of factors affecting the position and shape of these curves. It has been shown (141, 142) that most of the factors (i.e. testing conditions and rheological properties of the binder) are eliminated when the stiffness of the mix Smix (stress/strain) is plotted against the stiffness of the bitumen, Sbit, (calculated from the Van der Poel nomograph (127)). The shape and position of Smix vs Sbit curves, plotted on a double logarithmic scale depends now only on the composition of the mixture and its internal

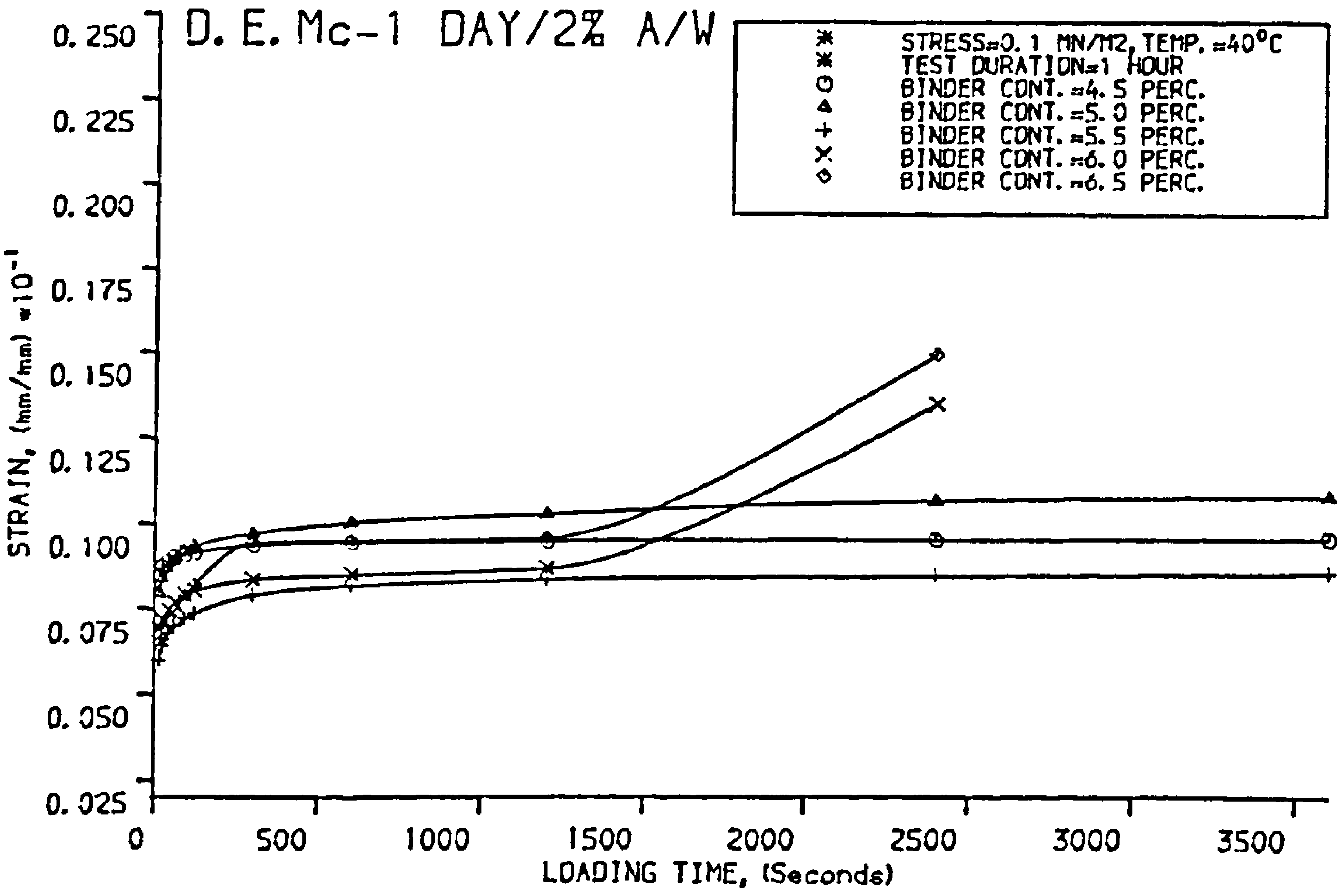


FIG. 10. 3 STRAIN vs LOADING TIME

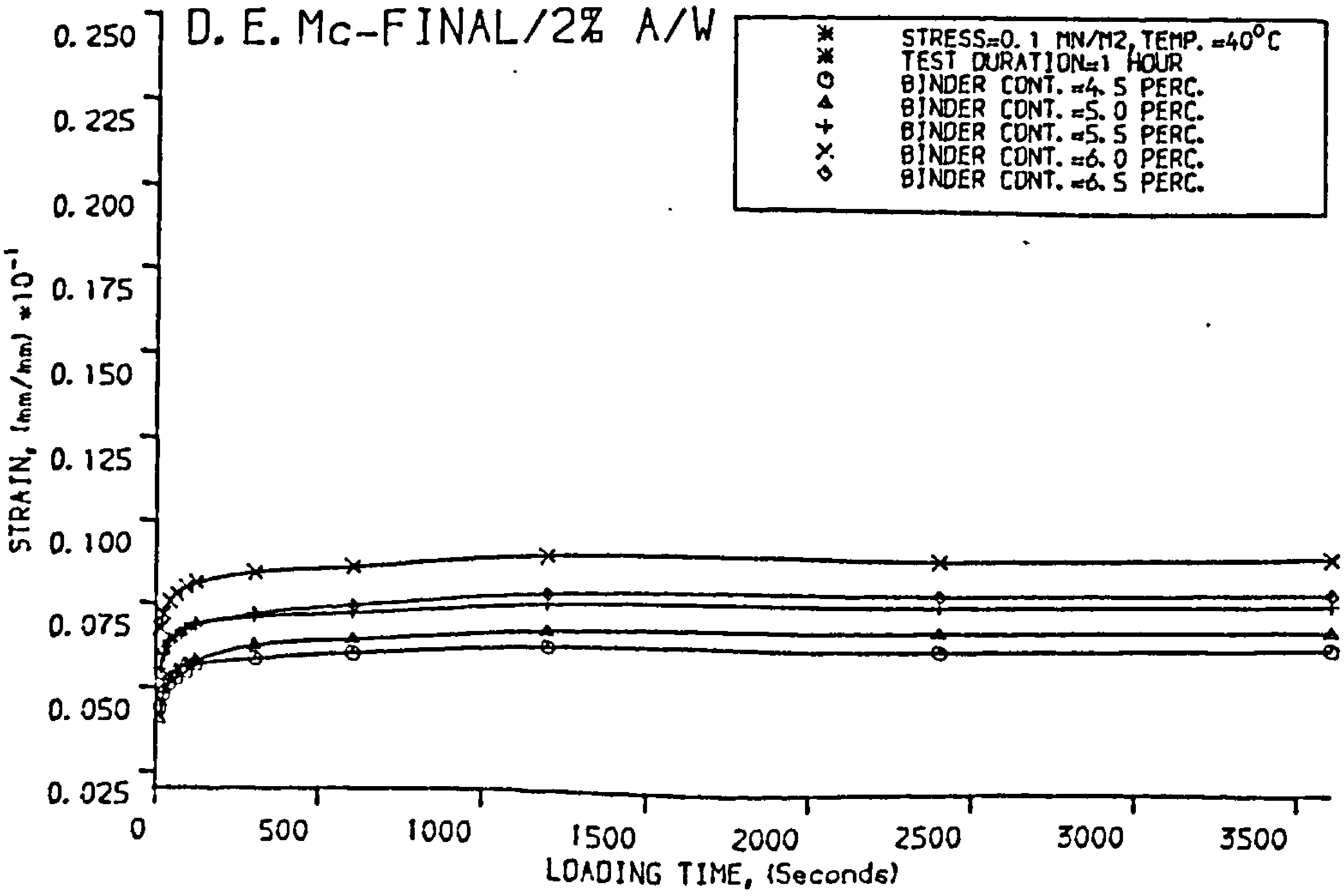


FIG. 10. 4 STRAIN vs LOADING TIME

properties.

The following discussion, therefore, will be based on the Smix vs Sbit curves drawn from the section of the curve where critical strain has not been reached. The evaluation of the repeatability of the creep test, however, will be based on the values of the stiffness of the mixture, calculated from the Smix vs loading time curve, at a loading time of 3600 sec, as suggested by de Hilster and Van de Loo (151). The formula used for the evaluation of the repeatability of the creep test carried out by the CANIK UL apparatus is as follows (151):

$$\text{Repeatability} = 1 + 2.77 \times \sqrt{(S_d/\bar{X})^2/N} \qquad \ldots\ 10.2$$

where S_d = Standard deviation
$\bar{X}$ = Mean value
N = Number of specimens

10.5.1.1. The effect of degree of coating and binder content on the permanent deformation of gap graded emulsion treated mixtures

The results of the creep deformation of Cold Rolled Asphalt (C.R.A.) mixtures, after one day of curing, have been tabulated in Tables 10.3 and 10.4. The average values of the stiffness of the two tested specimens (Smix) have been plotted against loading time (LT) and stiffness of the bitumen in a double logarithmic scale, and are shown in Figures 10.5 to 10.8. It can be seen that there is a good correlation between Smix vs LT and Smix vs Sbit when data were plotted in a double logarithmic scale. The equation therefore, of the lines has the form of:

$$\text{Log } Y = \log A \pm b \times \log X$$

or

$$Y = aX^{b}$$

C.R.A. MIXTURES ONE DAY CURING / COMPACTION AT 21°C								
Added water	Binder content	Smix vs Sbit [1]		Smix vs Load-time [1]		Smix at 3600 secs N/m^2	Standard deviation and Repeatability [2]	Smix at Sbit = $5000 N/m^2$
(%)	(%)	Slope "b" ($x10^{-1}$)	Const. coeff "a" ($x10^7$)	Slope "b" ($x10^{-1}$)	Const. coeff "a" ($x10^7$)	($x10^6$)		($x10^6$)
3%	7	0.432	0.886	-0.391	1.350	9.80	±0.813	12.80
		0.469	0.981	-0.424	1.550	10.95	1.15	14.63
	8	0.421	0.686	-0.381	1.030	7.54	±0.11	9.82
		0.655	0.633	-0.592	1.200	7.39	1.03	11.17
	9	0.514	0.639	-0.464	1.050	7.18	±0.45	9.90
		0.851	0.535	-0.770	1.230	6.55	1.13	11.04
	10_{F*}	0.938	0.282	-0.850	0.70	3.50	±0.0	6.27
		1.310	0.257	-1.180	0.92	3.50	1.0	7.84
	11_{F*}	1.810	0.238	-1.640	1.390	3.63	±0.01	11.12
		1.490	0.257	-1.350	1.100	3.64	1.0	9.14
	12_{F*}	1.910	0.138	-1.710	0.880	2.17	±0.0	7.02
		1.87	0.139	-1.671	0.851	2.17	1.0	6.83
4.5%	7	0.839	1.20	-0.763	2.720	14.56	±0.37	24.52
		0.585	1.23	-0.532	2.170	14.04	1.05	20.24
	8	0.911	0.801	-0.828	1.950	9.90	±1.19	17.40
		0.837	0.954	-0.761	2.160	11.58	1.22	19.46
	9	0.947	0.733	-0.865	1.850	9.11	±0.30	16.42
		1.090	0.740	-0.994	2.150	9.53	1.06	18.72
	10	1.250	0.643	-1.140	2.190	8.61	±0.44	18.65
		1.790	0.527	-1.620	3.010	7.99	1.10	24.21
	11_{F*}	1.390	0.468	-1.250	1.810	6.50	±0.14	15.29
		1.540	0.437	-1.380	1.950	6.30	1.12	16.22
	12_{F*}	1.680	0.349	-1.530	1.800	5.14	±0.11	14.60
		1.560	0.331	-1.400	1.510	4.98	1.04	12.50

1 = Equation of the form of $Y = a \times X^b$

2 = Repeatability = $1 + 2.77 \times \sqrt{(S_d/\bar{X})^2/N}$
where S_d = standard deviation
$\bar{X}$ = mean value
N = No. of observations

F*= Specimens reached the "critical" strain after approx 20 min

TABLE 10.3 CREEP RESULTS OF C.R.A. MIXTURES AFTER ONE DAY OF CURING (STRESS = $0.1 MN/m^2$, TEMP = 40°C, LOADING TIME = 1h)

C.R.A. FINAL CURING / COMPACTION AT 21°C

Added Water (%)	Binder Content (%)	Smix vs Sbit[1]		Smix vs Load-time[1]		Smix at 3600 secs N/m^2 $(x10^6)$	Standard deviation and Repeatability[2]	Smix at Sbit = $5000N/m^2$ $(x10^6)$
		Slope "b" $(x10^{-1})$	Const. coeft. "a" $(x10^7)$	Slope "b" $(x10^{-1})$	Constant coeff. "a" $(x10^7)$			
3%	7	0.818	1.180	-0.741	2.630	14.32	±1.79	23.68
		0.714	1.430	-0.646	2.860	16.85	1.22	26.27
	8	0.816	1.080	-0.740	2.380	12.98	±1.15	21.64
		0.950	1.170	-0.863	2.960	14.60	1.16	26.28
	9	0.990	0.718	-0.897	1.890	9.07	±0.42	16.68
		0.831	0.757	-0.752	1.790	9.67	1.09	15.35
	10	1.61	0.411	-1.460	1.970	5.96	±1.80	16.19
		1.23	0.639	-1.120	2.130	8.51	1.49	18.22
	11_F	2.11	0.205	-1.900	1.600	3.38	±1.06	12.37
		1.74	0.325	-1.580	1.780	4.88	1.50	14.31
	12_F	1.97	0.149	-1.790	1.030	2.38	±1.27	7.98
		1.61	0.287	-1.460	1.380	4.17	1.76	11.31

1 = Equation of the form of $Y = a \times X^b$

2 = Repeatability = $1 + 2.77 \times \sqrt{(S_d / \bar{X})^2 / N}$

where S_d = standard deviation
$\bar{X}$ = mean value
N = No of observations

F = Specimens reached the "critical" strain after approx 20 min.

TABLE 10.4 CREEP RESULTS OF C.R.A. MIXTURES AFTER FINAL CURING (STRESS = 0.1 MN/m^2, TEMP = 40°C, LOADING TIME = 1h) where a = the interception of the line with the Y-axis (Smix)

b = the slope of the line

Y = stiffness of the mixture (N/m^2)

X = either loading time (sec) or stiffness of the bitumen (N/m^2)

The two coefficients "a" and "b" are very important because they fully represent the mixture in terms of deformation performance. The constant "a" gives an indication of the stiffness of the mixture and the slope "b" indicates the sensitivity of the mixture to loading time or stiffness of the bitumen. It is apparent that the best mixture is the one with a high value "a" and low slope "b".

It can be seen, Figures 10.7 and 10.8 that for both types of mixture, the stiffness of the mixture decreases as the binder content increases and that the slope of the creep line increases as the bitumen content increases. Statistical analysis has shown, Table 10.2, that the change in slope due to binder content increase is highly significant (1% level of significance). This suggests that better resistance to deformation will be provided by the mixture with the least amount of binder.

A closer examination on the changes in the slope of the creep curves with respect to binder content revealed, Figure 10.9, that there was an exponential relationship between the two factors. This suggests that the effect of binder content is more pronounced at high contents than low ones. This is very important, because if it also holds for the "final" cured mixtures an optimum binder content may be determined from the sudden change of slope.

The effect of degree of coating can be seen by comparing the results shown in Figures 10.7 and 10.8. It is apparent that the slope increased slightly when more water (4.5%) was added to the aggregates, but this increase was not found to be statistically significant, at 5% level. There is, however, an increase in the stiffness of the mixture, which

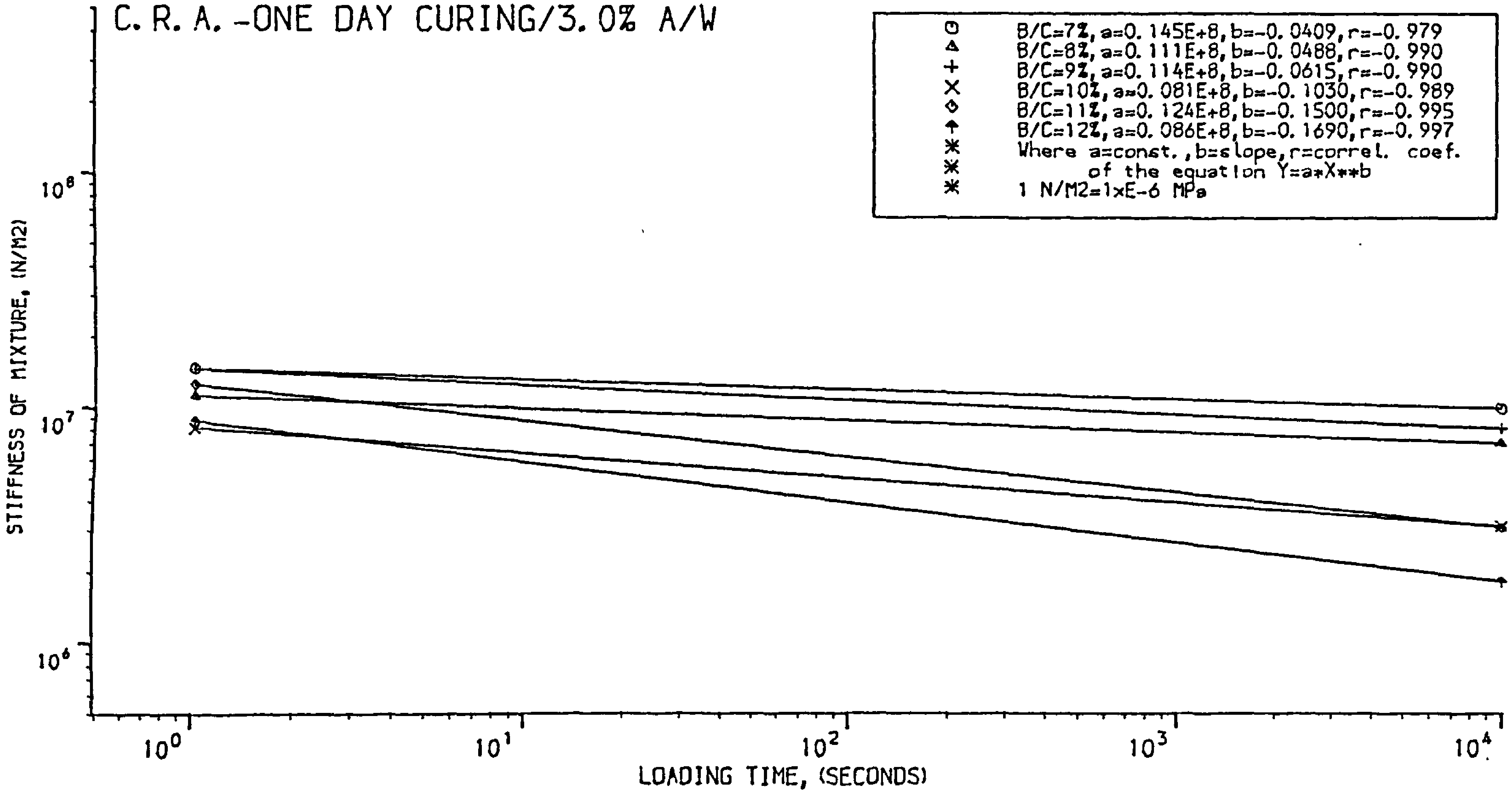


Fig. 10.5 STIFFNESS OF C.R.A. vs LOADING TIME

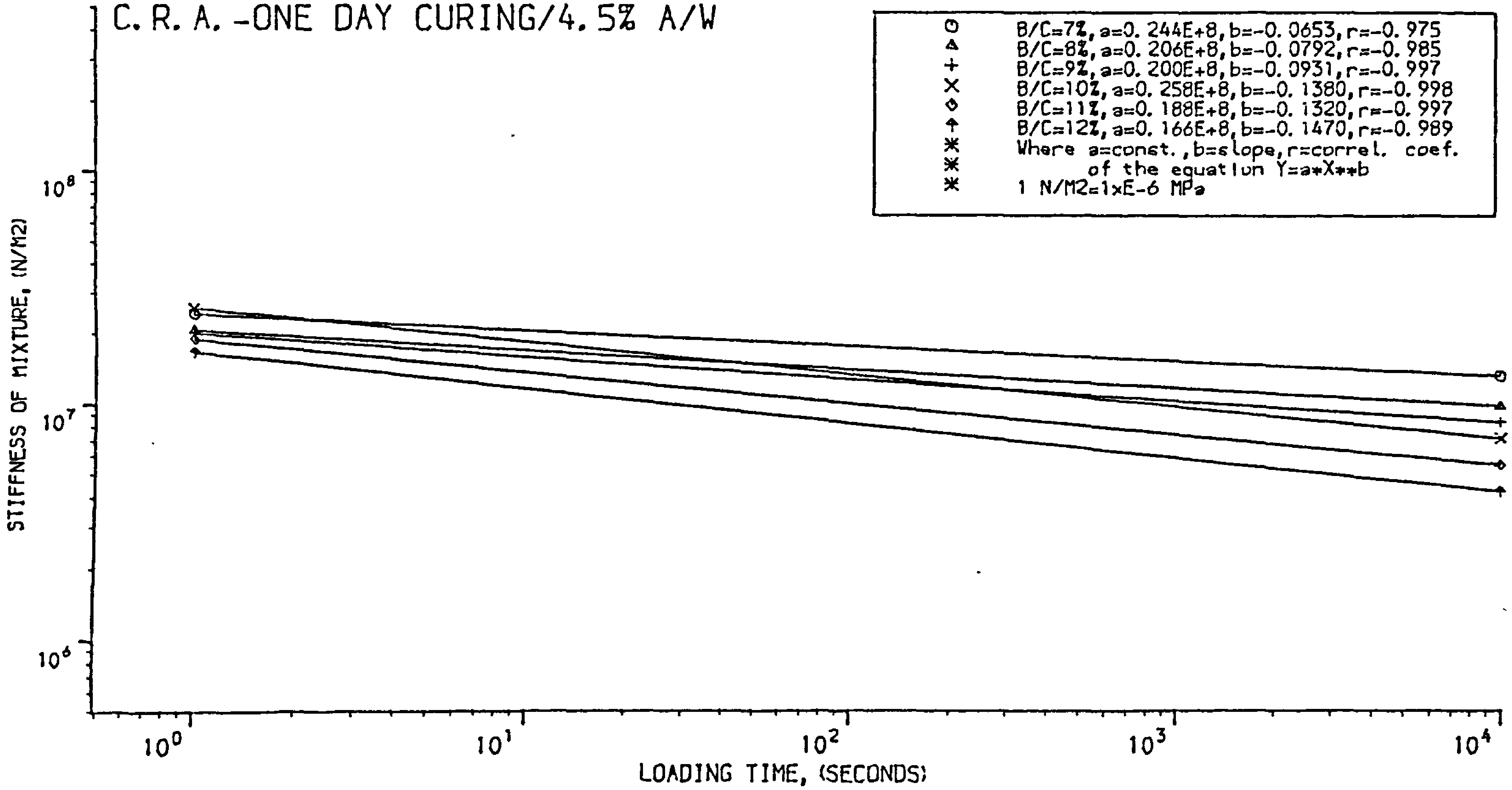


Fig. 10. 6 STIFFNESS OF C. R. A. vs LOADING TIME

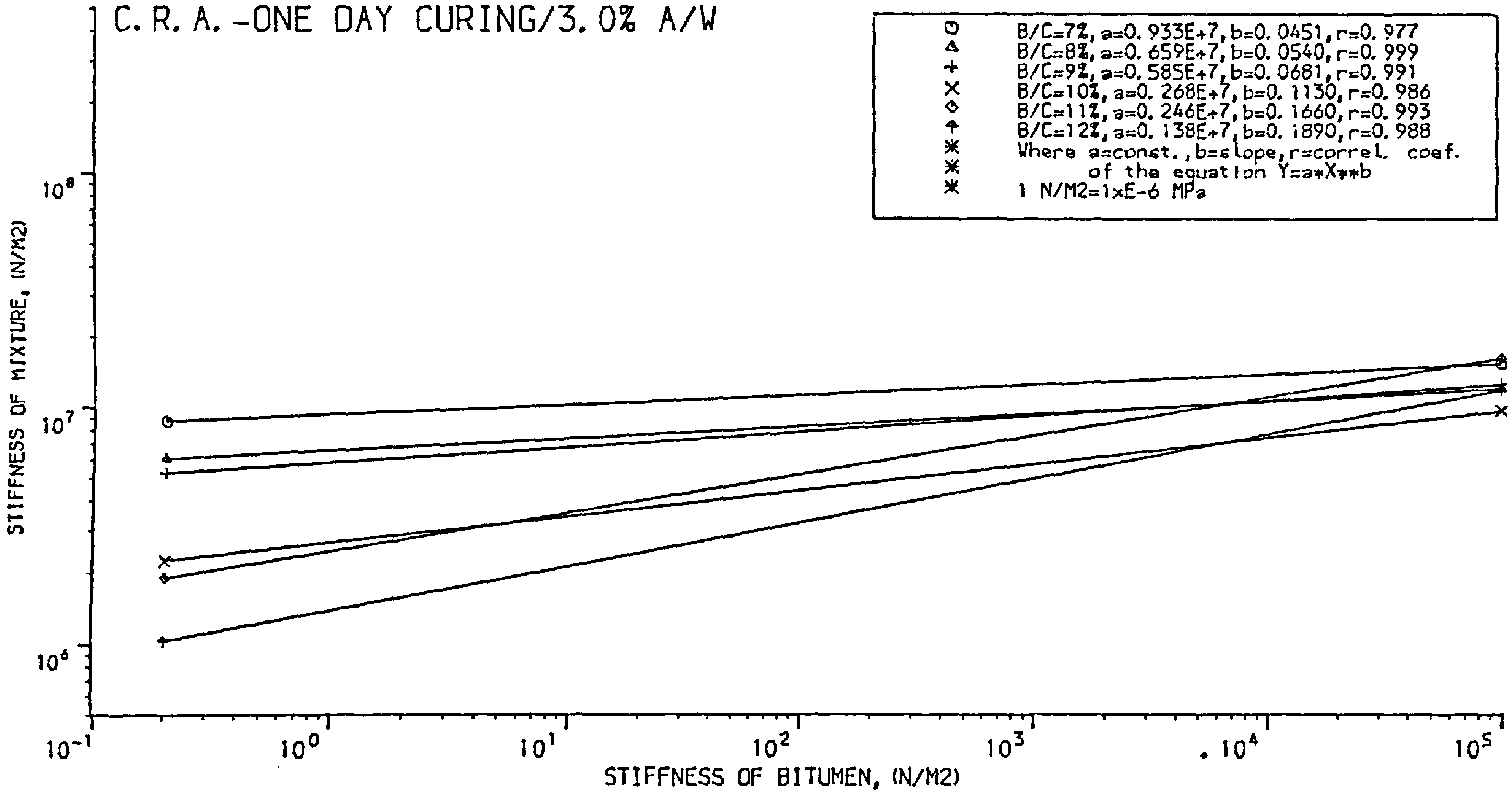


Fig. 10.7 STIFFNESS OF C.R.A. vs STIFFNESS OF BITUMEN

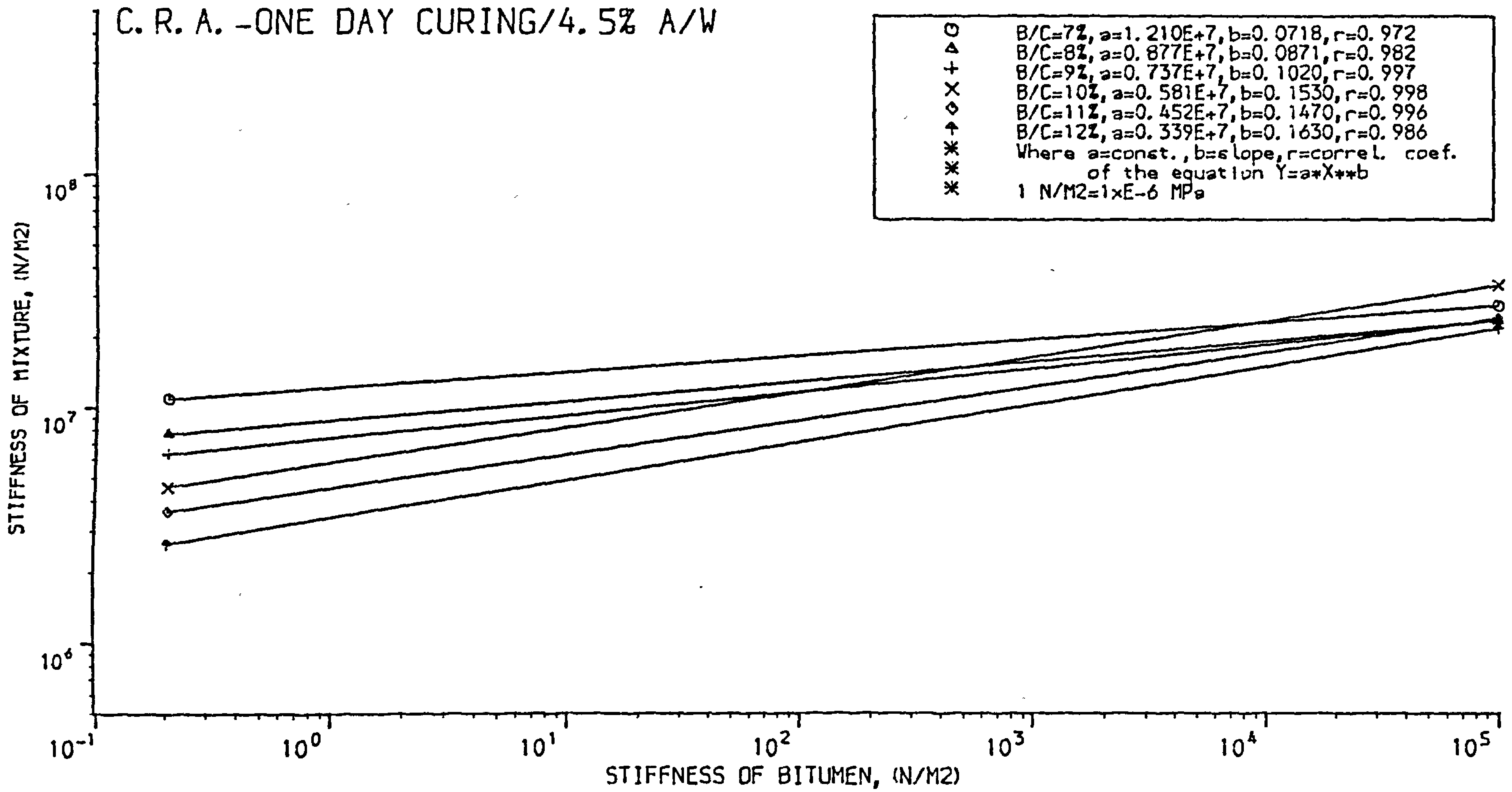


Fig. 10. 8 STIFFNESS OF C. R. A. vs STIFFNESS OF BITUMEN

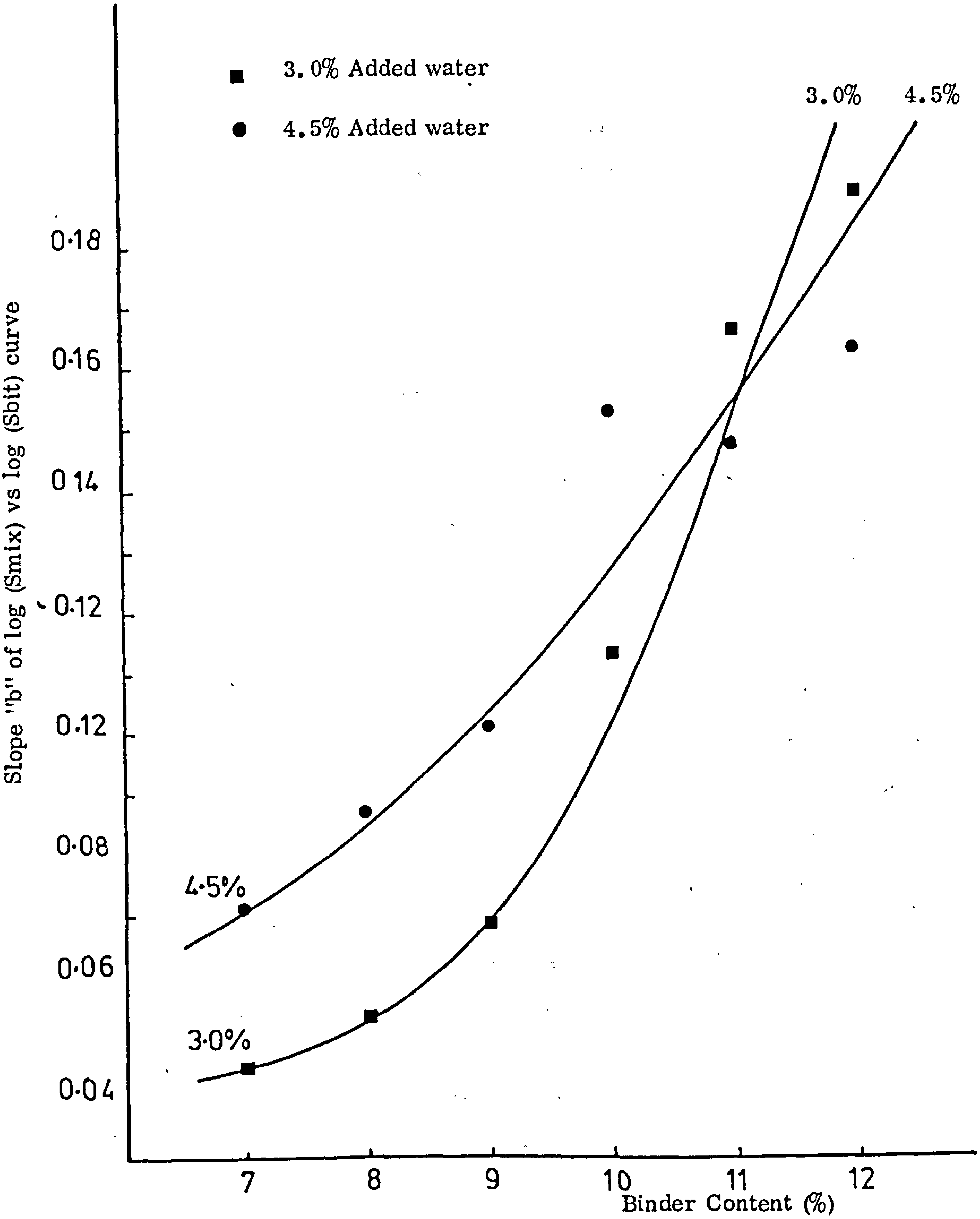


Fig. 10.9 THE EFFECT OF BINDER CONTENT ON THE SLOPE OF LOG (Smix) vs LOG (Sbit) CURVE.

may be attributed to the better distribution of binder.

The above findings revealed that, primarily, the creep deformation was affected by the binder content. The better coating does not affect the sensitivity of the mixture in terms of Sbit but it may result in better Smix values, due to the better distribution of binder.

The repeatability of the creep results was also checked using the formula 10.2, where the values of Smix were calculated at a loading time of 3600 sec, as recommended by de Hilster and Van de Loo (151). It was found (see Table 10.3 col.8) that a good repeatability of results was obtained at all levels of binder content. The repeatability values varied from 1.0 to 1.22. It must be noted that there was no indication at this stage, that deterioration of repeatability was related to binder content.

In comparison to the repeatability values obtained in this study, de Hilster and Van de Loo (151) have reported repeatability values of 1.23 to 1.35 depending on the type of mixture and type of apparatus. The lowest reported value of 1.23 was obtained from sand sheet bituminous mixture and using the Wykeham Farrance creep apparatus. Sand-bitumen mixtures using the CANIK UL apparatus were found to have repeatability values of 1.07 (see Chapter 5). The above suggests that the repeatability of the CANIK UL apparatus is good even when gap graded emulsion treated mixtures are used. The fact that better repeatability values were obtained with sand-bitumen mixtures is chiefly due to the homogenity of the mixtures.

10.5.1.2. The effect of curing time

The compacted specimens were cured for five days in the air and two days in the oven, and then tested for creep. During this curing procedure, final breaking of the emulsion was assumed to have taken place and therefore the binder to have completely developed its properties.

The results of the creep tests after "final" curing are shown in Table 10.4 and the creep curves are shown in Figures 10.10 and 10.11. Examining Figure 10.10 it is apparent that the effect of binder is similar to one-day cured mixtures, i.e. the stiffness decreases and the slope increases as the binder content increases.

Comparing the slope values of the creep curves of the "final" cured and "one day"cured mixtures, it could be seen that the slope values of the former were greater than the slope values of the latter almost at all levels of binder content. Statistical analysis has shown that the change in slope due to curing is highly significant (1% level of significance).

Comparing the constant coefficient "a" values, it can be seen that "final" cured mixtures have greater "a" values than "one day" cured mixtures at all levels of binder content, which suggests that the stiffness of the former mixtures is higher than the latter. To quantify the increase in stiffness due to curing, the values of Smix at 3600 secs were compared and the results are shown in Table 10.5. It can be seen that an average increase of 57.1% in stiffness of the mixture resulted due to the finally cured mixture. This is attributed to the full development of the properties of the bitumen.

The repeatability values of creep results, (see Table 10.4, col.8) were found to be good up to a certain binder content. The repeatability of the results deterioriated at a high percentage of binder content. Since at this stage, the properties of the bitumen have been fully developed, it can be said, that the repeatability of the results among other things is a function of binder content and it deteriorates as the mixture becomes richer.

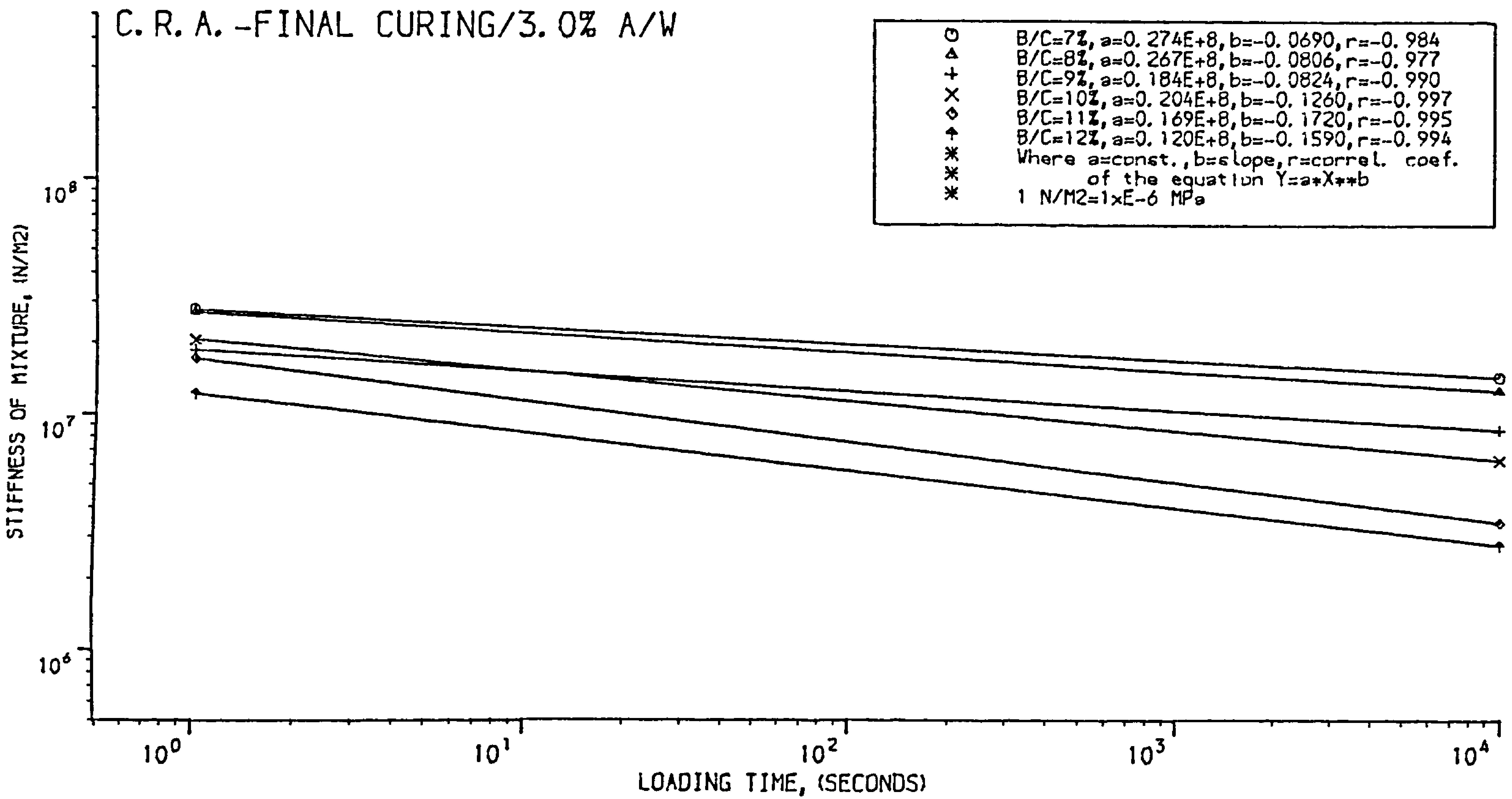


Fig. 10.10 STIFFNESS OF C.R.A. vs LOADING TIME

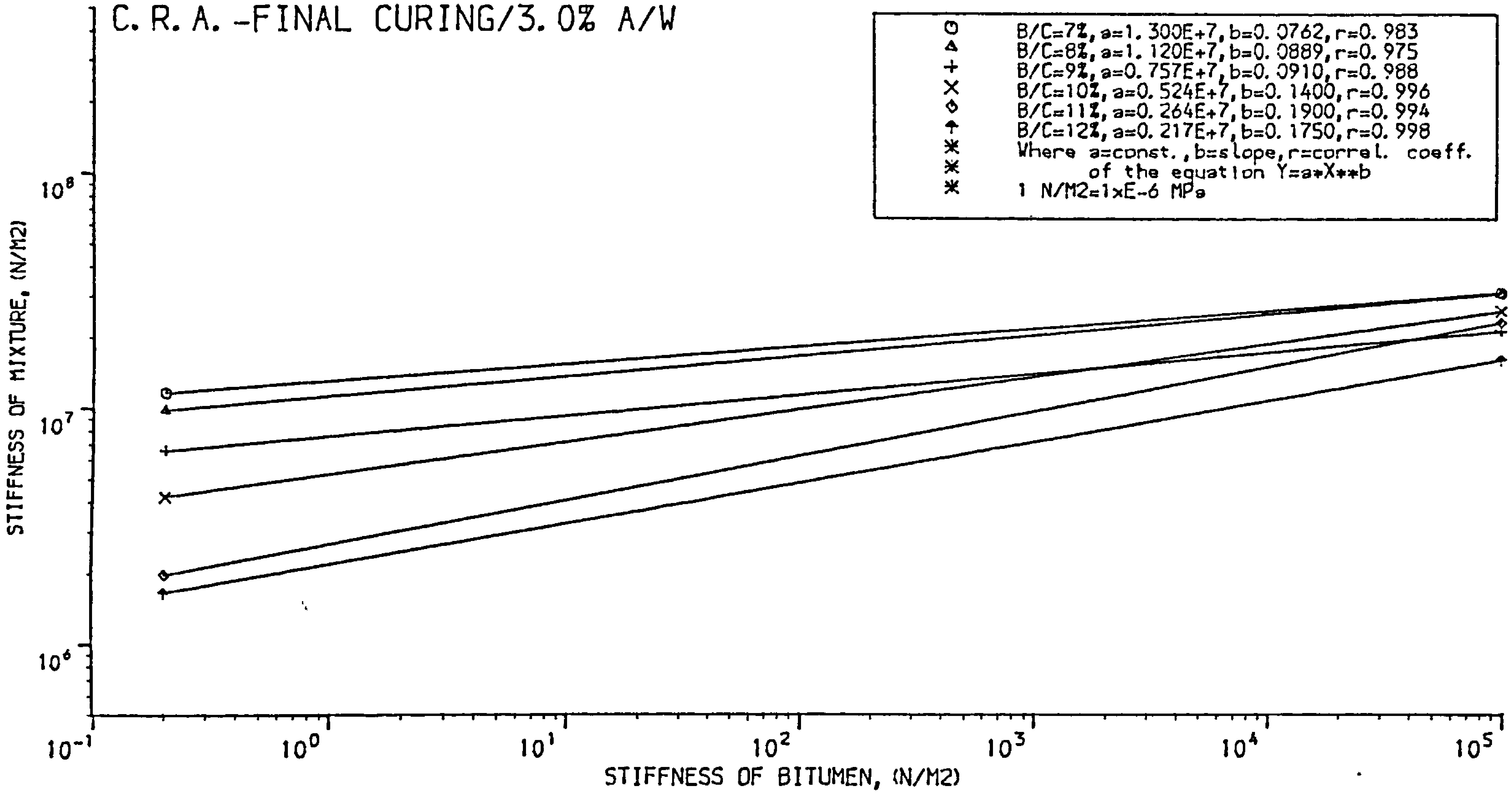


Fig. 10.11 STIFFNESS OF C.R.A. vs STIFFNESS OF BITUMEN

BINDER CONTENT (%)	"ONE DAY" CURING Smix at 3600 sec (N/m^2)	"FINAL" CURING Smix at 3600 sec (N/m^2)	CHANGE IN Smix (%)
	x 10^6	x 10^6	
7	10.42	15.59	+ 50.2
8.0	7.47	13.79	+ 84.7
9.0	6.87	9.37	+ 36.5
10.0	3.50	7.24	+ 106.9
11.0	3.64	4.13	+ 13.5
12.0	2.17	3.28	+ 50.7

AVERAGE = 57.1%

TABLE 10.5 CHANGE IN Smix DUE TO CURING (C.R.A.MIXTURES)

10.5.1.3. The effect of warm compaction

It has been shown (Chapter 8) that warm compaction improves the bulk density, reduces the air voids content but it does not have any positive effect on the modified Marshall stability of the mixtures.

This section investigates the warm compaction on the creep deformation of the emulsion treated gap graded mixtures. The specimens were compacted at 40°C, instead of 21°C, and tested for creep using the CANIK UL apparatus under the same testing conditions as previously. The results obtained were tabulated in Table 10.6 and plotted in Figures 10.12 to 10.15.

Comparing the results obtained between mixtures compacted at 40°C and mixtures compacted at 21°C, a summary of which is given in Table 10.7, the following have been revealed:

There was a significant decrease in the slope of the creep curves when mixtures were compacted at 40°C, which could only be seen on mixtures tested after "final" curing. This shows that mixtures compacted at 40°C become less sensitive to stiffness of the bitumen or loading time, which may account for the better compaction obtained.

The values of the constant "a" however, for both curing conditions and at all binder contents apart from one (7%) were decreased when the mixtures were compacted at 40°C. This indicates that the stiffness of these mixtures can be expected to be lower than for mixtures compacted at 21°C. Comparing the values of Smix at a loading time of 3600 sec it was found that there was a definite decrease in stiffness (apart from the lean mixture with 7% binder) due to warm compaction (results compared after final curing). The reason for this decrease may be the higher percentage of water content found in the specimens, due to reduction of air voids, which may have retarded the development of the properties of the bitumen. It can therefore be said that, in addition to

C.R.A. MIXTURES - ONE DAY CURING/ COMPACTION AT 40°C								
Added Water	Binder Content	Smix vs Sbit[1]		Smix vs Load-time[1]		Smix at 3600 secs N/m^2	Standard deviation and Repeatability[2]	Smix at Sbit = $5000 N/m^2$
		Slope	Const. coeff.	Slope	Constant coeff.			
(%)	(%)	$(x10^{-1})$	$(x10^7)$	$(x10^{-1})$	$(x10^7)$	$(x10^6)$		$(x10^6)$
3%	7	0.453	0.782	-0.415	1.290	9.18	± 0.05	11.50
		0.505	0.700	-0.460	1.348	9.25	1.01	10.76
	8	0.522	0.593	-0.485	1.224	8.23	± 0.06	9.25
		0.516	0.580	-0.470	1.196	8.14	1.02	9.00
	9	0.686	0.483	-0.683	1.100	6.29	± 0.33	8.66
		0.614	0.450	-0.700	1.200	6.76	1.10	7.59
	10	0.920	0.195	-0.810	1.002	5.16	± 0.04	4.27
		1.020	0.143	-0.849	1.030	5.22	1.02	3.41
	11_F	1.450	0.152	-1.290	1.000	3.48	± 0.23	5.23
		1.390	0.145	-1.240	1.050	3.80	1.12	4.74
	12_F	1.880	0.102	-1.649	1.052	2.73	± 0.26	5.06
		1.760	0.119	-1.605	1.151	3.09	1.17	5.33
C.R.A. MIXTURES - FINAL CURING /40°C COMPACTION								
4.5%	7	0.739	1.70	-0.654	3.450	20.49	± 0.27	31.79
		0.796	1.70	-0.705	3.650	20.19	1.02	33.49
	8	0.788	1.905	-0.714	1.950	10.87	± 0.28	17.71
		0.751	1.977	-0.682	1.830	10.47	1.05	18.52
	9	0.696	0.526	-0.631	1.040	6.20	± 0.04	9.52
		0.681	0.524	-0.618	1.020	6.15	1.01	9.36
	10	1.060	0.358	-0.957	1.000	4.57	± 0.04	8.83
		1.010	0.356	-0.918	0.958	4.52	1.02	8.41
	11_F	1.360	0.249	-1.230	0.938	3.42	± 0.01	7.93
		1.170	0.262	-1.060	0.818	3.43	1.00	7.10
	12_F	1.650	0.164	-1.470	0.811	2.43	± 0.03	6.69
		1.730	0.163	-1.540	0.873	2.47	1.02	7.11

1 = Equation of the form of $Y = a \times X^b$

2 = Repeatability = $1 + 2.77 \times \sqrt{(S_d/\bar{X})^2/N}$

where S_d = standard deviation
$\bar{X}$ = mean value
N = No. of observations

F = Specimens reached the "critical" strain after approx 20 min.

TABLE 10.6 CREEP RESULTS OF C.R.A. AFTER ONE DAY CURING
(Mixtures compacted at 40°C)

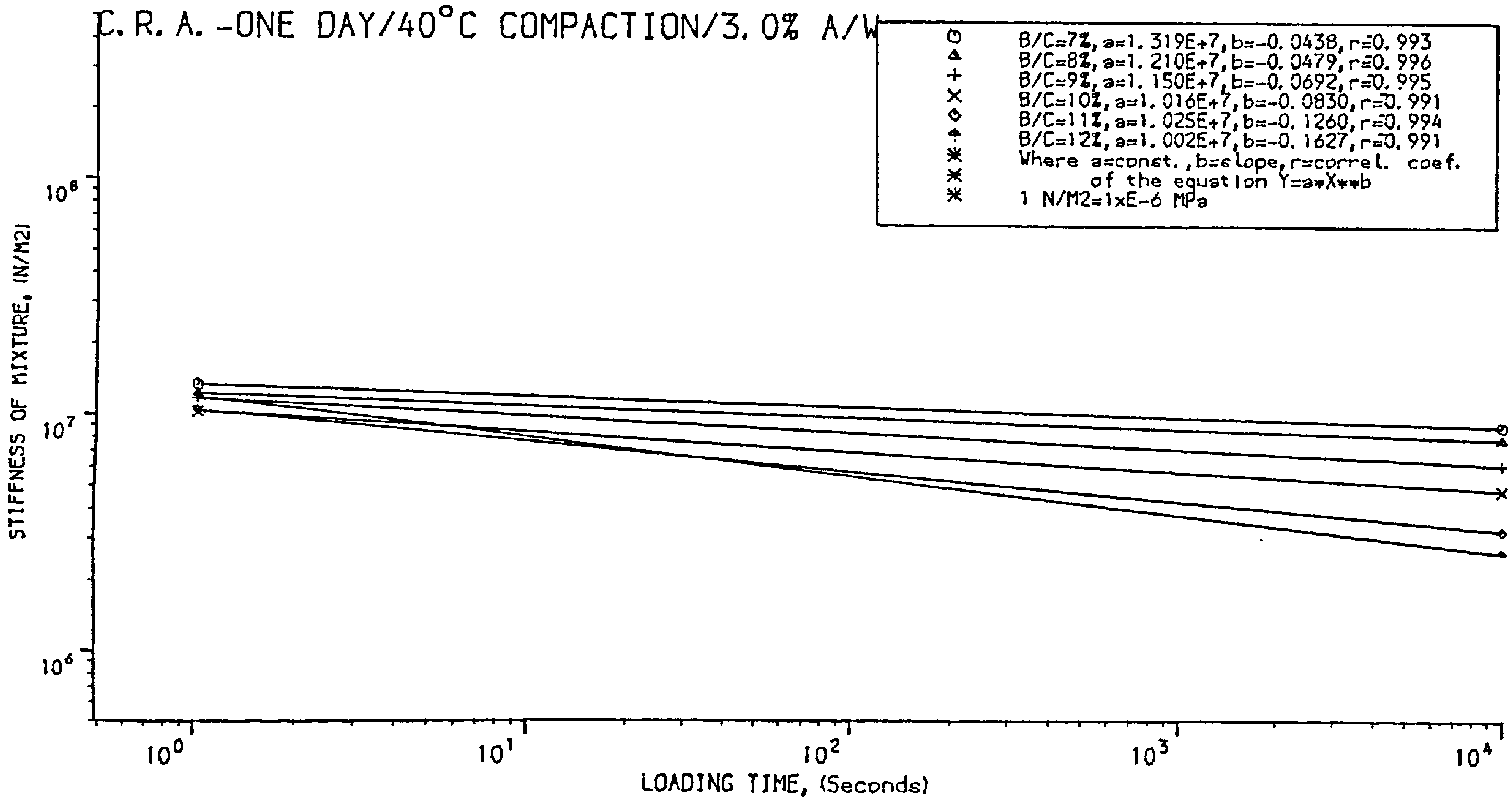


Fig. 10.12 STIFFNESS OF C.R.A MIXTURES vs LOADING TIME

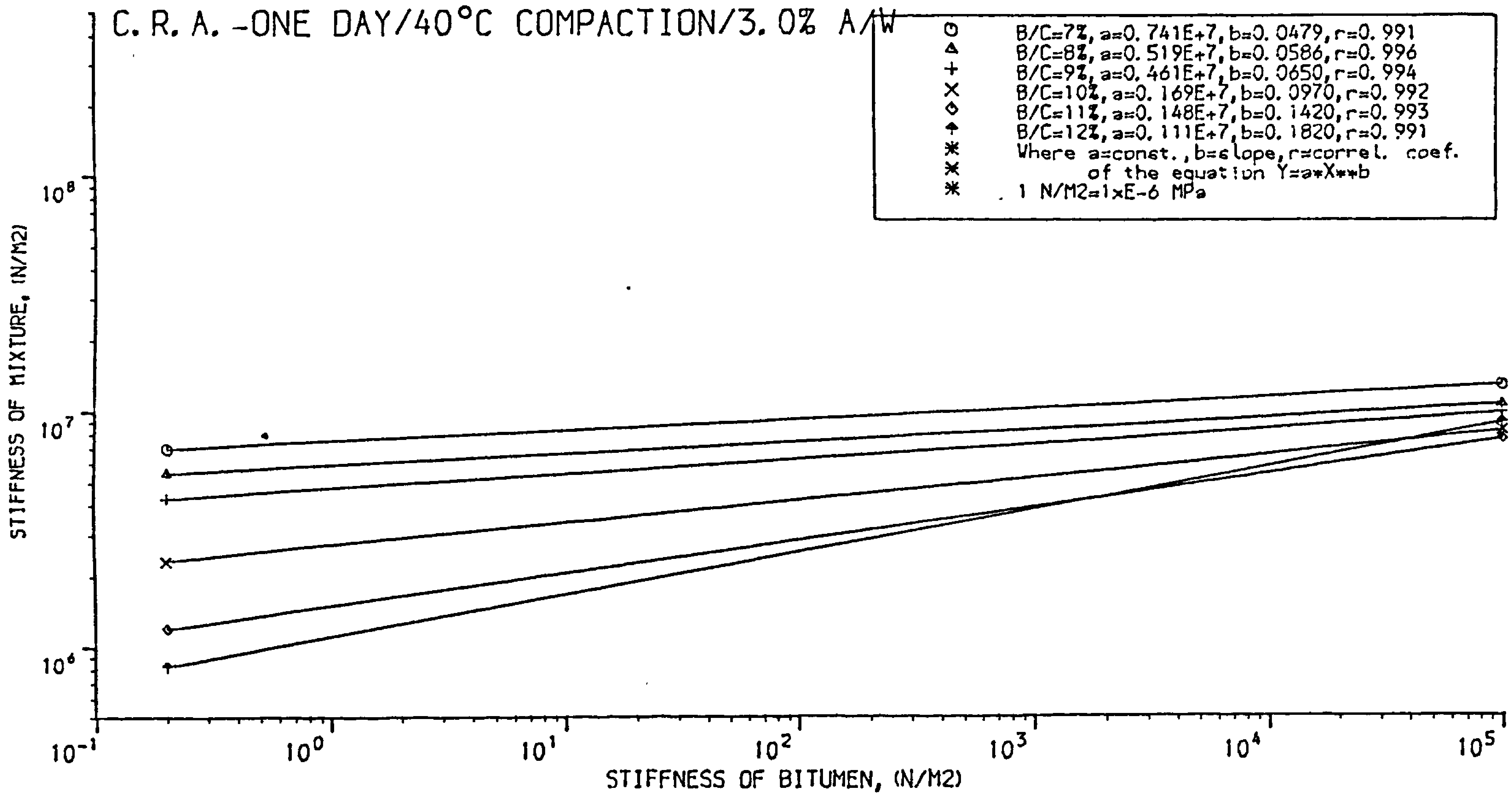


Fig. 10.13 STIFFNESS OF C.R.A MIXTURES vs STIFFNESS OF BITUMEN

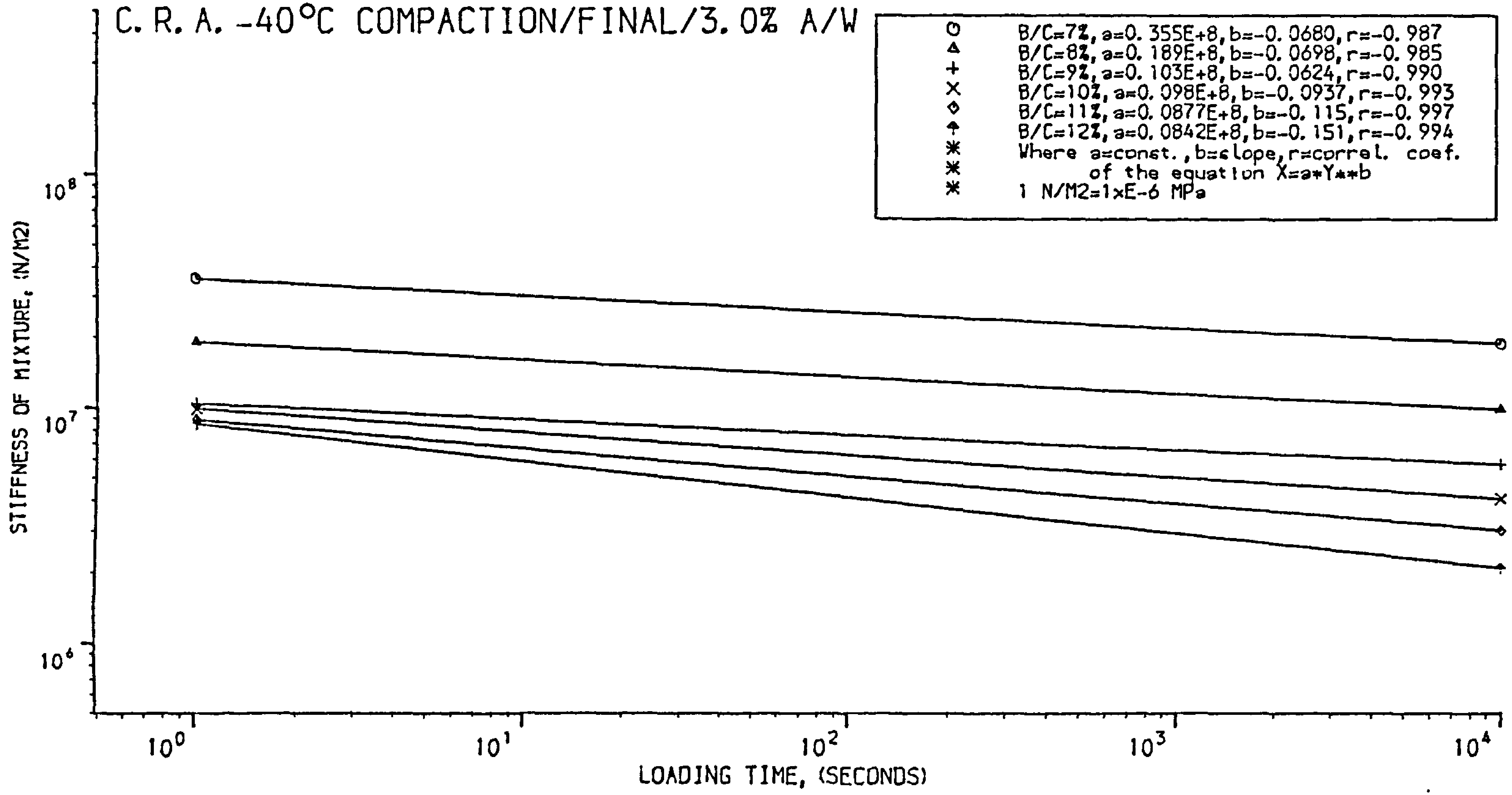


Fig. 10.14 STIFFNESS OF C.R.A. vs LOADING TIME

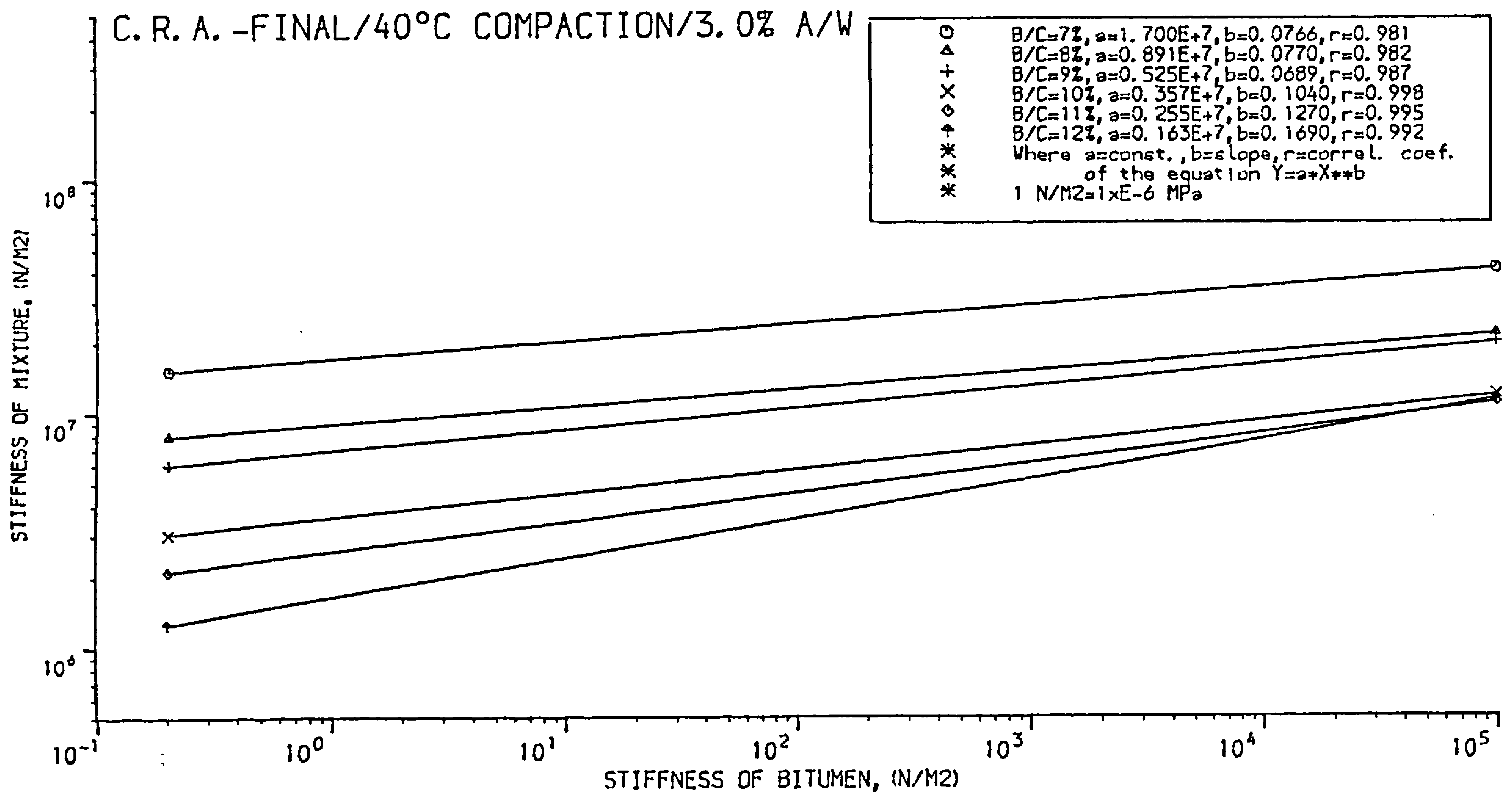


Fig. 10.15 STIFFNESS OF C.R.A. vs STIFFNESS OF BITUMEN

BINDER CONTENT %	COMPACTION AT $21^{o}C$		COMPACTION AT $40^{o}C$		PERCENTAGE CHANGE OF Smix DUE TO CURING	
	One day curing	Final Curing	One day curing	Final curing	One day curing	Final curing
	CREEP PARAMETERS OF THE MIXTURES					
	S=10.42	15.59	9.22	22.34	-11.9	+43.3
7	a=0.933	1.300	0.741	1.700	a_{21} a_{40}	a_{21} a_{40}
	b=0.045	0.076	0.048	0.077	b_{21} b_{40}	b_{21} b_{40}
	S=7.47	13.79	8.19	10.67	+ 9.6	-22.6
8	a=0.659	1.120	0.519	0.891	a_{21} a_{40}	a_{21} a_{40}
	b=0.054	0.089	0.059	0.077	b_{21} b_{40}	b_{21} b_{40}
	S=6.87	9.37	6.53	6.18	-4.9	-34.0
9	a=0.585	0.757	0.461	0.525	a_{21} a_{40}	a_{21} a_{40}
	b=0.068	0.091	0.065	0.069	b_{21} b_{40}	b_{21} b_{40}
	S=3.50	7.24	5.19	4.54	+ 19.3	-37.3
10	a=0.268	0.524	0.169	0.357	a_{21} a_{40}	a_{21} a_{40}
	b=0.113	0.140	0.097	0.104	b_{21} b_{40}	b_{21} b_{40}
	S=3.64	4.13	3.64	3.43	0.0	-16.4
11	a=0.246	0.264	0.148	0.255	a_{21} a_{40}	a_{21} a_{40}
	b=0.166	0.190	0.142	0.127	b_{21} b_{40}	b_{21} b_{40}
	S=2.17	3.28	2.91	3.45	+34.0	-5.2
12	a=0.138	0.217	0.111	0.163	a_{21} a_{40}	a_{21} a_{40}
	b=0.189	0.175	0.182	0.169	b_{21} b_{40}	b_{21} b_{40}

S = Stiffness at 3600 sec ($x10^{6}$ N/m^{2})

a = Constant coefficient of log (Smix vs Sbit) curve

b = Slope of log (Smix vs Smix) curve

a_{21}, a_{40} = Constant coefficients of mixtures compacted $21^{o}C$ and $40^{o}C$

b_{21}, b_{40} = Slope of creep curves of mixtures compacted at $21^{o}C$ and $40^{o}C$

TABLE 10.7 CREEP PARAMETERS OF C.R.A. MIXTURES COMPACTED AT $21^{o}C$ AND $40^{o}C$ (ALL MIXTURES MIXED WITH 3% ADDED WATER) binder content, the reduction of air voids due to warm compaction, reduces the air permeability of the mixtures and delays the evaporation of water which is responsible for the final breaking of the emulsion.

The interesting feature, however, observed in the mixtures compacted at 40°C as well as mixtures compacted at 21°C, is the change in slope of the creep curves due to the increase in binder content. As it can be seen, Figure 10.16, there is a distinct increase in the slope of the curves after a certain binder content. After this binder content, the mixture is too rich in binder, its stiffness decreases drastically and the expected permanent deformation will prove to be relatively high. This demonstrates the importance of using the correct amount of binder content in the mixture. It is obvious that from the creep stiffness point of view the best performance would be obtained from the leanest of the mixtures, but this would not satisfy the other requirements (modified Marshall). It is necessary, therefore, to find the optimum binder content which would be acceptable for both requirements. For acceptable permanent deformation, it is suggested that the maximum binder content be calculated from the curve, slope of creep curves versus binder content. The maximum acceptable binder content is found at the point of sudden change in the slope. This can be easily found by the interception of the two straight portions of the curve, as shown in Figure 10.16. Any binder content above this point would be regarded as unacceptable in terms of permanent deformation performance of the mixture. For the mixtures examined in this study, the suggested method revealed that the acceptable level of binder content, in terms of permanent deformation performance, is 9% by weight of dry aggregate.

One interesting feature of the proposed method is that the characterstic curve of slope vs binder content appears even after one day curing of the mixtures. This is very important, because it enables it to be seen whether or not any drastic changes take place in the nature of the mixture

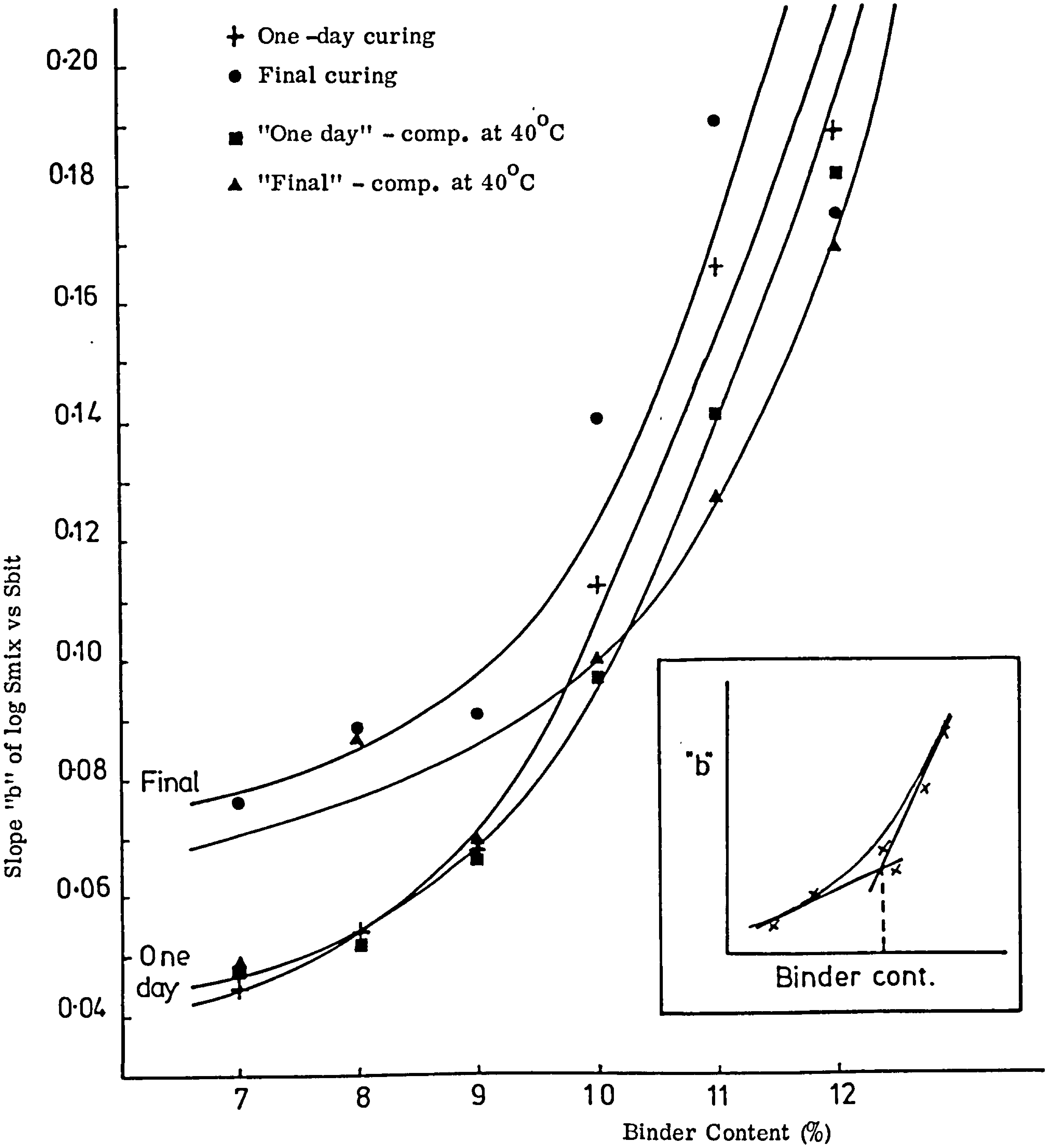


Fig. 10.16 SLOPE (log Smix vs log Sbit) vs BINDER CONTENT

during curing.

It can, therefore, be concluded that the binder content significantly affects the behaviour of the gap graded emulsion treated mixtures tested, at any curing stage. Its effect, however, was more pronounced at higher binder contents which shows the importance of using the correct amount of binder.

Curing also had an effect on the creep behaviour of the C.R.A. Despite the increase in slope of the creep curves, the creep stiffness of the mixtures increased due to curing by more than 50%. This reveals that pavements with C.R.A. mixtures are expected to deform faster at the early stage of the operation.

Improving compaction, by increasing the temperature at compaction, has an adverse effect on creep deformation. This was believed to be caused by the reduction of air voids which restrict the evaporation of water causing retardation of the development of the properties of bitumen. Reduction in air voids, in general, is the main cause of possible "over fill" of the mixture. It was estimated that the critical air voids content is 7%, when the mixtures were compacted at 21°C, and 6% when the mixtures were compacted at 40°C.

The effect of added water which is directly related to the degree of coating, was found to have no significant effect on the creep characteristics of the mixtures. This is no surprise because permanent deformation is primarily a function of the amount of binder in the system.

Finally, the repeatability of the creep test using the CANIK UL apparatus and gap graded emulsion treated mixtures was very good. The repeatability values ranged from 1 to 1.22 depending on the binder content. There was some evidence that repeatability may deteriorate with high binder content mixtures, which are associated with high slope creep curves and low creep stiffness.

10.5.2. The creep behaviour of the continuously graded emulsion treated mixtures

10.5.2.1. The effect of the degree of coating and the binder content

The continuously graded emulsion treated mixtures tested for creep, were dense graded Macadams (denoted as DEMc). The gradation and materials used were similar to the ones used in Chapter 9, details of which are given in Chapter 4.

The creep test conditions were similar to the ones used for the C.R.A. mixtures study. The results obtained, after one day of curing and testing, are shown in Table 10.8. The average value of stiffness of the mixture has been plotted against loading time and stiffness of the bitumen and the resulting curves are shown in Figures 10.17 to 10.20.

It can be seen that the creep curves at both levels of added water, with respect to binder content, are very closely spaced. This is an indication that the binder content may not affect the creep characteristics. Examining the slope of the curves more closely, it can be seen that there is a slight increase in slope due to binder content, but not a statistically significant one. (Table 10.9 at 5% level of significance). The same applies to the values of the coefficient "a". As the result of the above the calculated value of stiffness of the mixture at 3600 secs is almost the same at all levels of binder content (Table 10.8 col.7).

The statistical analysis in the slope of the creep curves with respect to added water has shown that there is a significant change due to added water (degree of coating). The better the distribution of binder (i.e. degree of coating) the lower the rate of deformation hence slope of the creep curves.

D.E.Mc. MIXTURES - ONE DAY / COMPACTION AT 21^{o}C								
Added Water	Binder Content	Smix vs Sbit ^{1}		Smix vs Load.time ^{1}		Smix at 3600 secs N/m^2	Standard deviation and Repeatability^2	Smix at Sbit = 5000N/m^2
		Slope	Const. coeff.	Slope	Constant coeff.			
(%)	(%)	(x10^{-1})	(x10^7)	(x10^{-1})	(x10^8)	(x10^6)		(x10^6)
2%	4.5	0.202	0.945	-0.183	1.150	9.90	± 0.62	11.22
		0.239	1.010	-0.217	1.280	10.78	1.12	12.38
	5.0	0.281	0.872	-0.255	1.150	9.33	± 0.27	11.08
		0.875	0.730	-0.790	1.710	8.95	1.06	15.38
	5.5	0.586	0.976	-0.531	1.730	11.12	± 0.11	16.08
		0.775	0.939	-0.702	2.000	11.28	1.02	18.17
	6.0_F	0.647	0.882	-0.572	1.650	10.27	± 1.02	15.30
		1.020	0.691	-0.908	1.850	8.80	1.21	16.47
	6.5_F	0.868	0.867	-0.771	2.010	10.69	± 2.71	18.16
		1.490	0.475	-1.32	2.020	6.86	1.60	19.90
3%	4.5	0.279	1.170	-0.253	1.540	12.52	± 0.42	14.84
		0.245	1.13	-0.222	1.430	11.92	1.07	13.92
	5.0	0.262	1.070	-0.237	1.390	11.45	± 0.37	13.38
		0.276	1.030	-0.249	1.340	10.93	1.06	13.03
	5.5	0.248	1.090	-0.224	1.390	11.57	± 0.14	13.46
		0.243	1.111	-0.221	1.410	11.77	1.02	13.66
	6.0_F	0.296	1.120	-0.268	1.500	12.04	± 1.47	14.41
		0.304	1.320	-0.276	1.700	14.12	1.22	17.10
	6.5_F	0.295	1.390	-0.267	2.120	14.87	± 0.64	17.87
		0.399	1.440	-0.361	2.120	15.77	1.08	20.23

1 = Equation of the form of $Y = a \times X^b$

2 = Repeatability = $1 + 2.77 \times \sqrt{(S_d/\bar{X})^2/N}$

where S_d = standard deviation

$\bar{X}$ = mean value

N = No. of observations

F = Specimen reached "critical" strain after approx. 20 min

TABLE 10.8 CREEP RESULTS OF D.E.Mc. MIXTURES AFTER ONE DAY OF CURING (STRESS = 0.1 MN/m^2, TEMP = 40^{0}C, LOADING TIME = 1h)

DENSE EMULSION MACADAM MIXTURES - (CONTINUOUSLY GRADED)						
Independent factors / Dependent factor	The effect of added water and binder content (based on one day curing)			The effect of curing time and binder content		
	Added Water (A/W)	Binder Content (B/C)	AW + B/C	Curing Time (C/T)	Binder Content (B/C)	C/T + B/C
Slope of Stiffness curve	S**	NS	NS	NS	NS	NS

NS = Not significant at 5.0% level of significance

S** = Significant at 1.0% level of significance

TABLE 10.9 STATISTICAL ANALYSIS SUMMARY RESULTS FOR THE PERMANENT DEFORMATION OF DEMc MIXTURES

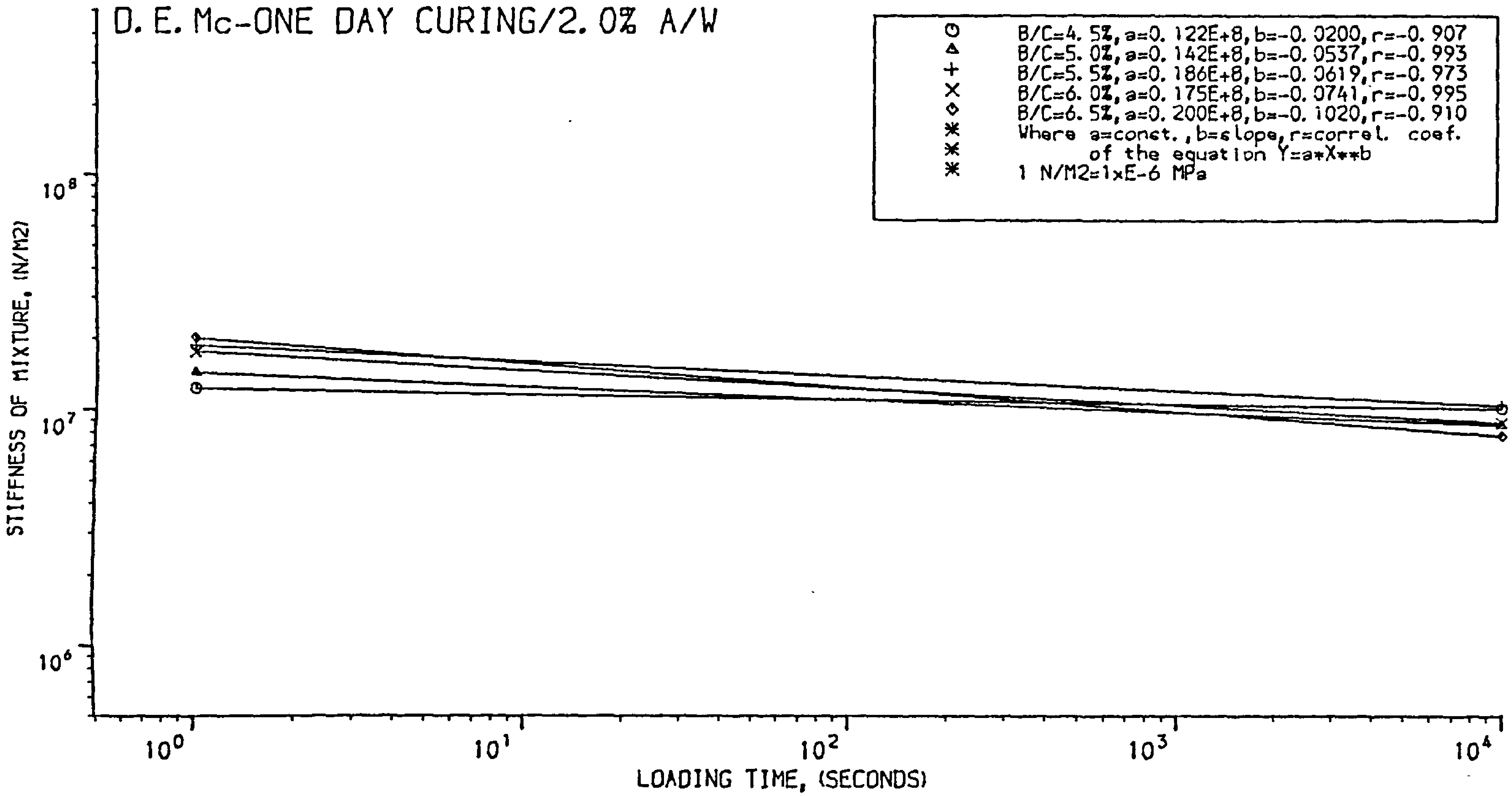


Fig. 10. 17 STIFFNESS OF D. E. Mc. vs LOADING TIME

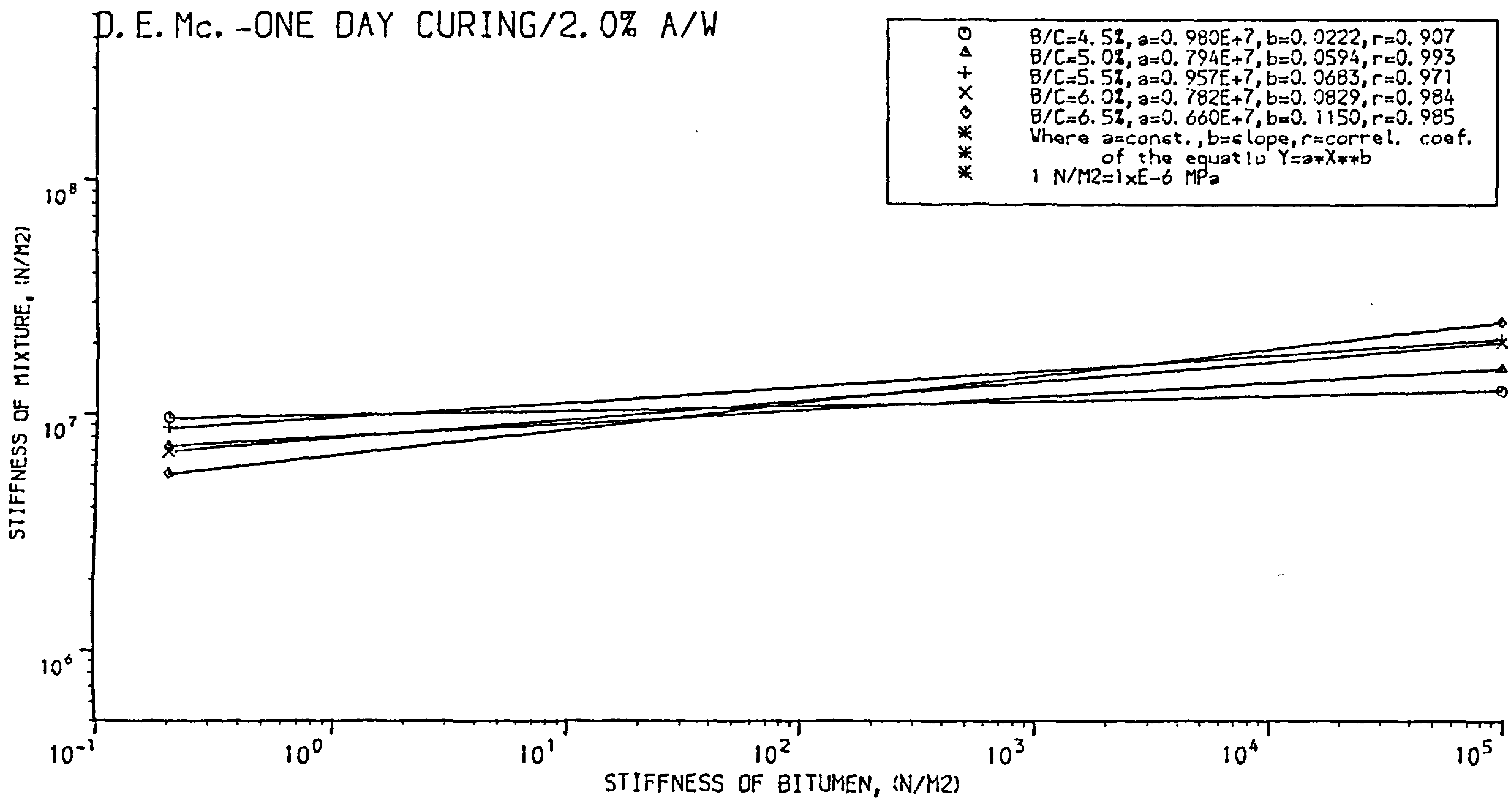


Fig. 10. 18 STIFFNESS OF D. E. Mc. vs STIFFNESS OF BITUMEN

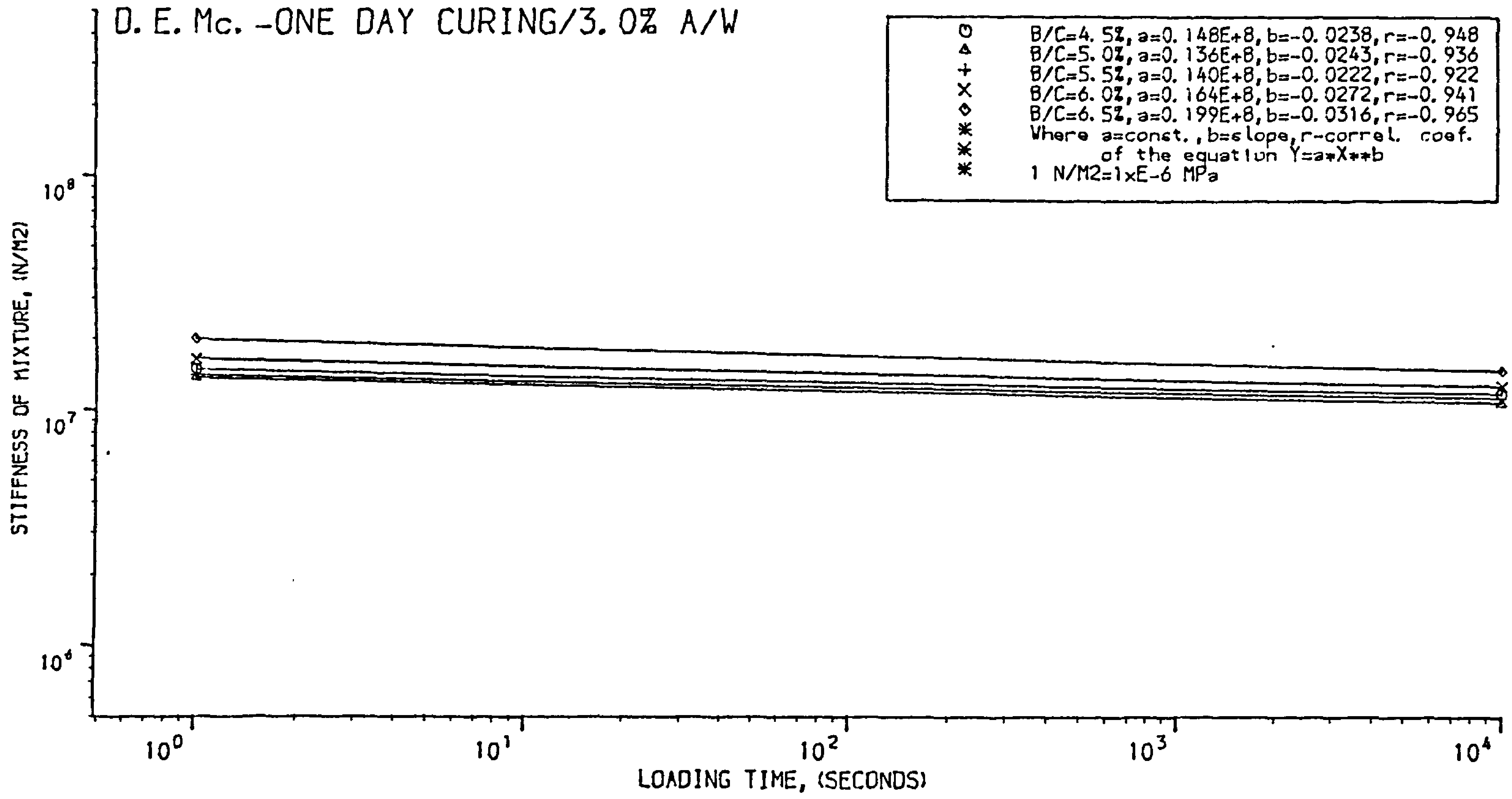


Fig. 10. 19 STIFFNESS OF D. E. Mc. vs LOADING TIME

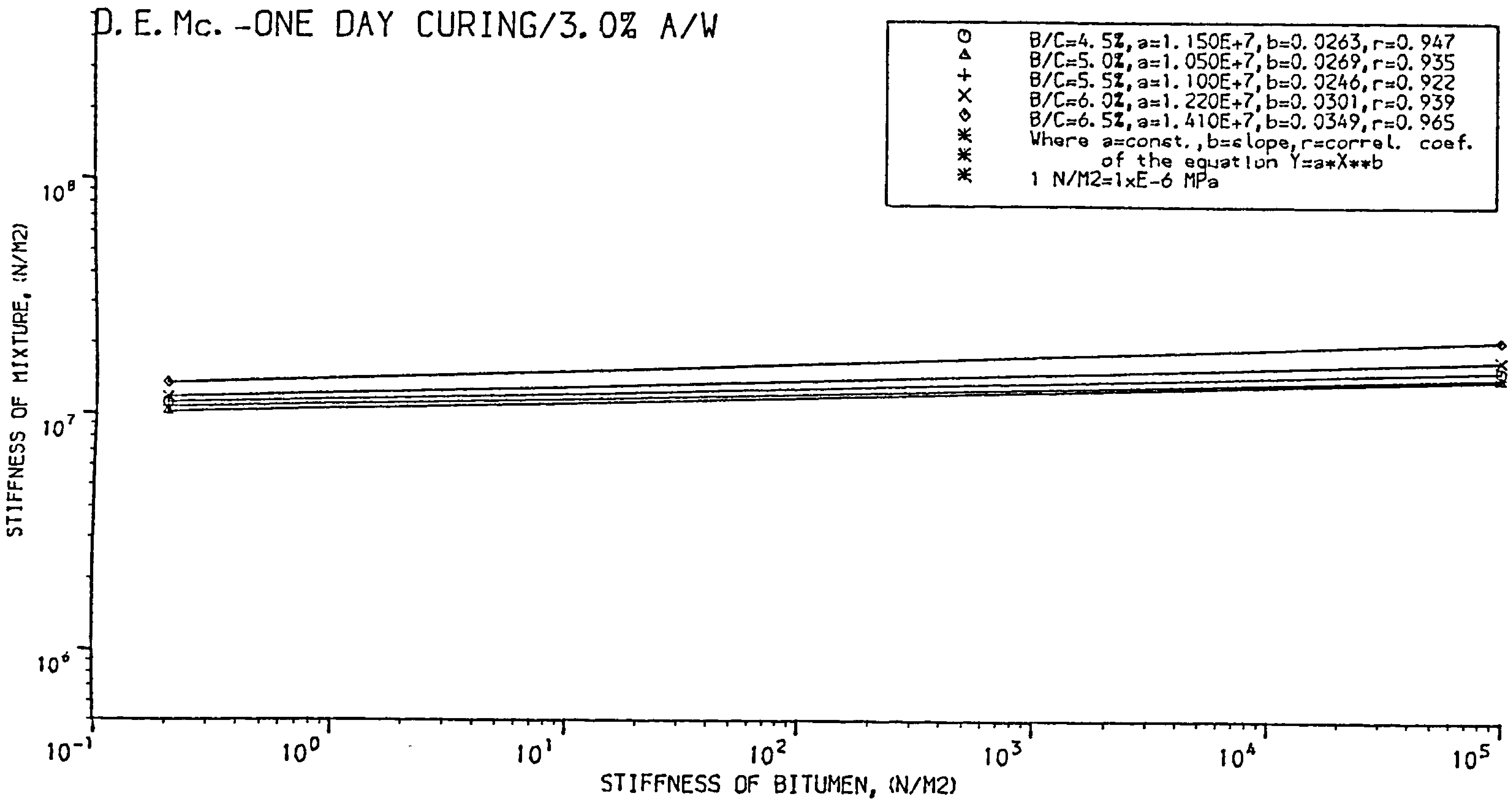


Fig. 10. 20 STIFFNESS OF D. E. Mc. vs STIFFNESS OF BITUMEN

The repeatability of the creep test performed by CANIK UL apparatus and the D. E. Mc mixtures was also measured and it was found to be very good. The repeatability values were determined on the basis of Smix at t = 3600 secs, and varied between 1.02 to 1.22. It must be noted however that some of the mixtures which were rich in binder gave repeatability values as high as 1.6. The deterioration of repeatability is believed to be caused by the low internal stability of the mixture also responsible for the premature arrival at the point of critical strain.

Comparing the stiffness values of the D.E.Mc with the stiffness of C.R.A. mixtures after one day of curing(at t = 3600 secs) it was found that, overall the stiffness of the D.E.Mc mixtures were higher. This indicates that D.E.Mc mixtures will undergo less deformation than C.R.A. mixtures at the early stage of pavement life.

10.5.2.2. The effect of curing time

The results obtained after curing the specimens for sufficient time until final breaking of the emulsion could be assumed to have occured, have been tabulated in Table 10.10. The average value of the stiffness of the mixtures has been plotted against loading time and bitumen stiffness, and are as shown in Figures 10.21 and 10.22. Comparing the creep curves of "final" cured mixtures with the "one day" cured mixtures, no apparent difference could be seen. The statistical analysis confirmed that the effect of curing on the slope of the creep curves was not significant, at 5% level of significance.

The coefficient "a" values however, were slightly increased due to curing of the mixtures. This increase was enough to cause an average increase in the stiffness of the mixture of 31.8%, see Table 10.11. This increase was low compared to the increased caused by curing on the stiffness of C.R.A. (57.1%), which suggests that smaller changes in

D.E.Mc MIXTURES - FINAL CURING / COMPACTION AT 21°C

Added Water (%)	Binder Content (%)	Smix vs Sbit[1]		Smix vs Load-time[1]		Smix at 3600 secs N/m^2 (x10^6)	Standard deviation and Repeatability[2]	Smix at Sbit= 5000N/m^2 (x10^6)
		Slope (x10^{-1})	Const. coeff. (x10^7)	Slope (x10^{-1})	Constant coeff. (x10^8)			
2%	4.5	0.645	1.330	-0.585	2.500	15.48	±0.47	23.04
		0.656	1.270	-0.594	2.410	14.81	1.06	22.21
	5.0	0.856	1.120	-0.779	2.580	13.63	±0.09	23.22
		0.879	1.120	-0.800	2.650	13.76	1.01	23.68
	5,5	0.555	1.100	-0.504	1.890	12.51	±0.17	17.57
		0.600	1.110	-0.544	1.990	12.75	1.03	18,50
	6.0	0.533	0.943	-0.483	1.590	10.71	±0.01	14.85
		0.537	0.945	-0.488	1.600	10.73	1.00	14.93
	6.5	0.689	1.030	-0.625	2.010	12.09	±0.01	18.52
		0.711	1.020	-0.645	2.050	12.09	1.00	18.69

1 = Equation of the form of $Y = a \times X^b$

2 = Repeatability = $1 + 2.77 \times \sqrt{(S_d/\bar{X})^2/N}$

where S_d = standard deviation

$\bar{X}$ = mean value

N = No.of observations

TABLE 10.10 CREEP RESULTS OF D.E.Mc MIXTURES AFTER FINAL CURING (STRESS = 0.1N/m^2, TEMP = 40°C, LOADING TIME = 1h)

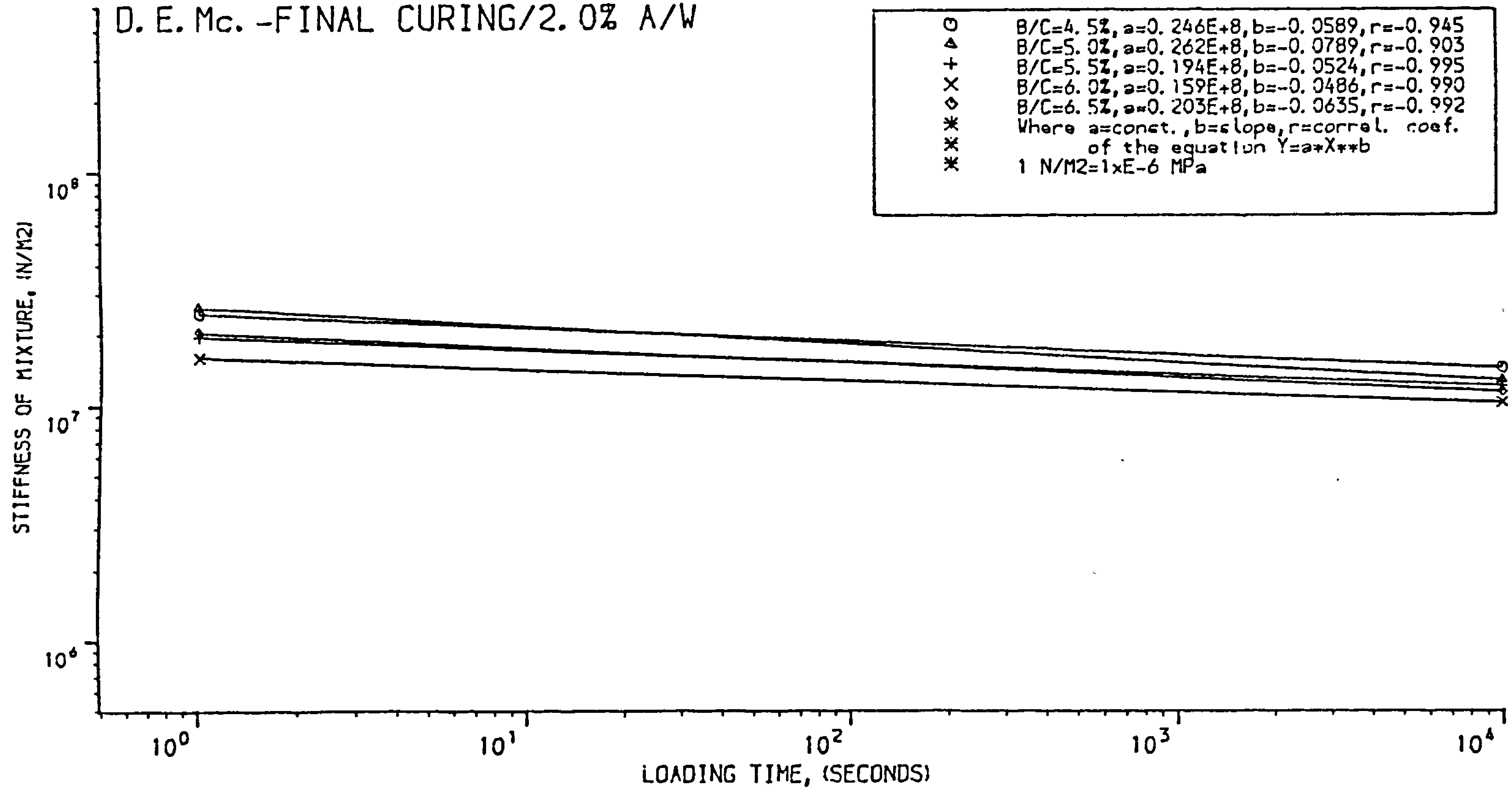


Fig. 10.21 STIFFNESS OF D.E.Mc. vs LOADING TIME

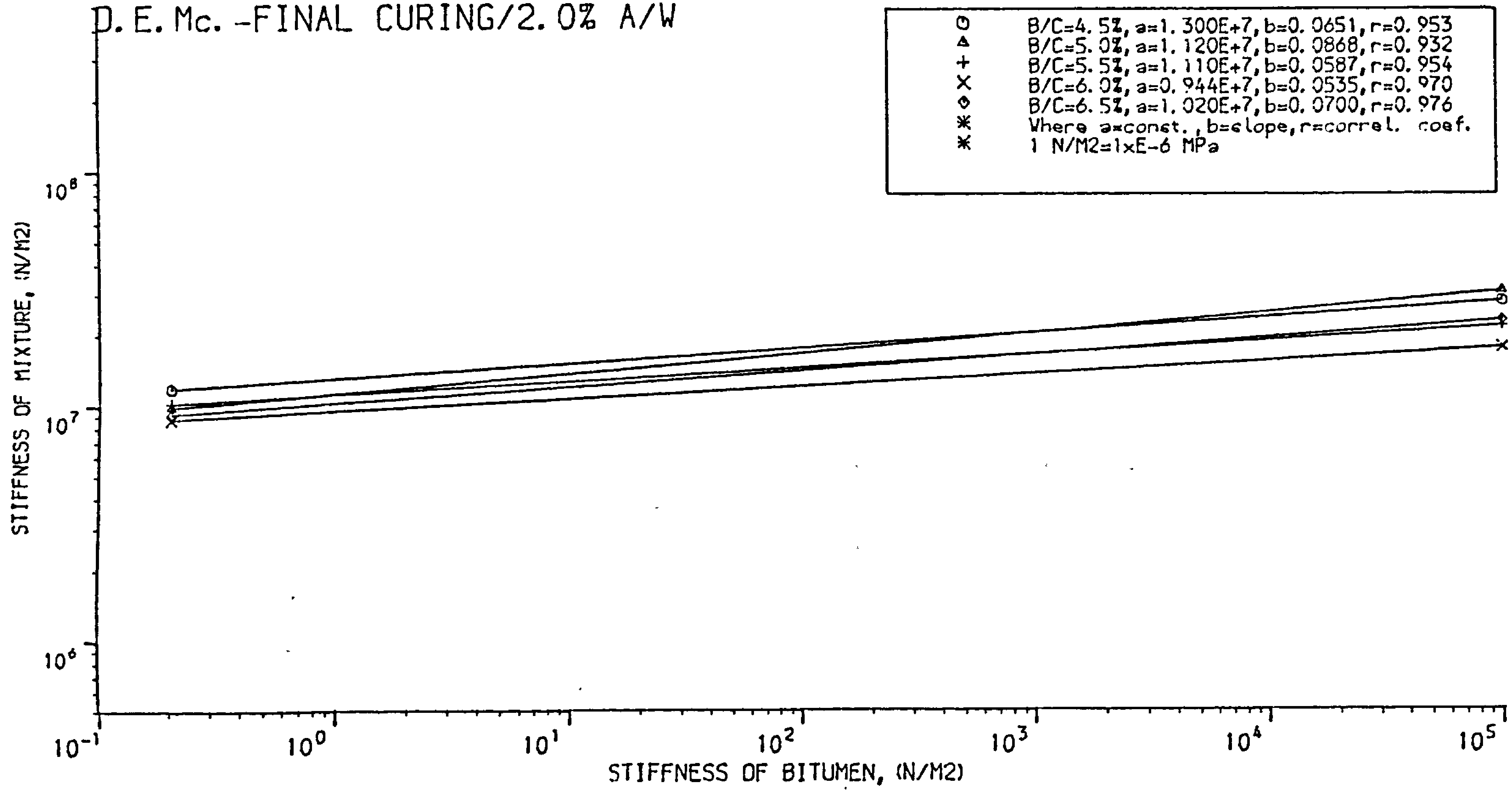


Fig. 10. 22 STIFFNESS OF D. E. Mc. vs STIFFNESS OF BITUMEN

D.E.Mc - 2% ADDED WATER			
Binder Content (%)	"One day" Smix at 3600 sec (N/m^2)	"Final" Smix at 3600 sec (N/m^2)	Percentage change due to curing (%)
4.5	10.34×10^6	15.15×10^6	+ 46.5%
5.0	9.14×10^6	13.70×10^6	+ 49.9%
5.5	11.20×10^6	12.63×10^6	+ 12.8%
6.0	9.54×10^6	10.72×10^6	+ 12.4%
6.5	8.78×10^6	12.07×10^6	+ 37.5%

AVERAGE = 31.8%

TABLE 10.11 THE EFFECT OF CURING ON THE STIFFNESS OF THE MIXTURES (D.E.Mc MIXTURES) permanent deformation performance should be expected with time on D.E.Mc.

The other interesting feature observed in the "final" cured D.E.Mc mixtures is the fact that all mixtures sustain the stress of 0.1 MN/m^2 for the whole period of testing, irrespective of binder content. This finding reinforces the suggestion made earlier, that the premature arrival at the point of critical strain in the case of emulsion treated mixtures is also a function of internal stability.

Unlike the C.R.A. mixtures the optimum or acceptable binder content in terms of permanent deformation, could not be detected by examining the slope of the creep curves. This is because the effect of binder content on the slopes of the creep curves was not significant. However, creep testing can still provide useful information with respect to the optimum binder content chosen by the modified Marshall test. For example, the optimum binder content determined by the Marshall method was found to be 6% by weight of dry aggregate. Examining the creep performance of the mixture with 6%, it can be seen that its stiffness value at both curing stages was much lower than the 5.5% mixture. Also, the mixture with 6.0% showed a premature arrival at the point of critical strain in the early stage of curing. This indicates that from a permanent deformation point of view, the mixture with 5.5% binder content is a better candidate, and if it satisfies all the other requirements, it should be chosen as the best "all round" mixture.

It can, therefore, be said that although the creep test, in the case of emulsion treated dense Macadam, does not give a clear indication of the optimum binder content it must be used as an additional test for checking the performance of the final mixture in terms of permanent deformation.

The repeatability of the results was very good. The repeatability values ranged from 1.00 to 1.06 regardless of the level of binder content. This reinforces the suggestion that the observed deterioration of repeatability on the one day cured mixtures with binder content was chiefly due to the lack of internal stability of these mixtures.

10.5.3. Correlation between creep test and modified Marshall test

Correlation between creep test parameters and Marshall test parameters, if it exists, would be beneficial, because in the absence of the creep test, the permanent deformation performance of the mixtures could be judged by the Marshall parameter alone. Brien (196) working with conventional Rolled Asphalt mixtures has shown that a good correlation ($r = 0.96$) exists between the creep stiffness and the Marshall Quotient,MQ. He also reported that good relationship exists between Marshall stability and creep stiffness but that would not match the high correlation coefficient of MQ and stiffness ($r = 0.74$ instead of 0.96). Jacobs (203), however, reported that both stability and MQ gave similar correlation coefficients ($r = 0.92$) with the rate of tracking and he suggested that this relationship of Marshall stability vs rate of tracking be used. It must be noted that in his relationship the rate of traffic was measured on Rolled asphalt mixtures (stone filled asphalts) and the Marshall stability on sand/filler/binder mortar. Although Brien and Jacobs did not find a good correlation of deformation with Marshall flow, Bolk (211) using asphaltic concrete mixtures found that Marshall flow correlates better than Marshall Quotient with the deformation measured by the wheel tracking test. ($r = 0.83$). Leech and Selves (205) related the deformation of dense coated Macadams (measured with wheel tracking machine) with voids in the mineral aggregate (V.M.A.) of the mixtures, and they found a good relationship. The correlation coefficient of the relationship has not been reported but from the graphs presented it was apparent that the correlation was dependent on the type of aggregate used. Granite and gravel mixtures appeared to correlate best with V.M.A. while limestone and blast-furnace slag had not good correlation values.

It appears that a relationship between deformation of bituminous mixtures and Marshall test parameters does exist. Which of these parameters correlate better, is probably a function of the way the deformation is measured and the type of mixture used.

10.5.3.1. Correlation between Creep and Marshall test using emulsion treated mixtures

The relationship between creep test and Marshall test was examined in terms of stiffness of the mixture, total strain, Marshall stability, Quotient, V.M.A. and Flow. It was decided that it would be better to correlate creep stiffness to stability and quotient, and the deformation (in terms of total strain) to flow and voids in the Mineral Aggregate Values (V.M.A). The values of Smix were calculated from Smix vs Sbit relationship at Sbit equivalent to the conditions of the Marshall test. It was found that the Sbit calculated using Van de Poel's nomograph (127) was equal to 5 x 10^3 N/m^2 for the conditions of Marshall test (temp = 21°C, loading time = 50.8 mm/min i.e. approximately equal to 330 sec and binder of 74 penetration grade with R-B temp. = 50.0°C and PI = -0.14).

Similarly, the values of the strain of the mixture (ε) were calculated from the strain vs loading time relationship (from creep test) at loading time = 3600 secs.

The results of the correlation of the above mentioned parameters have been tabulated in Tables 10.12 and 10.13.

It can now be seen, that in terms of Smix and Marshall stability or quotient, a good relationship exists only for the gap graded emulsion treated mixtures. For these mixtures the best correlation (r = 0.904) was found between Smix vs Marshall Quotient when the mixtures were cured for sufficient time until final breaking of the emulsion occured. It must

C.R.A. MIXTURES - GAP GRADED / COMPACTION AT 21°C			
"ONE DAY" CURING		"FINAL CURING"	
Stiffness of mix vs Dry stability (*)	Stiffness of mix vs Marshall Quotient (*)	Stiffness of mix vs Dry stability (*)	Stiffness of mix vs Marshall Quotient (*)
r = -0.725 $b = 9.62 \times 10^{8}$ a = -1.877	r = 0.180 $b = 6.61 \times 10^{6}$ a = 0.414	r = 0.850 $b = 4.43 \times 10^{4}$ a = 1.978	r = 0.904 $b = 4.42 \times 10^{6}$ a = 0.915
C.R.A. MIXTURES - GAP GRADED / COMPACTION AT 40°C			
r = -0.695 $b = 7.94 \times 10^{10}$ a = -3.800	r = 0.824 $b = 1.24 \times 10^{6}$ a = 1.932	- - -	- - -
D.E.Mc MIXTURES - CONTINUOUSLY GRADED / COMPACTION AT 21°C			
r = 0.094 $b = 8.69 \times 10^{6}$ a = 0.226	r = -0.202 $b = 1.91 \times 10^{7}$ a = -0.461	r = -0.777 $b = 5.01 \times 10^{9}$ a = -1.894	r = 0.119 $b = 2.78 \times 10^{6}$ a = 0.512

(*) The relationship has the form $Y = aX^{b}$

where Y = Stiffness of mixture (N/m^{2})

r = the correlation coefficient

TABLE 10.12 RELATION BETWEEN CREEP AND MARSHALL TEST IN TERMS OF STIFFNESS AND STABILITY OR QUOTIENT

C.R.A. MIXTURES - GAP GRADED / COMPACTION AT 21°C			
"ONE DAY" CURING		"FINAL" CURING	
Strain vs V.M.A. (*)	Strain vs Flow (*)	Strain vs V.M.A. (*)	Strain vs Flow (*)
r = 0.935 b = -2.28E-1 a = 9.44E-3	r = 0.750 b = -4.47E-2 a = 1.39E-2	r = 0.979 b = -4.39E-1 a = 1.71×10^{-2}	r = 0.990 b = -2.22E-2 a = 8.27E-3
C.R.A. MIXTURES - GAP GRADED / COMPACTION AT 40°C			
r = 0.911 b = -1.74E-1 a = 7.73F-3	r = 0.834 b = -3.06×10^{-2} a = 1.03×10^{-2}	- - -	- - -
D.E.Mc MIXTURES - CONTINUOUSLY GRADED / COMPACTION AT 21°C			
r = 0.677 b = 6.43E-3 a = 1.36E-4	r = 0.601 b = -8.84E-3 a = 2.93E-3	r = 0.621 b = -6.76E-2 a = 2.54E-3	r = 0.688 b = 9.16E-4 a = 1.21E-3

(*) The relationship has the form: $Y = \pm a X \pm b$

when Y = Total strain of the mixture (%) at 3600 sec loading time

X = x - axis variable

r = Correlation coefficient

TABLE 10.13 RELATION BETWEEN CREEP AND MARSHALL TEST IN TERMS OF STRAIN AND V.M.A. OR FLOW be noted, however, that the correlation between Smix and stability was also good (r = 0.850). Since the relationship of Smix vs Marshall Quotient seems to hold even after one day of curing (r = 0.824) it is reasonable to assume that for gap graded emulsion treated mixtures the above relationship would give better results.

When the creep test (in terms of strain) was related to Marshall test (in terms of V.M.A. and flow) again the gap graded mixtures gave the highest correlation coefficients Table 10.13. The best correlation was obtained between strain vs flow, after final curing (r = 0.990) but the relation of strain vs V.M.A. also gave a good correlation coefficient (r = 0.979). It can be seen that the above correlations are higher than the ones obtained between Smix vs MQ. Good correlations were also obtained between strain vs flow or V.M.A. even after one day of curing (r = 0.750 or 0.935).

The above findings indicate that the Marshall flow, in the case of emulsion treated bituminous mixtures, may provide better information than any other Marshall parameter, above the permanent deformation performance of the mixture. Figure 10.23 shows that the best relationship was found to exist between creep and Marshall test in terms of strain and flow. . Figure 10.24 shows the other relationships between strain and V.M.A.

Regarding the relation between creep and Marshall test, when D.E.Mc mixtures were used, it was found that none of the examined relationships (Tables10.12 and 10.13) gave high correlation coefficients. The highest correlation was obtained between strain vs flow (r = 0.688) but this is not high enough to justify the existence of the relationship. The fact that there was no correlation found between creep and Marshall test when dense graded emulsion treated Macadams were used, is not surprising. It is most probably due to the fact that binder content did not significantly

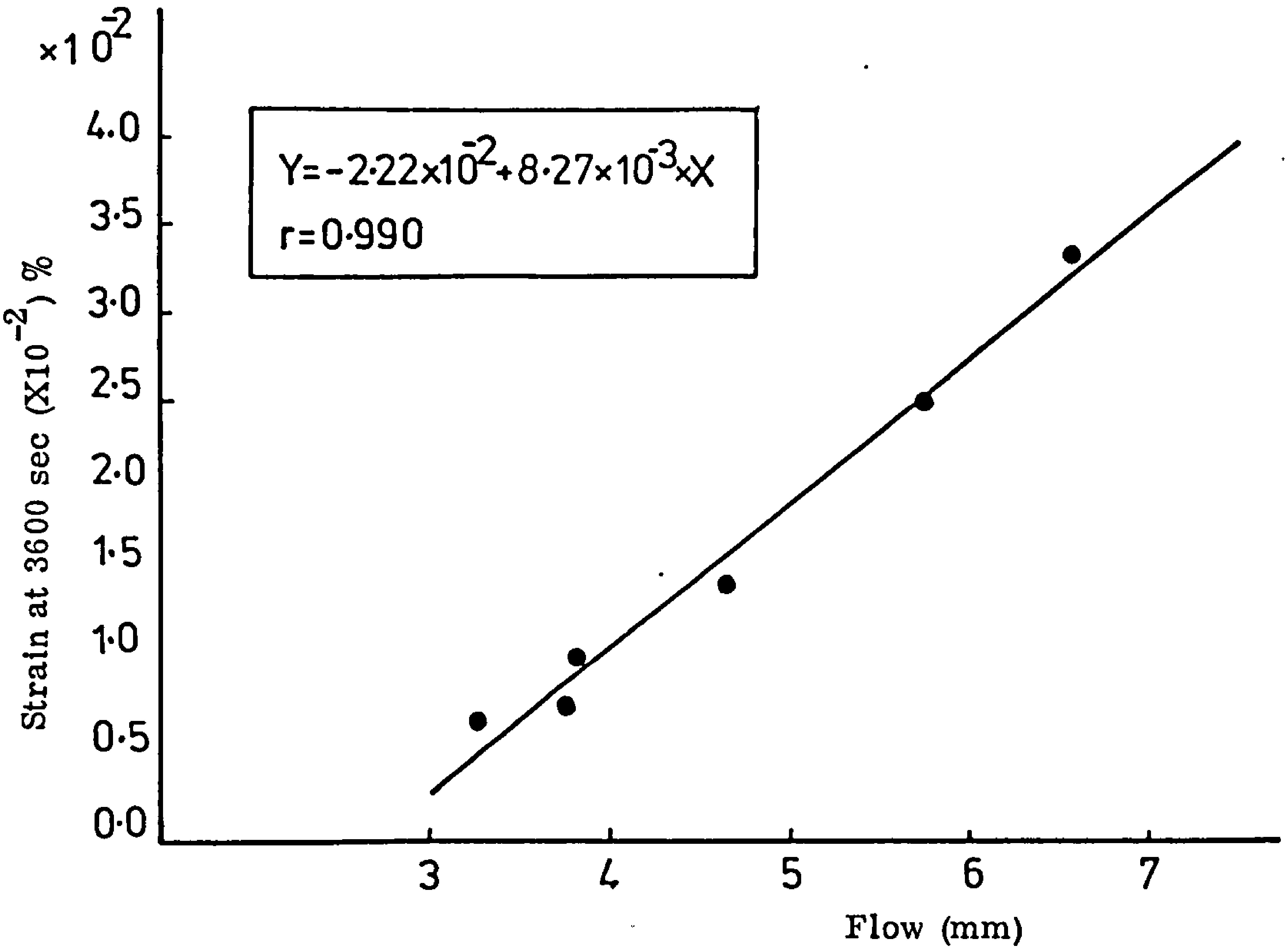


Fig. 10.23 STRAIN vs MARSHALL FLOW - C.R.A.
(Final curing/3.0%)

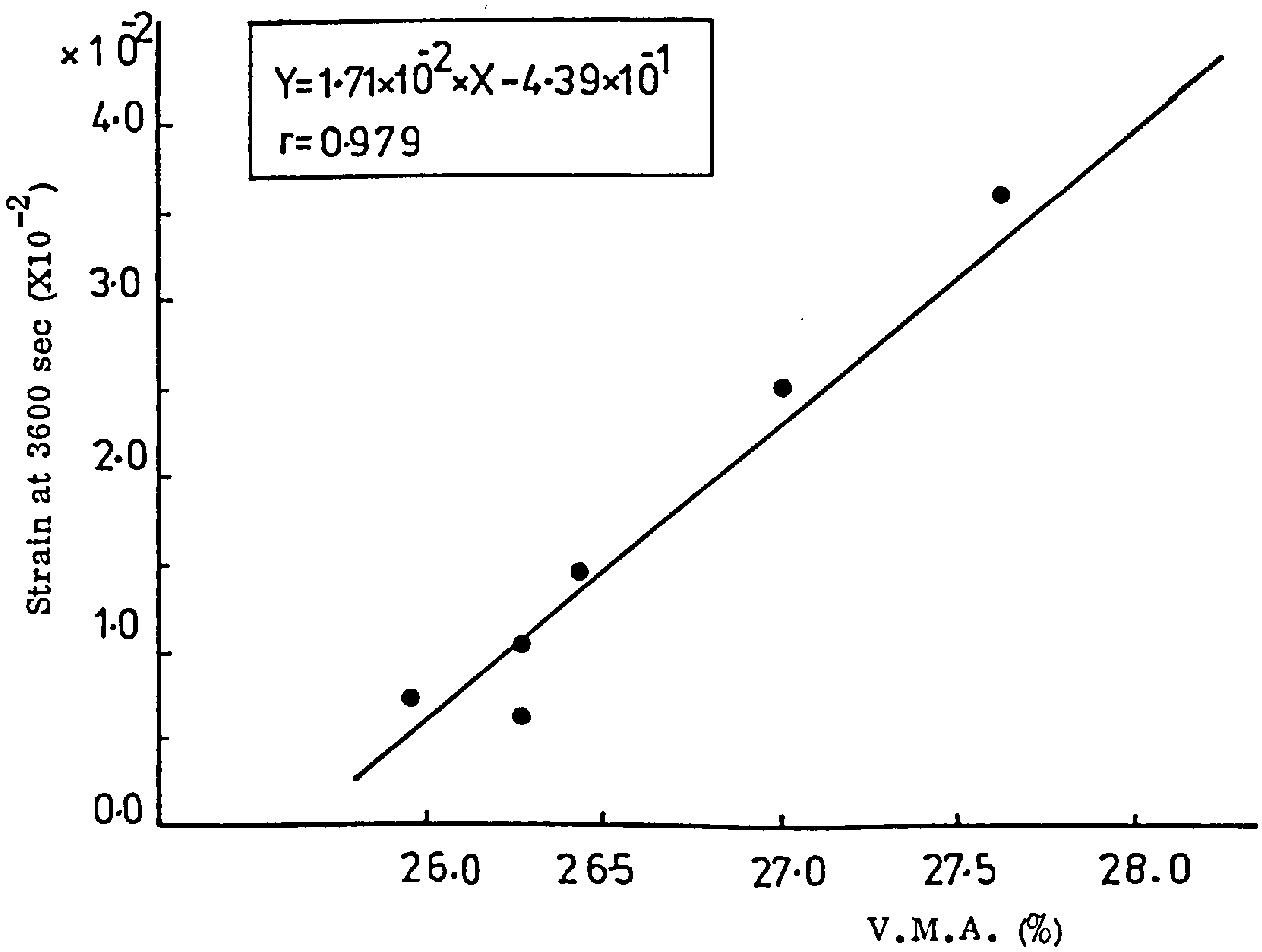


Fig. 10.24 STRAIN vs V.M.A. - C.R.A.
(Final curing/3% w/a)

affect the creep characteristics of those mixtures.

10.6 Comparison between C.R.A. and D.E.Mc mixtures in terms of permanent deformation

It has been shown that both binder content and curing time significantly affect the creep characteristics of the C.R.A. mixtures (gap graded). An increase in binder content causes an increase in the slope of the curves and a reduction in the constant coefficient "a" which is related to stiffness of the mixture. Curing the mixtures increases the value of "a" but at the same time increases the slope of the curves. This means that as the emulsion continues to break, the sensitivity of the mixture to properties of binder increases. This may result in an actual reduction of stiffness of the mixture, at a certain value of Sbit.

D.E.Mc mixtures - continuously graded dense Macadams - are not significantly affected by the binder content and curing. This suggests that, if satisfactory results are obtained from one day creep curve and at a certain binder content, they will also be satisfactory, or even better, at a later stage of curing.

However, in order to find the true effect of curing on the actual permanent deformation (rut depth), calculations on the actual permanent deformation were carried out using the "Shell" approach (147). The procedure has been explained briefly earlier on but a more detailed account is given in the Shell Pavement Design Manual (147). The step by step calculations for the calculation of rut depth using emulsion treated mixtures are given in the Appendix H. The design data used were similar to the ones used by Van de Loo (148), purely for comparison purposes. The rut depths of the two emulsion treated mixtures used as base course material (140mm thick) on a road which will carry 18×10^6 standard axles in 15 years time were calculated to be as in Table 10.14.

It can be seen that the calculated rut depth from the one day cured mixture data ,is higher than the rut depth calculated from the "final" cured mixture data. This shows that despite the increase in slope due to curing, the net effect is that permanent deformation is reduced and hence the behaviour of both mixtures in terms of permanent deformation improves. It must be emphasised that this is only true for relatively low values of slope obtained from these mixtures (0.068 to 0.091). The above finding also means that if the calculations are based on the one day curing data the resulting rut depth is going to be overestimated. It is difficult to say when final curing will occur on site and it is up to the engineers to decide this, based on experience and environmental conditions. As a rough estimate, final breaking of the emulsion may occur two years after construction (66).

It is interesting to note that the reduction in rut depth due to curing was 5.2mm for C.R.A. and only 1.4mm for D.E.Mc mixtures. This suggests that D.E.Mc mixtures remain almost unaffected by the final breaking of the emulsion.

It was mentioned before that the slope values of the creep curves were relatively low compared to conventional mixtures (slopes found by Van de Loo (148) and ranged from 1.0 to 2.0 depending on the type of the mixture). The reason for the small values found on the emulsion treated mixtures is believed to lie in the nature of the mixtures. Emulsion treated mixtures do not possess the same degree of coating as conventional hot mixtures and therefore they have a larger number of dry contact areas between adjacent aggregates. Dry contact areas do not contribute to deformation under static load and most probably they oppose it. As a result, the rate of deformation decreases with an increase in the number of dry contact areas, and hence creep curves of emulsion treated mixtures are expected to have lower slope values.

The effect of dry contact areas on the calculations of permanent deformation is taken care of,indirectly,by the introduction of the Cm constant. Experimental studies (141, 146, 147) have shown that the discrepancy between calculated and measured deformation was increased as the mixtures became leaner and hence increased the chances of having a number of contact areas. The values, therefore, of Cm given in the Shell manual vary from 1.0 for dense and rich mixtures, to 2.0 for lean and open mixtures. Unfortunately there are no values given for emulsion treated mixtures. The values used in the calculations of rut depth shown in Appendix H have been assumed to be representative. This may itself lead to errors because the influence of Cm on the calculations of rut depth can be significant. Using, for example, a value of Cm = 1.3 instead of 1.6, would underestimate the rut depth by 18.75%. Hence it is necessary to carry out further comparison tests between wheel tracking and creep test using emulsion treated mixtures. This will enable one to determine accurately the values of Cm and hence the rut depth of these mixtures.

The calculated rut depth of the two emulsion treated mixtures was compared with some conventional mixtures used by Van de Loo (148) see Table 10.14. It was found that the rut depth of emulsion treated mixtures, when used as a base course material, was comparable with the dense bitumen macadam (DBM) with 50 pen bitumen, and much lower than DBM with 100 pen Macadam.

It can therefore be concluded that emulsion treated mixtures can be used successfully, in terms of permanent deformation,as base course material.

Continuously graded emulsion treated mixtures (D.E.Mc) are unaffected by binder content or curing time and they undergo less deformation than gap graded emulsion treated mixtures (C.R.A. mixtures), provided that everything else is equal i.e. adequate compaction , traffic

TABLE 10.14 PERMANENT DEFORMATION OF EMULSION TREATED MIXTURES UNDER GIVEN TRAFFIC AND ENVIRONMENTAL CONDITIONS

Construction Type	Construction Layer	Type of Mixture	Bitumen	Layer thickness mm	Calculated depth (mm)	
					Per layer	Total
One day curing 1	Wearing course base course base course	Dense Asphaltic Concrete (DAC) Cold Rolled Asphalt (CRA)	100pen 74pen	40 140	6.0 18.5	24.5
Final curing 2	Wearing course base course	DAC CRA	100pen 74pen	40 140	6.0 13.3	19.3
One day curing 3	Wearing course base course	DAC Dense Emulsion Macadam (DEMc)	100pen 74pen 74pen	40 140	6.0 15.6	21.6
Final curing 4	Wearing course base course	DAC DEMc	100pen 74pen	40 140	6.0 14.2	20.2
5	Wearing course base course	DAC Dense Bitumen Macadam (DBM)	100pen 100pen	40 140	6.0 33.0	39.0*
6	Wearing course base course	DAC DBM	100pen 50pen	40 140	6 19	25.0*
7	Wearing course base course	DAC Lean Sand Asphalt	100pen 50pen	40 140	6 4	10.0*

Note: *The calculated rut depth is due to permanent deformation caused during a design life of 15 years at* 25^{o}C mean annual average temperature and traffic of 2000 standard axles per lane per day (Traffic growth 2% per year)

*After ref.148

and environmental conditions etc.

Gap graded emulsion treated mixtures are significantly affected by the binder content and hence curing. This shows the importance of using the right amount of bitumen in the mixture in order to avoid excessive deformation.

In general the deformation of the emulsion treated mixtures is reduced by decreasing the amount of binder. Any reduction in binder content to meet deformation requirements should be checked to ensure that the resulting mixture satisfies the Marshall requirements. Marshall properties, on the other hand, have been shown to improve with an increase in binder content, and the resulting mixtures should always be tested for deformation performance. It is therefore apparent that both tests, Marshall and creep, are necessary to design a balanced mixture good in stability and permanent deformation.

10.7 Conclusions

The examination of creep performance of emulsion treated mixtures and in particular gap graded (C.R.A.) and continuously graded mixtures (D.E.Mc) has revealed the following:

1. The binder content significantly affects the creep behaviour, only, of gap graded mixtures. The effect was more pronounced at high binder contents, which facilitates the determination of optimum binder content in terms of permanent deformation performance.
2. Curing of the mixtures,and in particular the C.R.A. mixtures,affects the creep performance of the mixture. Mixtures at the early stage of curing will deform more.
3. The degree of coating significantly affects,only,the creep characteristics of the D.E.Mc mixtures.
4. Improving the compaction of the gap graded mixtures by increasing the temperature at compaction from 21°C to 40°C does not improve the

creep performance. On the contrary, it results in mixtures being more sensitive to change in the stiffness of the bitumen, and with slightly less stiffness value (Smix).

5. The repeatability of the creep results using the CANIK UL apparatus was found to be very good for both mixtures and at almost all binder contents.
6. The creep test is related to the Marshall test when gap graded mixtures are used. The best correlation was found to exist between creep strain and Marshall flow ($r = 0.990$) but good correlation was also found between stiffness and Marshall Quotient ($r = 0.904$).
7. The calculated rut depth of the mixtures, when used as base course material, was comparable and in some cases better than dense bitumen Macadam mixture, under the same traffic and environmental conditions. This suggests that emulsion treated mixture can be used as base course material, without undergoing any greater deformation than the conventional equivalent mixtures.

CHAPTER ELEVEN

CONCLUSIONS AND RECOMMENDATIONS

This study has presented an investigation on the suitability of slow setting cationic emulsions in dense graded mixtures (high in fine aggregate content), a study on their rheological behaviour and an evaluation of the engineering properties of the resulting emulsion treated mixtures. The main factors that have been considered were the type of the emulsifier, the viscosity of the emulsion, the binder content in the emulsion and in the mixture, the water added to the aggregate to promote efficient mixing, the different curing periods, the aggregate gradation, the temperature and the total moisture content at compaction.

The examination of the slow setting emulsions has provided useful parameters to assess the properties of slow setting emulsions. It has also shown the limitations of the current British Standards (BS434 Part 1 and 2) with reference to the evaluation of acceptance of a cationic emulsion suitable for coating dense aggregate mixtures with high percentage of fine aggregate.

The examination of the properties of the mixtures has revealed that their properties are a result of a complex interaction of the factors mentioned earlier in this chapter. Careful consideration of these factors is essential for an acceptable design procedure.

The detailed conclusions presented in the following pages have been divided in relation to:

a) the properties of the emulsion
b) the fundamental differences between the two mixtures studied, and
c) the factors affecting the properties of the mixtures.

a) The properties of the emulsions

1. A new stable and slow setting cationic emulsion the NH-10 has been developed which is the only one that can coat satisfactorily the dense graded limestone mixtures, conforming to BS594 and BS4987. NH-10 is a mildly cationic emulsion, the emulsifier of which consists of ethylene oxide/nonyl phenol, aluminium chloride and ethoxylated tallow diamine.

2. The type of flow of the cationic emulsions is a function of the type of the emulsifier. NH-10 emulsion possesses a thixotropic flow, while the Redicote E-11 possesses rheopexic type of flow. The thixotropic non-Newtonian behaviour of NH-10 is more distinct at high percentages of binder content (70%).

3. Despite the non-Newtonian flow the NH-10, viscosity measurements between rotational viscometer and glass capillary viscometer (only applicable to Newtonian liquids) have shown good agreement, within the temperature range of 20°C to 25°C. Good relationship was also obtained between dynamic viscosity measured by the rotational viscometer and the Engler viscosity. The relationship found to be as follows:

   $$\text{Dynamic viscosity (cP)} = 1.96 \times (\text{Engler})^{1.32}$$

4. The dynamic viscosity is affected by the binder content and the temperature. An increase in binder content caused an exponential increase in the viscosity and a decrease in temperature caused a further increase in the viscosity. The increase due to binder content was larger than the viscosity increase due to a temperature decrease, specially at binder contents above 65%.

5. Although an increase in temperature reduces the viscosity of the emulsion, temperatures above 30°C should be avoided, when NH-1C

is used, because the coating of the aggregates deteriorates at temperatures above 30°C.

6. The viscosity of NH-10 at 20°C was almost three times higher than the maximum permissible given in the British Standard BS434. Nevertheless it was used successfully in coating dense graded mixtures. This shows the necessity of reviewing the appropriate British Standards.

b) Fundamental differences between gap graded (i.e. C.R.A.) and dense Macadam (i.e. D.E.Mc) mixtures

7. The evaluation of the properties of the Cold Rolled Asphalt (C.R.A.) mixtures (gap graded) and Dense Emulsion Macadams (D.E.Mc) has revealed that there are distinct differences between the two mixtures. In general, C.R.A. mixtures possess lower voids, higher stability values, absorb less water during capillary soaking, retain more stability after 96h soaking, require more binder content, deform slightly more, and their compactability is lower than D.E.Mc mixtures.

8. The other significant difference between the two mixtures is that C.R.A. mixtures due to relatively low volume of air voids can not be compacted easily immediately after mixing. This is because the total liquid content at mixing, and in particular, the free water content, cannot be accommodated in the air voids available and as a result the compactability and the compacted density decreases. D.E.Mc mixtures, on the other hand, can be compacted immediately after mixing.

c) Factors affecting the properties of the gap graded and dense graded Macadam emulsion mixtures

9. The main factors affecting the properties of the emulsion treated mixtures are the binder content, the added water to the aggregate prior to mixing (which is associated with the degree of coating) and the curing of the mixtures. Due to the nature of the mixtures, the binder content is the most important for the C.R.A. mix properties, and the added water for the D.E.Mc mix properties, at a given curing time. Curing improves the stability and the creep stiffness of both mixtures.

10. The binder content significantly affects all the properties of C.R.A. mixtures. Maximum values of wet stability after final curing, and bulk density are obtained at certain binder contents, which can be used for the determination of the optimum binder content of the mixture. The V.M.A. increases suddenly after a certain binder content which can also be used for the determination of the optimum binder content. The increase in binder content increases the rate of deformation and from the exponential curve obtained the maximum binder content can be determined. As expected, the voids decrease and the Marshall flow increases as the binder content increases.

11. The added water significantly affects only the Marshall stability, Marshall quotient, permeability and the water content remaining in the mixture after curing of the C.R.A. mixtures. However, the interaction effect between added water and binder content significantly affects all the properties of the C.R.A. mixtures, specially at the early stage of curing.

12. The permeability of the C.R.A. mixtures is affected significantly by both the binder content and added water. An increase in binder content results in lower permeability (minimum values are reached) and an increase in added water improves the coating which results in higher permeability values. The permeability of C.R.A. correlates well with air voids and water absorption during capillary soaking

specially at the early stage of curing.

13. The retained stability of C.R.A. mixtures, which is used as an indicator of resistance of the mixture to water damage, is affected by both the binder content and water content, at the early stage of curing. In general, the retained stability increases as the binder content increases. Mixtures with high added water content possess lower retained stability.

14. Compacting the C.R.A. at 40°C is beneficial; the compactability of the mixtures improves and as a result the voids and amount of water absorbed is reduced. Similarly, the wet stability and retained stability slightly improves. Compaction at 40°C also provides useful information regarding the optimum binder content for most effective compaction.

15. The added water to the aggregate prior to mixing is the predominant factor affecting the properties of D.E.Mc mixtures. It affects significantly all the properties apart from the Marshall flow and the permanent deformation. Due to the nature of the mixture (relatively low binder contents and high voids) an increase in added water improves coating which result in lower bulk densities and higher air voids. Improvement in aggregate coating results in better stability values (wet and dry) and higher retained stability.

16. The binder content is the second predominant factor which affects the properties of D.E.Mc mixtures, and it affects only the Marshall properties and the voids of the mixtures. The effect of binder on the stability can be seen clearly only on the mixtures which have been cured for 5 days. The dry stability continuously increases as the binder content increases, while the wet stability shows a maximum value at a certain binder content. This can be used exclusively for the determination of binder content.

17. The percentage of water retained in the D.E.Mc mixtures after curing, is significantly affected by both the binder and added water content. Mixtures with high binder and added water content retain more water than others which may cause delays in the development of the properties of the bitumen and possible stripping of the binder.

18. The retained stability of D.E.Mc mixtures, in general, increases as the binder content increases and mixtures with good coating possess higher retained stability. The moisture absorption during the capillary soaking test is related to binder content and air voids; it decreases as the binder content increases and as the air voids decrease. Similar results observed in C.R.A. mixtures.

19. The use of G.T.M. compaction enables the determination of the compactability of the mixtures and in special cases to determine the optimum binder content or total liquid at compaction,for the most efficient compaction.

20. The creep behaviour of C.R.A. mixtures is distinctly different to the creep behaviour of D.E.Mc mixtures. The creep stiffness and the rate of deformation of the C.R.A. mixtures is significantly affected by the binder content and curing time, while the creep characteristics of D.E.Mc are not affected by either of the above two factors. The creep characteristics of the D.E.Mc mixtures are only affected by the degree of coating. Better distribution of binder (i.e. better coating) results in lower rate of deformation and higher creep stiffness. The effect of binder content on the rate of deformation of C.R.A. is such that a maximum binder content can be determined from the exponential relation for an acceptable rate of deformation.

21. The creep test was carried out by the newly designed apparatus called the CANIK U.L. creep testing machine. It is portable, easy to operate under any conditions and it requires only the supply of

compressed air and electricity. The repeatability of the results is very good, for both mixtures used.

22. Good statistical correlation is found between Marshall test and creep test, only for the C.R.A. mixtures. The best correlation exists between the creep strain and Marshall flow (r = 0.990). The correlation between creep stiffness and Marshall quotient came second with correlation coefficient, 'r' equal to 0.904.

In view of the results of the overall investigation and in order to use successfully the dense graded emulsion treated mixtures as a structural material in pavement construction, the following recommendations are in order:

1. The type of flow of the emulsion to be used should be determined and its viscosity and temperature susceptibility should be measured. Emulsions with rheopexic type of flow and/or high viscosity (greater than 200cP at 20°C) and/or high temperature susceptability (greater than 20% for a 10°C change from 20°C) should be avoided.

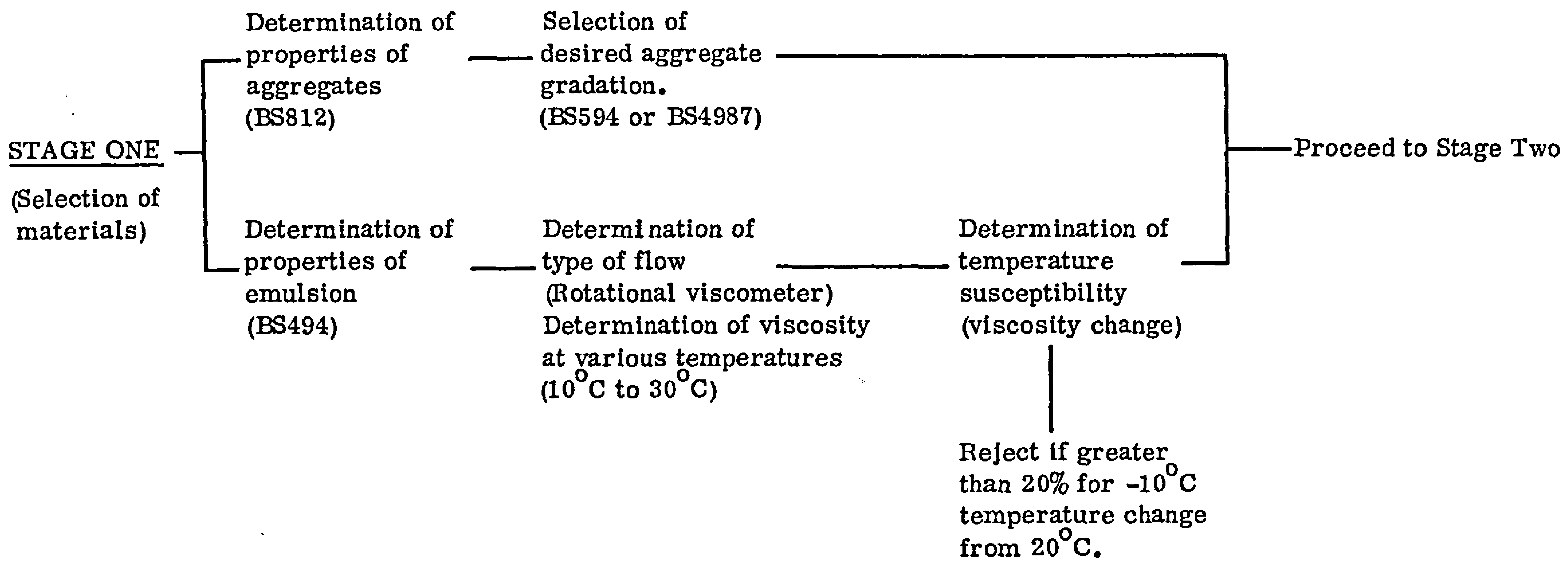
2. It is desirable for emulsion treated mixtures to be aerated for a certain period of time before compaction takes place. Aeration before compaction is essential for the low voids gap-graded, C.R.A. mixtures.

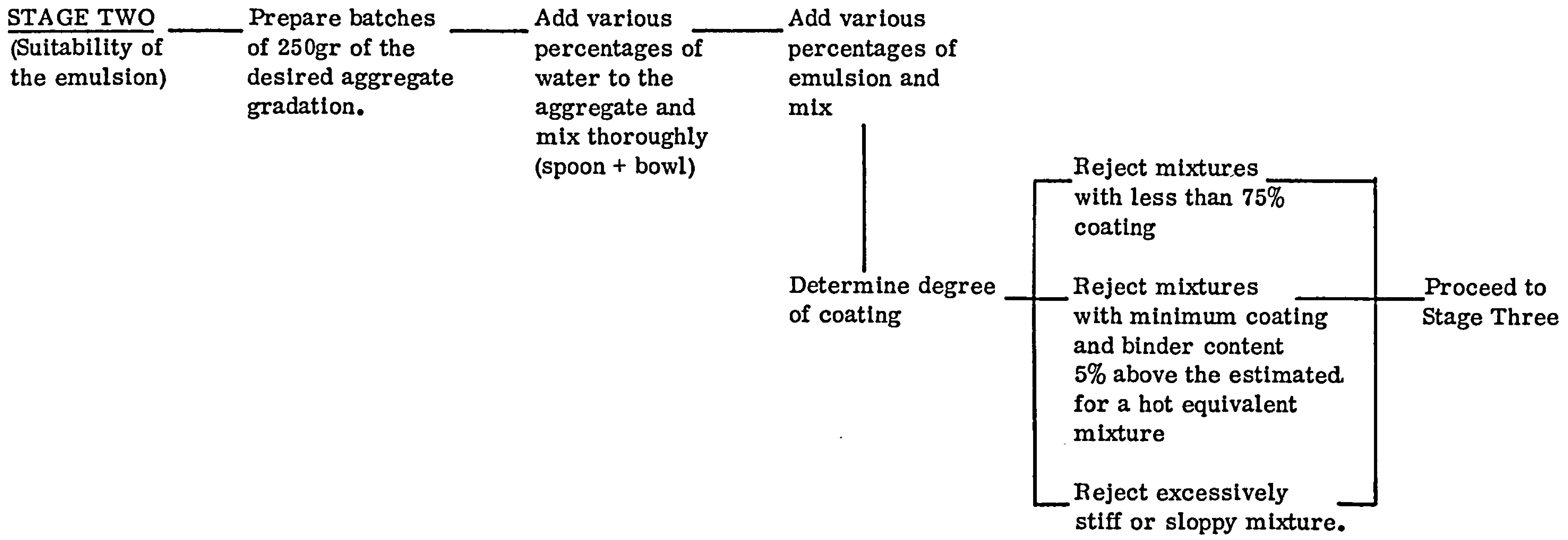
3. The added water content to the aggregate prior to mixing is as important factor as the binder content and both should be determined accurately. The determination of the added water content should not be based on the coating of the aggregate but on its response to the properties of the mixtures in conjunction with binder content. It is recommended that at least two levels of added water and five levels of binder content should be used for the design of an emulsion treated mixture.

4. Two curing periods (early and final) are essential for the evaluation of the properties of the emulsion treated mixtures. Emphasis should be given to the properties of the mixtures at the early curing condition, and in particular to the stability and retained stability of the mixtures.

5. The creep test should always be performed along with the modified Marshall test. This will provide enough information to design an emulsion treated mixture with good stability and good resistance to permanent deformation.

In view of the findings of this research study the following mix design procedure is recommended. The procedure is divided into four stages: Stage one - the selection of materials, Stage two - suitability of the emulsion, Stage three - mix preparation and compaction of the specimens, and Stage four - determination of mixture properties and optimum values of binder and added water content.


STAGE ONE
(Selection of materials)
Determination of properties of aggregates (BS812)
Selection of desired aggregate gradation. (BS594 or BS4987)
Determination of properties of emulsion (BS494)
Determination of type of flow (Rotational viscometer) Determination of viscosity at various temperatures (10°C to 30°C)
Determination of temperature susceptibility (viscosity change)
Reject if greater than 20% for -10°C temperature change from 20°C.
Proceed to Stage Two


STAGE TWO
(Suitability of the emulsion)
Prepare batches of 250gr of the desired aggregate gradation.
Add various percentages of water to the aggregate and mix thoroughly (spoon + bowl)
Add various percentages of emulsion and mix
Determine degree of coating
Reject mixtures with less than 75% coating
Reject mixtures with minimum coating and binder content 5% above the estimated for a hot equivalent mixture
Reject excessively stiff or sloppy mixture.
Proceed to Stage Three

STAGE THREE
(Mix preparation and compaction of specimens)

Prepare desired gradation in batches of 3600gr.

Mix thoroughly (mechanically) for a minimum of 2 minutes and maximum 5 minutes.

Add emulsion (minimum 5 levels) and mix for a further 1½ to 2 min. (mixing should be interrupted for checking aggregate segregation).

Cure the mixtures

Cure gap graded (C.R.A.) mixtures in a 60°C air ventilated oven until desired total moisture content obtained. (Recommended total m/c = 3%)

Curing of the dense graded Macadam mixtures is not essential. Immediate compaction may be followed.

Compact mixtures in 101.6mm dia.mould using a G.T.M. (30 revs, 1° of gyration, 1.38MPa pressure).

Extrude specimens, soon after compaction and cure them for 1 and 5 days (5 days spec. should be placed in a 60°C oven for further two days).

Proceed to stage four

STAGE FOUR (Determination of mix properties and optimum binder and added water content. Three specimens per point.)

Measure density, voids and V.M.A.

Measure air permeability (non destructive test)

Measure dry Marshall stability of 1 and 5 days cured specimens at room temperature.

Place specimens cured for 1 and 5 days for 96h capillary exposure

Measure wet Marshall Stability and Flow

Determine optimum stability value

Accept if greater than 2.3kN

Determine Retained stability of optimum mixture

Reject if less than 40% after one day curing.

Measure creep stiffness of 1 and 2 days cured specimens.

Determine optimum binder content for acceptable permanent deformation (mainly applicable to C.R.A. mixtures)

Determine optimum binder and added water content

Check optimum values with values obtained from creep test and adjust. Final determination of optimum values of binder and added water content.

CHAPTER TWELVE

RECOMMENDATIONS FOR FURTHER RESEARCH

In order to generalise the validity of the results obtained in this investigation and to improve further the properties of the emulsion treated mixtures, the following recommendations are suggested:

1. The thixotropic behaviour of the cationic emulsions should be investigated in terms of its effect on the long term storage and usage.

2. In this study only one type of aggregate, binder and filler was used. In order to assess the influence of aggregate type, nature of filler and bitumen viscosity it is recommended that studies, in the future, be carried out with other types of materials.

3. Since emulsion treated mixtures contain appreciable amounts of water, their resistance to frost effect should be studied.

4. In this investigation the stiffness of the mixtures was evaluated in terms of static stiffness. However, a need exists to evaluate the dynamic stiffness and the resilient modulus of the mixtures in order to be used in structural pavement design.

5. A study should be initiated, using trial sections on various sites such as to study the performance of emulsion treated mixtures under U.K. conditions. This would be of tremendous importance because it would link the laboratory results with the actual performance of the mixtures.

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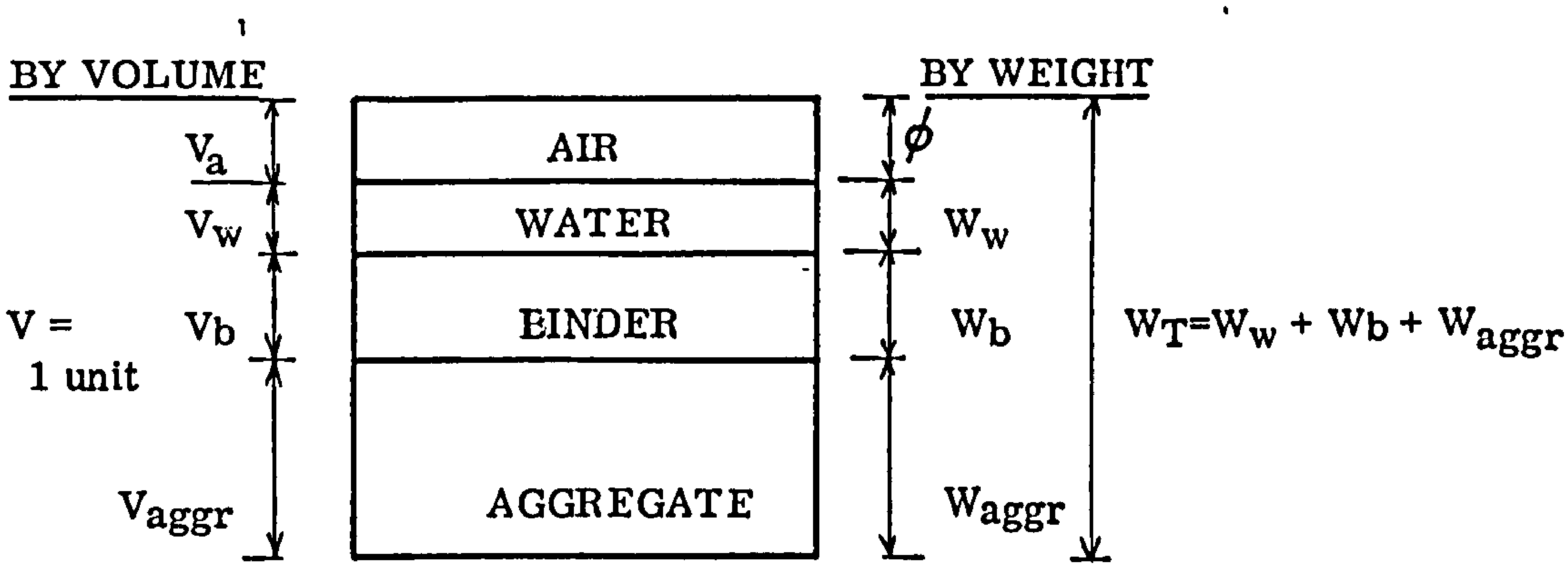
APPENDICES A TO H

APPENDIX A

NOTATION USED THROUGHOUT THE PROJECT WORK



where V = Total Volume of specimen

V_a = Volume of air voids (%)
V_w = Volume of water (cm^3)
V_b = Volume of binder (cm^3)
V_{aggr} = Volume of aggregate (cm^3)

$$V = V_a + V_w + V_b + V_{aggr}$$

$\% V_w$ = Volume of water as percentage of total volume
$\% V_b$ = Volume of binder as percentage of total volume
$\% V_{aggr}$ = Volume of aggregate as percentage of total volume

W_w = Weight of water (gr)
W_b = Weight of binder (gr)
W_{aggr} = Weight of aggregate
W_T = Total weight of the specimen

γ_{th} = theoretical compacted density (gr/cm^3)
γ_m = compacted bulk density of the mixture (gr/cm^3)
γ_d = compacted dry density (gr/cm^3)
G_b = specific gravity of binder (gr/cm^3)
G_{aggr} = specific gravity of mixed aggregate (gr/cm^3)
γ_w = density of water ($=1\ gr/cm^3$)

APPENDIX B

FORMULAE FOR BULK DENSITY, COMPACTED AGGREGATE DENSITY, TOTAL VOIDS, AIR VOIDS V.M.A.

BULK DENSITY, (BD) $= \dfrac{W_T}{W_T - W_{sw}}$, (gr/cm^3)

where W_{sw} = weight of specimen in water, (gr)

COMPACTED AGG. DENSITY (CAD)

(excluding the water) = BD x (1 - Perc.of water) x (1 - Perc of binder), (gr/cm^3)

where Perc. of water = % of water by total water

Perc. of binder = % of binder by total weight

TOTAL VOIDS, (TV) $= \dfrac{100 \times (THD - DCD)}{THD}$, (%)

where THD = Theoretical compacted density

$$= \frac{100}{\dfrac{\%W_{agg}}{G_{aggr}} + \dfrac{\%\,W_{binder}}{G_b} + \%\,W_w}$$

where % W_{aggr} = % of weight of total aggr. by total weight

% W_{binder} = % of binder by total weight

% W_w = % of water by total weight

and DCD = Dry compacted density

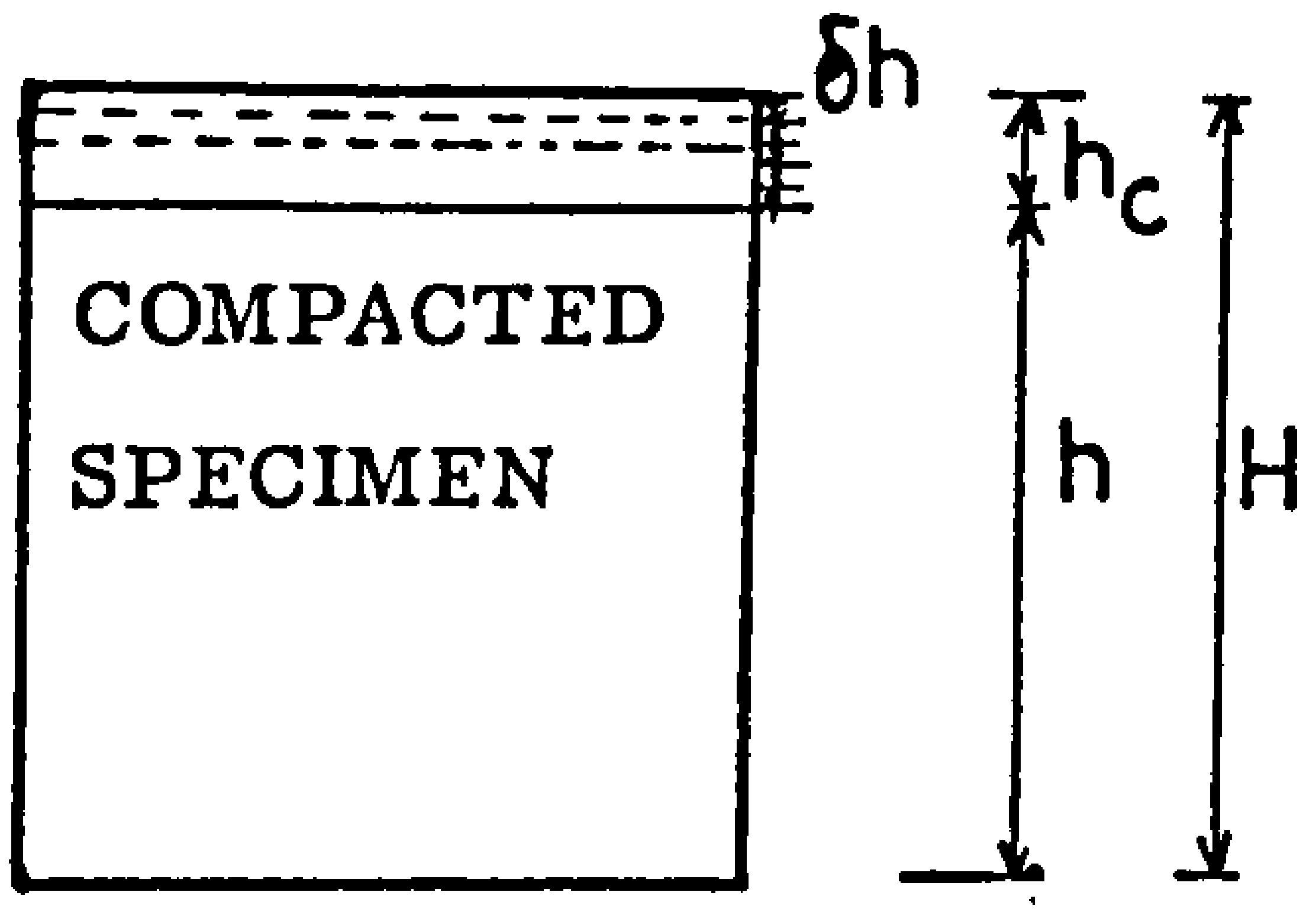
= (BD)/(1 + % W_w)

AIR VOIDS, (AV) $= \dfrac{100 \times (THD - BD)}{THD}$, (%)

Voids in Mineral Aggregate (V.M.A.) = (1 - % W_{aggr} x BD)/G_{aggr}, (%)

APPENDIX C

CALCULATION OF THE CUMULATIVE REDUCTION OF TOTAL VOIDS DURING COMPACTION USING THE G.T.M.



H = specimen's height before compaction (cm)
h = specimen's height after compaction
hc = total height reduction due to compaction (cm)
δ h = cumulative reduction of height due to compaction (cm)

Total Voids at any stage of compaction (TV_{ij})

$$= \frac{\gamma_{th} - \gamma'_{dij} \times 100}{\gamma_{th}} \quad , \quad (\%)$$

where (i, j) = 5 to 30 in steps of 5 revolutions

Dry compacted density at any stage of compaction (γ'_{dij})

$$= \frac{W_T}{A \times (h + \delta h)}$$

where A = Area of the specimen (cm^2)

See also Appendix B.

APPENDIX D

CORRECTION FACTORS TABLE FOR MARSHALL STABILITY

VOLUME RANGE (cm3)	CORRECTION FACTOR
200-213	5.56
214 225	5
226 237	4.55
238 250	4.17
251-264	3.85
265-276	3.57
277-289	3.33
290-301	3.03
302-316	2.78
317-328	2.5
329-340	2.27
341-353	2.08
354-367	1.92
368-379	1.79
380-392	1.67
393-405	1.56
406-420	1.47
421-431	1.39
432-443	1.32
444-456	1.25
457-470	1.19
471-482	1.14
483-495	1.09
496-508	1.04
509-522	1.00
523-535	0.96
536-546	0.93
547-557	0.89
560-573	0.86
574-585	0.83
586-598	0.81
599-610	0.78
611-625	0.76

APPENDIX E - MAIN COMPUTER PROGRAMMES USED, MARCAL 2 FOR MARSHALL DESIGN AND CREGR 1 FOR CREEP CALCULATIONS

```
FILE: MARCAL2  FORTRAN  A   LEEDS UNIVERSITY VM/SP 1.12


C 'MARCAL2' IS THE PROGRAMME WHICH DOES THE REQUIRED MARSHALL
C           CALCULATIONS OF THE EMULSION TREATED MIXTURES.
C           THE PROGRAMME MAY ALSO BE USED WITH CONVENTIONAL
C           MIXTURES PROVITED THAT THE DATA FOR WATER ADDED IS EQUAL
C           TO ZERO AND THE DATA FOR PERCENTAGE OF BINDER CONTENT(PC)
C           IS EQUAL TO 100%.
C THE DATA ARE GIVEN IN FIVE FILES,IN CHANNELS 20,21,22,23 AND 24
C           CHANNEL 20-PERC. OF BINDER CONTENT(IN THE EMULSION)
C           CHANNEL 21-WT.OF AGGR.1,SPEC. GRAVITY OF AGGR.1
C                     -WT.OF AGGR.2,SPEC. GRAVITY OF AGGR.2
C                     -WT.OF AGGR.3,SPEC. GRAVITY OF AGGR.3
C                     -e.t.c
C                     -PERC. OF WATER ABSORPTION BY AGGR.,SPEC. GRAVITY
C                      OF BITUMEN.
C           CHANNEL 22-WT. OF EMULSION USED,WT.OF ADDED WATER,WT.OF
C                      SPECIMEN IMMEDIATELY AFTER COMPACTION,WT.OF
C                      SPEC. AFTER CURING,WT. OF SPEC. IN WATER,HEIGHT
C                      OF THE SPEC.,STABILITY VALUE(IN UNITS,CHECK THE
C                      EQUATION FOR CONVERTING UNITS TO KN),FLOW VALUES
C                      THOUSAND OF AN INCH.
C           CHANNEL 23-CONSTANT DATA FOR CORRECTION OF MARSHALL
C                      STABILITY,i.e.VOLUME RANGE,CORRECTION FACTOR
C           CHANNEL 24-COMPACTION DATA,i.e. NO. OF GTM REVOLUTIONS,
C                      CUMULATIVE HEIGHT CHANGE.
C ALL SETS OF DATA ARE TERMINATED WITH NEGATIVE VALUES.
C
      DIMENSION W(10),D(10),WE(200),WW(200),WA(200),WWS(200),
     1           ST(200),FL(200),B(50),A(50),C(50),X(6),
     2         STKN(200),Y(6),Z(6),TW(200),PER(6),PERB(200),
     1          PERW(200),THD(200),AJD(200),DCS(200),VCS(200),
     2          VMA(200),VOL(200),CST(200),CFL(200),AMQ(200),
     3           PEAG(200),CAGD(200),TWW(200),WB(200),H(200),
     4          AVWC(100),AVBC(100),AVCD(100),AVTV(100),
     5          AVVM(100),AVST(100),AVFL(100),AVMQ(100),
     6       AVTD(100),AVH(100),AVWA(100),DH(100),OH(100),
     7     R5(100),R10(100),R15(100),R20(100),R25(100),R30(100),
     8     D5(100),D10(100),D15(100),D20(100),D25(100),D30(100),
     9     VT5(100),VT10(100),VT15(100),VT20(100),VT25(100),
     *     VT30(100),CR5(100),CR10(100),CR15(100),CR20(100),
     1    CR25(100),GTW(100),WTW(100),WTR(100),PWT(100),WCC(100),
     2    A1(100),A2(100),A3(100),A4(100),A5(100),
     3    AVT1(100),AVT2(100),AVT3(100),AVT4(100),AVT5(100),
     4    AVT6(100),HC(100),ACAD(100),WA1(100),W1(100),W2(100),
     5 .  W3(100),W4(100),DD(100),DDAG(100),TVCS(100),A6(100),PWT1(100),
     6   AVAIR(200)
      DATA IY/'Y'/,IN/'N'/
      WRITE(6,10)
10    FORMAT(' THE PROGRAM DOES ALL THE NECESSARY CALCULATIONS'/
     2' FOR THE MARSHALL TEST USING BITUMINOUS EMULSIONS'/
     3' THE DATA ARE GIVEN IN FOUR FILES'/)
C PB IS THE PERCENTAGE OF BINDER IN THE EMULSION
      READ(20,*)PB
      DO 30 I=1,10
      READ(21,*)W(I),D(I)
C TERMINATE THE DATA WITH A NEGATIVE VALUE
```

```
FILE: MARCAL2  FORTRAN  A   LEEDS UNIVERSITY VM/SP 1.12

      IF (D(I).LT.0.0)GOTO 40
30    CONTINUE
40    M=I-1
      DO 50 I=1,200
      READ(22,*)WE(I),WW(I),WA1(I),WA(I),WWS(I),H(I),ST(I),FL(I)
C TERMINATE THE DATA WITH A NEGATIVE VALUE
      IF (WE(I).LT.0.0)GOTO 60
50    CONTINUE
60    N=I-1
      DO 70 I=1,50
      READ(23,*)A(I),B(I),C(I)
C TERMINATE THE DATA WITH A NEGATIVE VALUE
      IF(A(I).LT.0.0)GOTO 80
70    CONTINUE
80    L=I-1
C CALCULATE THE PERCENTAGE OF AGGR.,BINDER,WATER
      Z(1)=0.0
      Y(1)=0.0
      IM=M-1
      DO 90 I=1,IM
      X(I)=Y(I)+W(I)
      Y(I+1)=X(I)
90    CONTINUE
      DO 100 II=1,IM
      PER(II)=W(II)/X(IM)*100.
100   CONTINUE
      WRITE(6,101)
101   FORMAT(' IS THE WATER CONTENT AT COMPACTION 3% ANSWER Y OR N ')
      READ(5,102)IS
102   FORMAT(A1)
      DO 110 I=1,N
C WT.OF TOTAL WATER
      TWW(I)=WW(I)+(100-PB)/100*WE(I)
C PERC. OF WATER & BINDER CONT. BY DRY AGGR. AT MIXING
      PERW(I)=TWW(I)/X(IM)*100
      PERB(I)=WE(I)*PB/X(IM)
      IF (IS.EQ.IY) GOTO 103
C TOTAL WEIGHT OF MASS AT COMPACTION
      GTW(I)=3600+PB*WE(I)/100+PERW(I)*3600/100
C WATER CONTENT AT COMPACTION BY TOTAL MASS
      WCC(I)=PERW(I)*3600/GTW(I)
      GOTO 104
C TOTAL WEIGHT OF MASS AT COMPACTION
103   GTW(I)=3600+PB*WE(I)/100+0.03*3600
C WATER CONTENT AT COMPACTION BY TOTAL MASS
      WCC(I)=0.03*3600/GTW(I)*100
C TOTAL WEIGHT OF WATER AT COMPACTION
104   WTW(I)=WCC(I)*WA1(I)/100
C WEIGHT OF WATER REMAINED AT TESTING
      WTR(I)=WTW(I)-(WA1(I)-WA(I))
C PERC. OF WATER AT TESTING BY TOTAL MASS
      PWT(I)=WTR(I)/WA(I)*100
C PERC.OF WATER AT TESTING BY DRY AGGR.
      PWT1(I)=WTR(I)/X(IM)*100
      WB(I)=WE(I)*PB/100.
```

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FILE: MARCAL2  FORTRAN  A   LEEDS UNIVERSITY VM/SF 1.12


C TOTAL WT. OF MASS AT TESTING
      TW(I)=X(IM)+WB(I)+3600*PWT1(I)/100
      A1(I)=W(1)/TW(I)/D(1)
      A2(I)=W(2)/TW(I)/D(2)
      A3(I)=W(3)/TW(I)/D(3)
      GAG=3600/(W(1)/D(1)+W(2)/D(2)+W(3)/D(3)+W(4)/D(4))
      PAG=W(1)/TW(I)+W(2)/TW(I)+W(3)/TW(I)+W(4)/TW(I)
      A4(I)=W(4)/TW(I)/D(4)
      A5(I)=WB(I)/TW(I)/D(5)
      A6(I)=3600*PWT1(I)/TW(I)/100/1
      THD(I)=1./(A1(I)+A2(I)+A3(I)+A4(I)+A5(I)+A6(I))
C RELATIVE DENSITY OF COMP. SPECIMEN
      DCS(I)=WA(I)/(WA(I)-WWS(I))
C COMPACT. AGGR DENSITY
      CAGD(I)=DCS(I)/(1+(WB(I)/TW(I)))
C  DRY COMP. DENS.
      DD(I)=DCS(I)/(1+PWT(I)/100.)
C COMP. AGGR. DENS. BASED ON DRY COMP. DENS.
      DDAG(I)=DCS(I)*(1-PWT(I)/100.)*(1-WB(I)/TW(I))
C AIR VOIDS IN THE COMP. SPEC.
      VCS(I)=100*(THD(I)-DCS(I))/THD(I)
C  TOTAL VOIDS IN COMP. SPEC.
      TVCS(I)=100*(THD(I)-DD(I))/THD(I)
C VOIDS IN THE MINERAL AGGR.
      VMA(I)=(1-PAG*DCS(I)/GAG)*100
      VOL(I)=ANINT(H(I)*101.6*101.6*3.14159/4/1000.)
      IF (VOL(I).LT.A(1).OR.VOL(I).GT.B(33)) GOTO 999
C STABILITY IN KN
      STKN(I)=.0612*ST(I)-.0013
      DO 120 IK=1,L
      IF (VOL(I).GE.A(IK).AND.VOL(I).LE.B(IK)) GOTO 130
120   CONTINUE
130   CST(I)=STKN(I)*C(IK)
C FLOW IN MILIMETERS
      CFL(I)=FL(I)*0.001*25.4
C MARHALL QUOTIENT
      AMQ(I)=CST(I)/CFL(I)
110   CONTINUE
      K=1
      IL=N/3
      DO 200 II=1,IL
      AVBC(II)=(PERB(K)+PERB(K+1)+PERB(K+2))/3
      AVWC(II)=(PERW(K)+PERW(K+1)+PERW(K+2))/3
      AVCD(II)=(DD(K)+DD(K+1)+DD(K+2))/3
      ACAD(II)=(DDAG(K)+DDAG(K+1)+DDAG(K+2))/3
      AVTV(II)=(TVCS(K)+TVCS(K+1)+TVCS(K+2))/3
      AVVM(II)=(VMA(K)+VMA(K+1)+VMA(K+2))/3
      AVST(II)=(CST(K)+CST(K+1)+CST(K+2))/3
      AVFL(II)=(CFL(K)+CFL(K+1)+CFL(K+2))/3
      AVMQ(II)=(AMQ(K)+AMQ(K+1)+AMQ(K+2))/3
      AVTD(II)=(THD(K)+THD(K+1)+THD(K+2))/3
      AVH(II)=(H(K)+H(K+1)+H(K+2))/3
      AVWA(II)=(WA(K)+WA(K+1)+WA(K+2))/3
      AVAIR(II)=(VCS(K)+VCS(K+1)+VCS(K+2))/3
      K=K+3
```

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FILE: MARCAL2  FORTRAN  A   LEEDS UNIVERSITY VM/SF 1.12

200    CONTINUE
       WRITE(7,140)PER(M-(M-1)),PER(M-(M-2)),PER(M-(M-3))
      1,PER(M-(M-4)),W(M),D(M)
140    FORMAT(3X,'PERCENT.OF COARCE AGGR.  =',F10.2,3X,'0/0'/
      2        3X,'PERCENT.OF FINE AGGR.    =',F10.2,3X,'0/0'/
      3        3X,'PERCENT.OF DUST AGGR.    =',F10.2,3X,'0/0'/
      4       3X,'PERCENT.OF FILLER        =',F10.2,3X,'0/0'/
      5      3X,'WATER ABSORPTION OF AGGR.=',5X,F5.2,3X,'0/0'/
      6        3X,'DENSITY OF BINDER        =',5X,F5.3,3X,'G/CM3'//)
       WRITE(7,150)
150       FORMAT(' SPEC.',2X,'WATER',3X,'BINDER',2X,'W.C AT ',
      *           2X,'COMPACTED TOTAL ',
      *        'COMPACTED',3X,'VOIDS MINER.',
      1  3X,'MARSHALL  MARSHALL MARSHALL  AIR'/' NO.',4X,'CNT',
      2       5X,'CONT.',3X,'TESTING', 2X,'DENSITY',3X,'VOIDS AGGR.DENS.',
      *     '  AGGREGATE      STABILITY FLOW',
      3   5X,'QUOTIENT  VOIDS'/8X,'0/0',5X,'0/0',7X,'0/0',5X,'G/CM3',4X,
      4 '0/0',5X,'G/CM3',8X,'0/0',9X,'KN',8X,'MM',7X,'KN/MM',6X,'0/0'/
      5' ==============================================',
      6'=====================================================================/)
       DO 160 I=1,N
       WRITE(7,170)I,PERW(I),PERB(I),PWT(I),DD(I),TVCS(I),DDAG(I),VMA(I),
      1         CST(I),CFL(I),AMQ(I),VCS(I)
170    FORMAT(I3,4X,F5.2,3X,F5.2,3X,F5.2,5X,F5.3,5X,F5.2,3X,F5.3,6X,F5.2,
      2       9X,F5.2,5X,F5.2,5X,F5.2,5X,F5.2)
160    CONTINUE
       WRITE(7,210)
210    FORMAT(' ==================================================',
      1        '======================================================'/,
      2        ' *',10X,'A V E R A G E   V A L U E S   O F   T H R E E',
      3        '  S P E C I M E N S',4X,'*'/' ====================',
      4        '================================================',
      5        '========================================'/,
      5        ' *TYPE ',2X,'WATER',3X,'BINDER',2X,'COMPACTED TOTAL ',
      6 'COMPACTED',3X,'VOIDS MINER.',3X,'MARSHALL  MARSHALL MARSHALL',
      *  2X,'AIR      *'/,
      7     ' * OF',4X,'CONT.',3X,'CONT.   DENSITY',3X,'VOIDS AGGR.DE',
      8'NS  ',' AGGREGATE      STABILITY FLOW',5X,'QUOTIENT',2X,
      9 'VOIDS    *'/' *MIX.',3X,'0/0',5X,'0/0',5X,'G/GM3',5X,'0/0',4X,
      * 'G/CM3',8X,'0/0',11X,'KN',7X,'MM',8X,'KN/MM',5X,'0/0',4X,'*'/,
      1     '=======================================================',
      2     '========================================================'/)
       DO 215 LK=1,IL
       WRITE(7,220)LK,AVWC(LK),AVBC(LK),AVCD(LK),AVTV(LK),
      1        ACAD(LK),AVVM(LK),AVST(LK),AVFL(LK),AVMQ(LK),AVAIR(LK)
220    FORMAT(1X,I3,4X,F5.2,3X,F5.2,4X,F5.3,5X,F5.2,3X,F5.3,7X,F5.2,
      2       8X,F5.2,5X,F5.2,4X,F5.2,4X,F5.2/)
215    CONTINUE
       WRITE(7,230)
230    FORMAT(' =========================================',
      1      '==============================================')
       DO 300 IA=1,N
       READ(24,*)R5(IA),R10(IA),R15(IA),R20(IA),R25(IA),
      1          R30(IA)
       IF (R5(IA).LT.0.0) GOTO 310
```

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FILE: MARCAL2  FORTRAN  A   LEEDS UNIVERSITY VM/SP 1.12


300    CONTINUE
310    DO 320 IB=1,N
       DH(IB)=R30(IB)*0.001*24.5
       HC(IB)=40*WA(IB)/(10.16*10.16*3.14159*DD(IB))
       OH(IB)=DH(IB)+HC(IB)
       CR5(IB)=R5(IB)*0.001*24.5
       CR10(IB)=R10(IB)*0.001*24.5
       CR15(IB)=R15(IB)*0.001*24.5
       CR20(IB)=R20(IB)*0.001*24.5
       CR25(IB)=R25(IB)*0.001*24.5
       D5(IB)=WA(IB)/((OH(IB)-CR5(IB))*101.6*101.6*3.14159/4/1000)
       D10(IB)=WA(IB)/((OH(IB)-CR10(IB))*101.6*101.6*3.14159/4/1000)
       D15(IB)=WA(IB)/((OH(IB)-CR15(IB))*101.6*101.6*3.14159/4/1000)
       D20(IB)=WA(IB)/((OH(IB)-CR20(IB))*101.6*101.6*3.14159/4/1000)
       D25(IB)=WA(IB)/((OH(IB)-CR25(IB))*101.6*101.6*3.14159/4/1000)
       D30(IB)=WA(IB)/(HC(IB)*101.6*101.6*3.14159/4/1000)
       VT5(IB)=100*(THD(IB)-D5(IB))/THD(IB)
       VT10(IB)=100*(THD(IB)-D10(IB))/THD(IB)
       VT15(IB)=100*(THD(IB)-D15(IB))/THD(IB)
       VT20(IB)=100*(THD(IB)-D20(IB))/THD(IB)
       VT25(IB)=100*(THD(IB)-D25(IB))/THD(IB)
       VT30(IB)=100*(THD(IB)-D30(IB))/THD(IB)
320    CONTINUE
       KL=1
       DO 325 I=1,IL
       AVT1(I)=(VT5(KL)+VT5(KL+1)+VT5(KL+2))/3
       AVT2(I)=(VT10(KL)+VT10(KL+1)+VT10(KL+2))/3
       AVT3(I)=(VT15(KL)+VT15(KL+1)+VT15(KL+2))/3
       AVT4(I)=(VT20(KL)+VT20(KL+1)+VT20(KL+2))/3
       AVT5(I)=(VT25(KL)+VT25(KL+1)+VT25(KL+2))/3
       AVT6(I)=(VT30(KL)+VT30(KL+1)+VT30(KL+2))/3
       KL=KL+3
325    CONTINUE
       WRITE(7,330)
330    FORMAT(' *',10X,'D A T A   F O R   C O M P A C T I O N',
     1      '  C U R V E S   ',12X,'*'/' =====================',
     2     '==================================================',
     3     '====='/
     3      ' * TYPE   VOIDS   VOIDS   VOIDS   VOIDS   VOIDS',
     4      '   VOIDS',20X,'*'/' *  OF     5REVS   10REV   15REV',
     5      '   20REV   25REV   30REV',20X,'*'/' * MIX     0/0     0/0',
     6      '     0/0     0/0     0/0     0/0',22X,'*'/
     7     '==================================================',
     8     '============================')
       DO 340 LC=1,N
       WRITE(7,350)LC,VT5(LC),VT10(LC),VT15(LC),VT20(LC),
     8           VT25(LC),VT30(LC)
350    FORMAT(2X,I3,5X,F5.2,3X,F5.2,3X,F5.2,3X,F5.2,3X,
     9      F5.2,3X,F5.2)
340    CONTINUE
       WRITE(7,345)
345    FORMAT(' *  A V E R A G E   V A L U E S   O F   T H R E E',
     1        '  S P E C I M E N S',4X,'*'/'==================',
     2        '==============================================',
     3        '=====')
```

```
FILE: MARCAL2  FORTRAN  A   LEEDS UNIVERSITY VM/SP 1.12

       DO 360 I=1,IL
       WRITE(7,370)I,AVT1(I),AVT2(I),AVT3(I),AVT4(I),
     1            AVT5(I),AVT6(I)
370    FORMAT(2X,I3,5X,F5.2,3X,F5.2,3X,F5.2,3X,F5.2,3X,
     1       F5.2,3X,F5.2/)
360    CONTINUE
       GOTO 1000
999    WRITE(7,998)I
998    FORMAT(2X,'THERE IS AN ERROR IN YOUR DATA.CHECK THE',
     2       'VOLUME OF YOUR SPECIMENS,SPECIMEN NO.',I2,
     3       'IS OUT OF RANGE FOR CORRECTION')
1000   STOP
       END
```

```
C 'CREGR1' HAS BEEN WRITEN  FOR THE CALCULATIONS REQUIRED IN
C          THE STATIC CREEP TEST.ALTHOUGH THE PROGRAMME HAS BEEN
C          DEVELOPED TO BE USED WITH EMULSION TREATED MIXTURES IT CAN
C          ALSO BE USED WITH CONVENTIONAL MIXTURES.THE MODIFICATIONS
C          REQUIRED ARE MINOR.
C          IT USES THE TEST DATA OF TWO SAMPLES (IN TERMS OF
C          CUMULATIVE DEFORMATION AND LOADING TIME).IT CALCULATES
C          THE STIFFNESS OF THE MIXTURE AND TABULATES THE RESULTS IN
C          TERMS OF LOADING TIME,DEFORMATION,STRAIN AND STIFFNESS OF THE
C          MIX.THE PROGRAMME ALSO PRINTS THE CONSTANT COEFFICIENT,THE
C          SLOPE AND THE CORRELATION COEFFICIENT OF ALL THE NECESSARY
C          CREEP CURVES(BEST FIT STRAIGHT LINE METHOD HAS BEED USED).
C          THE STIFFNESS OF THE BITUMEN USED IS CALCULATED FROM THE
C          VAN DE POELS NOMOGRAPH.
C
C THE DATA ARE GIVEN IN ONE FILE,FROM CHANNEL 11,AS FOLLOWS:
C INPUT LINE ONE:HEIGHT OF SPEC1,HEIGHT OF SPEC2,STRESS LEVEL USED,
C                BINDER CONTENT AND ADDED WATER CONTENT.
C INPUT LINE TWO:LOADING TIME,CUM.DEFORMATION1,CUM.DEFORMATION2,
C                STIFFNESS OF THE BITUMEN.
C EACH SET OF DATA(OF TWO SAMPLES) ARE TERMINATED BY FOUR NEGATIVE
C NUMBERS(ANY),WHILE THE WHOLE SET OF DATA BY 999 FOLLOWED BY FOUR
C NUMBERS(ANY).
       DIMENSION  T(20),D1(20),D2(20),SB(20),AVSE(20),AVD(20),
     1      SE1(20),SE2(20),SM1(20),SM2(20),AVSM(20),SM(20),
     2      NSE1(20),NSE2(20),NSM1(20),NSM2(20),NAVSE(20),NAVSM(20),
     3      AX(2),AY1(2),AY2(2),AXX(2),ANY(2),BXX(2),BNY(2),
     4      NSMM1(20),NSMM2(20),NAVM1(20)
       DO 111 III=1,10
       N=0
       READ(11,*)H1,H2,STRS,BC,WC
       IF(H1.EQ.999)GOTO 1000
       DO 10 I=1,20
       READ(11,*)T(I),D1(I),D2(I),SB(I)
       IF(T(I).LT.0.0)GOTO 20
       N=N+1
10     CONTINUE
20     DO 25 I=1,N
       AVD(I)=(D1(I)+D2(I))/2
       SE1(I)=D1(I)/H1
       SE2(I)=D2(I)/H2
       SM1(I)=STRS/SE1(I)*1000000
       SM2(I)=STRS/SE2(I)*1000000
       AVSM(I)=(SM1(I)+SM2(I))/2
       AVSE(I)=(SE1(I)+SE2(I))/2
25     CONTINUE
C BEST FIT STR. LINE
       CALL BEFIT(T,SE1,A1,B1,R1,NSE1,N)
       CALL BEFIT(T,SE2,A2,B2,R2,NSE2,N)
       CALL BEFIT(T,SM1,A5,B5,R5,NSMM1,N)
       CALL BEFIT(T,SM2,A6,B6,R6,NSMM2,N)
       CALL BEFIT(SB,SM1,A3,B3,R3,NSM1,N)
       CALL BEFIT(SB,SM2,A4,B4,R4,NSM2,N)
       CALL BEFIT(T,AVSE,CE,BE,RE,NAVSE,N)
       CALL BEFIT(SB,AVSM,CS,BS,RS,NAVSM,N)
```

```
       CALL BEFIT(T,AVSM,CS1,BS1,RS1,NAVM1,N)
       WRITE(6,30)BC,WC,STRS
30     FORMAT(' BINDER CONTENT =',F4.1,' O/O',
     1        '   WATER ADDED =',F3.1,' O/O',
     2        '   STRESS LEVEL =',F3.1,' MN/M2')
       WRITE(6,40)H1
40     FORMAT(' HEIGHT OF SPECIMEN =',F4.1,'MM')
       WRITE(6,50)
50     FORMAT(' LOADING   DEFORMATION     STRAIN      MIXTURE',
     1'          BINDER    '/' TIME',34X,'STIFFNESS        STIFFNESS'/
     2        '  (SECS)          (MM)',19X,'    (N/M2)',4X,'    (N/M2)')
       DO 55 I=1,N
       WRITE(6,60)T(I),D1(I),SE1(I),SM1(I),SB(I)
60     FORMAT(2X,F6.1,5X,F5.3,7X,E10.3,3X,E10.3,5X,E10.3)
55     CONTINUE
       WRITE(6,40)H2
       WRITE(6,50)
       DO 65 I=1,N
65     WRITE(6,60)T(I),D2(I),SE2(I),SM2(I),SB(I)
       WRITE(6,70)
70     FORMAT('A V E R A G E  O F  T W O  S P E C I M E N S')
       WRITE(6,30)BC,WC,STRS
       WRITE(6,50)
       DO 80 I=1,N
80     WRITE(6,60)T(I),AVD(I),AVSE(I),AVSM(I),SB(I)
       WRITE(6,90)
90     FORMAT(' THE FOLLOWING NOTATION HAS BEEN USED THROUGHOUT'/
     1        '         C=CONSTANT'/
     2        '         B=SLOPE'/
     3        '         R=CORRELATION COEFFICIENT')
       WRITE(6,40)H1
       WRITE(6,105)A5,B5,R5
105    FORMAT(' STIFFNESS V LOADING TIME EQUAT.'/' C=',E10.3,
     1       3X'B=',E10.3,3X,'R=',F6.4)
       WRITE(6,40)H2
       WRITE(6,105)A6,B6,R6
       WRITE(6,40)H1
       WRITE(6,100)A1,B1,R1
100    FORMAT(' STRAIN V TIME EQUAT'/' C=',E10.3,3X,'B=',E10.3,
     1       3X,'R=',F6.4)
       WRITE(6,40)H2
       WRITE(6,100)A2,B2,R2
       WRITE(6,40)
       WRITE(6,110)A3,B3,R3
110    FORMAT(' STIFFNESS OF MIX V STIFFNESS OF BITUMEN EQUAT.'/
     1        ' C=',E10.3,3X,'B=',E10.3,3X,'R=',F6.4)
       WRITE(6,40)H2
       WRITE(6,110)A4,B4,R4
       WRITE(6,70)
       WRITE(6,105)CS1,BS1,RS1
       WRITE(6,100)CE,BE,RE
       WRITE(6,110)CS,BS,RS
       AX(1)=1
       AX(2)=10000
       AY1(1)=0.001
```

```
FILE: CREGR1    FORTRAN  A    LEEDS UNIVERSITY VM/SP 1.12

      AY1(2)=0.1
      AY2(1)=1000000
      AY2(2)=100000000
      AXX(1)=5.0
      AXX(2)=9000.0
      ANY(1)=(CE)*AXX(1)**BE
      ANY(2)=(CE)*AXX(2)**BE
      BXX(1)=4.0
      BXX(2)=5000
      BNY(1)=(CS)*BXX(1)**BS
      BNY(2)=(CS)*BXX(2)**BS
      CALL SIZE(-500)
      CALL PAGE(19.0,27.0)
      CALL JBAXES(AX,-2,12.0,'LOADING TIME (SECS)',19,
     1            AY1,-2,15.0,'STRAIN',6)
      DO 801 I=1,N
      CALL MARKPT(T(I),SE1(I),1)
801   CALL MARKPT(T(I),SE2(I),2)
      CALL BRKNCV(AXX,ANY,2,0)
      CALL SETKY('T','R',3,18)
      CALL MARKKY(1,'SPECIMEN NO.1',13)
      CALL MARKKY(2,'SPECIMEN NO.2',13)
      CALL LINEKY(0,'BEST STRAIGHT LINE',18)
      CALL TITLE('H','L','STRESS         0.1 MN/M2',22)
      CALL TITLE('H','L','BINDER CONTENT      0/0',22)
      CALL TITLE('H','L','WATER ADDED         0/0',22)
      CALL TITLE('L','C','STRAIN',6)
      CALL TITLE('L','C','   V  ',6)
      CALL TITLE('L','C','LOADING TIME',12)
      CALL JBAXES(AX,-2,12.0,'STIFFNESS OF BITUMEN (N/M2)',27,
     1            AY2,-2,15.0,'STIFFNESS OF MIXTURE (N/M2)',27)
      DO 901 I=1,N
      CALL MARKPT(SB(I),SM1(I),1)
      CALL MARKPT(SB(I),SM2(I),2)
901   CONTINUE
      CALL BRKNCV(BXX,BNY,2,0)
      CALL SETKY('T','R',3,18)
      CALL MARKKY(1,'SPECIMEN NO.1',13)
      CALL MARKKY(2,'SPECIMEN NO.2',13)
      CALL LINEKY(0,'BEST STRAIGHT LINE',18)
      CALL TITLE('H','L','STRESS         0.1 MN/M2',22)
      CALL TITLE('H','L','BINDER CONTENT      0/0',22)
      CALL TITLE('H','L','WATER ADDED         0/0',22)
      CALL TITLE('L','C','STIFFNESS OF MIXTURE',20)
      CALL TITLE('L','C','         V          ',20)
      CALL TITLE('L','C','STIFFNESS OF BITUMEN',20)
 111  CONTINUE
 1000 CALL ENDPLT
      STOP
      END
      SUBROUTINE BEFIT(X1,Y1,A,B,R,NY,N)
      DIMENSION X(20),Y(20),NY(20),X1(20),Y1(20)
      DO 800 I=1,N
      X(I)=ALOG10(X1(I))
      Y(I)=ALOG10(Y1(I))
```

```
FILE: CREGR1    FORTRAN  A    LEEDS UNIVERSITY VM/SP 1.12

800   CONTINUE
      SUMX=0.0
      SUMY=0.0
      SUMXY=0.0
      SUMX2=0.0
      SUMY2=0.0
      DO 900 I=1,N
      SUMX=SUMX+X(I)
      SUMY=SUMY+Y(I)
      SUMXY=SUMXY+X(I)*Y(I)
      SUMX2=SUMX2+X(I)*X(I)
      SUMY2=SUMY2+Y(I)*Y(I)
900   CONTINUE
      AVX=SUMX/N
      AVY=SUMY/N
      SDX=SQRT(SUMX2/N-AVX*AVX)
      SDY=SQRT(SUMY2/N-AVY*AVY)
      B=(SUMXY-SUMX*SUMY/N)/(SUMX2-SUMX*SUMX/N)
      A=10**(SUMY/N-B*SUMX/N)
      R=(SUMXY/N-AVX*AVY)/SDX/SDY
C CALCULATE THE NEW Y VALUES
      DO 910 I=1,N
910   NY(I)=B*X(I)+A
      RETURN
      END
```

APPENDIX F

ANALYSIS OF VARIANCE OUTPUT (EXAMPLE)

```
SPSS BATCH SYSTEM                                                                   12/23/82          PAGE     1

SPSS FOR VM/CMS, VERSION M, RELEASE 9.0, OCTOBER 1, 1981

                                          CURRENT DOCUMENTATION FOR THE SPSS BATCH SYSTEM
ORDER FROM MCGRAW-HILL:  SPSS, 2ND ED. (PRINCIPAL TEXT)          ORDER FROM SPSS INC.:  SPSS STATISTICAL ALGORITHMS
                         SPSS UPDATE 7-9 (USE W/SPSS,2ND FOR REL. 7, 8, 9)              KEYWORDS: THE SPSS INC. NEWSLETTER
                         SPSS POCKET GUIDE, RELEASE 9
                         SPSS PRIMER (BRIEF INTRO TO SPSS)

DEFAULT SPACE ALLOCATION..      ALLOWS FOR..    102 TRANSFORMATIONS
WORKSPACE      71680 BYTES                      409 RECODE VALUES + LAG VARIABLES
TRANSPACE      10240 BYTES                     1641 IF/COMPUTE OPERATIONS

                  1 RUN NAME        ANOVA OF ONE-DAY DRY CRETM
                  2 FILE NAME       DE.VO.VM.ST.FL.MQ WITH BINDER,ADWATER,TLIQUID
                  3 VARIABLE LIST   BINDER,ADWATER,TLIQUID,WATEST,BDENSITY,VOIDS,VMA/
                  4                 STABILITY,FLOW,MQUOTIENT
                  5 INPUT FORMAT    FREEFIELD
                  6 N OF CASES      54
                  7 VAR LABELS      BINDER      BINDER CONTENT/
                  8                 ADWATER     ADDED WATER/
                  9                 TLIQUID     TOTAL LIQUID/
                 10                 WATEST      WATER AT TESTING
                 11                 BDENSITY    BULK DENSITY/
                 12                 VOIDS       PERC. OF VOIDS/
                 13                 VMA         VOIDS IN THE MINERAL AGGREGATE/
                 14                 STABILITY   DRY STABILITY AFTER ONE DAY/
                 15                 FLOW        DRY FLOW/
                 16                 MQUOTIENT   DRY MARSHALL QUOTIENT/
                 17 VALUE LABLES    ADWATER  (1) 1.5 PERCENT (2) 3.0 PERCENT (3) 4.5 PERCENT
                 18                 BINDER  (1) 7 PERC. (2) 8 PERC. (3) 9 PERC./
                 19                         (4) 10 PERC. (5) 11 PERC. (6) 12 PERC.
                 20 MISSING VALUES ALL (0)
                 21 MANOVA           STABILITY BY BINDER(1,6) ADWATER(1,3)
                 22 STATISTICS      ALL
                 23 READ INPUT DATA


ANOVA OF ONE-DAY DRY CRETM                                                          12/23/82          PAGE     2

FILE   DE.VO.VM (CREATION DATE = 12/23/82)   WITH BINDER,ADWATER,TLIQUID

* * * * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E * * * * * * * * * * * * * * * * * * * *

    54 CASES ACCEPTED.
     0 CASES REJECTED BECAUSE OF OUT-OF-RANGE FACTOR VALUES.
     0 CASES REJECTED BECAUSE OF MISSING DATA.
    18 NON-EMPTY CELLS.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

CORRESPONDENCE BETWEEN EFFECTS AND COLUMNS OF BETWEEN-SUBJECTS DESIGN

 STARTING  ENDING
  COLUMN   COLUMN    EFFECT NAME

     1        1      CONSTANT
     2        6      BINDER
     7        8      ADWATER
     9       18      BINDER BY ADWATER

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
ANOVA OF ONE-DAY DRY CRETM                                                    12/23/82        PAGE    3

* * * * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E * * * * * * * * * * * * * * * * * * * *

 TESTS OF SIGNIFICANCE FOR STABILIT USING SEQUENTIAL SUMS OF SQUARES

 SOURCE OF VARIATION                          SUM OF SQUARES        DF    MEAN SQUARE          F      SIG. OF F

 WITHIN CELLS                                      23.62524          36        .65626
 CONSTANT                                        7192.41950           1    7192.41950  10959.76518         0.0
 BINDER                                            17.91767           5       3.58353      5.46057        .001
 ADWATER                                           53.01924           2      26.50962     40.39520         0.0
 BINDER BY ADWATER                                 47.27556          10       4.72756      7.20382         0.0

 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -


 ESTIMATES FOR STABILIT

 CONSTANT

  PARAMETER        COEFF.        STD. ERR.        T-VALUE        SIG. OF T    LOWER .95 CL    UPPER .95 CL

          1   11.5409251672         .11024      104.68890             0.0        11.31735        11.76450

 BINDER

  PARAMETER        COEFF.        STD. ERR.        T-VALUE        SIG. OF T    LOWER .95 CL    UPPER .95 CL

          2   -1.0809254470         .24650       -4.38501            .000        -1.58086        -.58099
          3    -.2264812611         .24650        -.91877            .364         -.72642         .27345
          4     .1446299730         .24650         .58672            .561         -.35530         .64456
          5     .4490741800         .24650        1.82177            .077         -.05086         .94901
          6    -.0264812399         .24650        -.10743            .915         -.52642         .47345

 ADWATER

  PARAMETER        COEFF.        STD. ERR.        T-VALUE        SIG. OF T    LOWER .95 CL    UPPER .95 CL

          7   -1.2987034939         .15590       -8.33019             0.0        -1.61489        -.98252
          8     .1935188152         .15590        1.24128            .223         -.12267         .50971

 BINDER BY ADWATER

  PARAMETER        COEFF.        STD. ERR.        T-VALUE        SIG. OF T    LOWER .95 CL    UPPER .95 CL

          9    1.0220368527         .34861        2.93175            .006          .31502        1.72905
         10   -1.1068520723         .34861       -3.17504            .003        -1.81387        -.39984
         11    1.0742587867         .34861        3.08155            .004          .36724        1.78127
         12    1.0020365538         .34861        2.87438            .007          .29502        1.70905
         13    -.0235185800         .34861        -.06746            .947         -.73053         .68350
         14    -.1724076448         .34861        -.49456            .624         -.87942         .53461
         15    -.6112965654         .34861       -1.75352            .088        -1.31831         .09572
```

APPENDIX G

LINEAR REGRESSION ANALYSIS OF COMPACTION CURVES

Binder Content	Specimen No. 1			Specimen No. 2			Specimen No. 3		
	b	a x10^{-3}	r	b	a x10^{-3}	r	b	a x10^{-3}	r
COMPACTION AT 40°C/ONE DAY CURING									
DRY TESTING									
7	1.15	-6.07	-0.991	1.19	-6.34	-0.981	1.11	-5.09	-0.98
8	1.14	-6.09	-0.985	1.11	-6.64	-0.982	1.11	-7.55	-0.98
9	1.02	-6.36	-0.957	1.02	-6.89	-0.950	0.99	-6.49	-0.96
10	0.95	-5.11	-0.920	0.92	-5.85	-0.923	0.92	-6.28	-0.95
11	0.90	-1.95	-0.980	0.87	-3.81	-0.980	0.88	-5.78	-0.96
12	0.83	-3.51	-0.970	0.70	-8.99	-0.981	0.82	-3.86	-0.99
WET TESTING									
7	1.17	-5.21	-0.98	1.17	-6.15	-0.99	1.21	-5.12	-0.99
8	1.09	-7.88	-0.99	1.08	-7.16	-0.99	1.13	-7.03	-0.99
9	1.02	-6.87	-0.96	0.98	-7.03	-0.97	1.03	-6.68	-0.96
10	0.97	-6.87	-0.95	0.94	-6.64	-0.95	0.97	-5.40	-0.95
11	0.93	-1.68	-0.98	0.93	-2.35	-0.99	0.88	-5.12	-0.95
12	0.82	-3.74	-0.97	0.79	-5.03	-0.96	0.82	-4.29	-0.98
COMPACTION AT 20°C/ONE DAY CURING									
DRY TESTING									
7	1.21	-6.64	-0.991	1.22	-5.96	-0.991	1.21	-6.46	-0.990
8	1.57	-7.39	-0.982	1.14	-5.89	-0.991	1.17	-7.25	-0.993
9	1.15	-7.64	-0.990	1.16	-5.93	-0.990	1.16	-8.21	-0.991
10	1.16	-7.70	-0.990	1.16	-7.88	-0.993	1.16	-8.20	-0.992
11	1.05	-9.73	-0.989	1.03	-11.08	-0.990	1.04	-10.37	-0.987
12	1.11	-10.09	-0.990	1.05	-9.64	-0.985	1.08	-9.87	-0.990
WET TESTING									
7	1.26	-4.90	-0.991	1.25	-5.10	-0.990	1.26	-4.64	-0.983
8	1.19	-6.84	-0.990	1.20	-6.38	-0.986	1.22	-6.53	-0.991
9	1.13	-9.28	-0.990	1.10	-10.73	-0.994	1.10	-11.06	-0.990
10	1.20	-8.44	-0.991	1.19	-7.80	-0.952	1.20	-7.96	-0.992
11	1.17	-8.86	-0.993	1.18	-8.60	-0.988	1.18	-8.74	-0.995
12	1.09	-9.51	-0.993	1.07	-9.78	-0.992	1.08	-9.63	-0.991

b = constant coefficient, a = slope, r = correlation coefficient

The equation has the form $\log Y = aX + b$, where Y = Total voids (%) and X = No. of Gyratory revolutions. (From Tables $r_{(0.01, 4)} = 0.917$).

APPENDIX H

ANALYTICAL CALCULATIONS OF THE PERMANENT DEFORMATION (RUT DEPTH) USING THE "SHELL" METHOD

The design data are similar to the ones used by Van de Loo (148) for calculating the rut depth of conventional hot mixtures and are as follows:

Number of vehicles per day per lane (W_d) = 2000
Traffic growth per year = 2%
Design life = 15 years
Subgrade, silty clay, C.B.R. = 5%
Modulus = 5×10^7 N/m^2
Monthly Mean Air Temp (MAAT) is equivalent
to MAAT effective for the pavement = 25°C
Wearing course, 40mm dense asphaltic concrete
Base course, emulsion treated bituminous mixture, two alternatives:

i) Cold Rolled Emulsion Treated Mixture with 74 penetration bitumen (C.R.A. 70)
ii) Macadam (dense) Emulsion Treated Mixture with 74 penetration bitumen (D.E.Mc 70)

The thickness of the base course was fixed at 140mm for both the above mixtures.

Road base, 300mm unbound layer.

The permanent deformation was determined by using the procedure given in the Shell Pavement Design Manual (147). The formula used for the calculation of the permanent deformation of each bituminous layer was:

$$\text{Permanent Deformation (PD)} = C_m \times H \times \sigma_{av} / S_{mix} \qquad \ldots H1$$

(Rut Depth, RD)

where C_m = correction factor for dynamic effect

C_m was taken as equal to 1.5 for C.R.A. -70 and 2.0 for D.E.Mc-70

H = Layer thickness in mm

σ_{av} = Average stress in the pavement under moving wheels. This depends on the structure and geometry of the pavement and on the wheel load spectrum. Under traffic loading, (0.01 - 0.1 sec) bitumen behaves mainly elastically and average stress is proportional to contact stress σ_o, i.e. $\sigma_{av} = Z \times \sigma_o$. The factor Z encompasses the stress distribution within depth of the pavement, the dynamic modulus of the structural layer and the Poisson's ratio. Values of Z for various conditions have been calculated using BIZAR programme and have been tabulated in Chart tables Z1 to Z96 in the Shell manual. The contact stress, however, for a standard axle load of 80 kN with dual wheels has been fixed to 6×10^5 N/m^2.

S_{mix} =Value of the stiffness of the mixture from the creep curve at the value of Sbit that is related to the design life of the pavement.

$S_{bit} = 3 \times VISC_{yeff} / to \times W$ ... H2

Where $VISC_{yeff}$ = Viscosity of the bitumen at yearly effected temperatures (depending also on the depth of the pavement).

to = loading time due to traffic, assumed to be equal to 0.02 sec,

W = equivalent number of wheel load.

The representative creep curves of the emulsion treated mixtures for the calculation of permanent deformation were:

For C.R.A. -70	Curve with 9% binder content, hence slope q_1 = 0.0681 after one day of curing slope q_F= 0.091 after "final" curing
For D.E.Mc -70	Curve with 5.5% binder content, hence slope q_1 = 0.068 after one day of curing slope q_F= 0.059 after "final" curing

The relevant quantities obtained at each step for the calculation of permanent deformation are given in Table H1.

Column 1 gives the two alternative mixtures and the subdivision on early and late creep stiffness of the mixtures.

Column 3 gives the division into sub-layers for a better account of the effect of temperature on the viscosity of the bitumen.

Column 4 gives the yearly effective temperature per sub-layer calculated from Chart T (Shell design manual) and column 5 gives the yearly effective viscosity of the bitumen using chart V-2*.

Column 6 gives the slope of the creep curves as resulting from Chapter 10.

Column 7 lists the values of equivalent wheel road W calculated from the formula W = (Cumulative number of standard axles per lane, N) x A

Where A = wheel load conversion factor, function of slope of creep curve and calculated from Chart A.

$N = 18 \times 10^{6}$ standard axles (equivalent to 2000 vehicles for 15 years with 2% annual growth, in fact, $N = 2000 \times 365 \times 1.4 \times \left(\sum_{i=1}^{15} (1 + 0.02)^{i} \right)$

In column 8 the Sbit,visc values are listed calculated with equation H2 and then the corresponding values of Smix are calculated from the creep curves at values of Sbit equivalent to Sbit, visc (column 9).

The determination of the dynamic stiffness E of each sub layer necessary for the determination of Z was obtained from Chart M-2*. For the determination of the E value of emulsion treated mixtures curves S1-100 and S2-100 was assumed to be representative for C.R.A.-70 and D.E.Mc -70 respectively.

The Z values were derived from Z-tables, as given in the Shell Pavement Design Manual (column 11).

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*From the Shell Pavement Design Manual

Column 12 gives the C_m values as derived from Table 6.9*. It must be noted that emulsion treated mixtures are not included in Table 6.9*, and therefore assumed values were used $C_m = 2.0$ for D.E.Mc -70 and 1.5 for C.R.A. - 70.

Finally the permanent deformation per sub-layer was calculated using equation H1 (column 13) and the total cumulative deformation is listed in column 14.

(1)		(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Construction		Mix type	H_{mm}	T_{yeff} °c	$Visc_{yeff}$ Ns/m^2	Slope "q"	W	Sbit,visc N/m^2	Smix N/m^2	Modulus E N/m^2	Z	C_m	δ(PD) mm	P.D mm
CRA 70	1	DAC100	40	39	2.6xE4	0.100	3.2xE2	1.2xE-2	3.0xE6	3.0xE8	0.6	1.2	6.0	24.5
	One day	CRA-70	40	36	3.5xE4	0.068	5.4xE9	9.7xE-4	3.6xE6	5.0xE8	0.6	1.5	6.0	
	curing	CRA-70	100	33	7.0xE4	0.068	5.4xE9	9.7xE-4	3.6xE6	6.5xE8	0.5	1.5	12.5	
	2	DAC100	40	39	2.6xE4	0.100	3.2xE8	$1.2x10^{-2}$	3.0xE6	3.0xE8	0.6	1.2	6.0	19.3
	Final	CRA-70	40	36	3.5xE4	0.091	5.4xE8	9.7xE-3	5.0xE6	5.0xE8	0.6	1.5	4.3	
	curing	CRA-70	100	33	7.0xE4	0.091	5.4xE8	9.7xE-3	5.0xE6	6.5xE8	0.5	1.5	9.0	
DEMc 70	3	DAC100	40	39	2.6xE4	0.100	3.2xE8	1.2xE-2	3.0xE6	3.0xE8	0.6	1.2	6.0	21.6
	One day	DEMc-70	40	36	3.5xE4	0.068	5.4xE9	9.7xE-4	6.0xE6	2.2xE8	0.7	9.0	5.6	
	curing	DEMc-70	100	33	7.0xE4	0.058	5.4xE9	9.7xE-4	6.0xE6	3.2xE8	0.5	9.0	10.0	
	4	DAC100	40	39	2.6xE4	0.100	3.2xE8	1.2xE-2	3.0xE6	$3x10^{8}$	0.6	1.2	6.0	20.2
	Final	DEMc-70	40	36	3.5xE4	0.059	3.6xE10	1.5xE-4	6.6xE6	2.2xE8	0.7	2.0	5.1	
	curing	DEMc-70	100	33	7.0xE4	0.059	3.6xE10	1.5xE-4	6.6xE6	3.2xE8	0.5	2.0	9.1	

TABLE H1 CALCULATION OF PERMANENT DEFORMATION OF CRA AND DEMc (CALCULATIONS WERE BASED ON THE EARLY CURING AND LATE CURING STIFFNESS OF THE MIXTURES, THE BINDER USED WAS OF R & B = 50°C PENETRATION AT 25°C = 74 (0.1mm) AND P.I. = -0.14