THE INFLUENCE OF MATERIAL INGREDIENTS ON ASPHALT WORKABILITY

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by

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TO MY PARENTS, MY WIFE,
MY BROTHERS AND MY SISTERS.

I hereby declare that the work presented in this thesis was carried out by myself at Heriot-Watt University, Edinburgh, except where due acknowledgement is made, and has not been submitted for any other degree.

D. S. E. Fordyce	Kadhim A. Khweir
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ABSTRACT

Laboratory experiments were conducted on hot rolled asphalt mixes to study the effect of material ingredients on the property of mix workability.

There is no standard test to evaluate asphalt workability in spite of the need for this measure. Much research work has been carried out to evaluate asphalt workability, but the development of a high temperature triaxial cell was a turning point in this work. The data gathered from the high temperature triaxial cell and the consistency of this data with laboratory compacted slabs of asphalt using a full scale roll are highly significant and highlight a number of points regarding the influence of the ingredients on the resistance to internal movement of an asphalt mix.

The results suggest an upper critical temperature for asphaltic mixes. Layer compaction at temperatures higher than the upper critical value is likely to lead to material decompaction. The filler present in a mix may also play a different role at high mix temperature compared with low mix temperature; the filler is shown to be a lubricant at high mix temperatures, aiding the process of material compaction.

The packing of the fine aggregate fraction within a hot rolled asphalt mix is critical to bitumen demand and the influence of the filler fraction on the basic frictional resistance of a mix, and mix cohesion and mix viscosity.

The study also showed that the use of EVA does not appear to enhance asphalt workability as is commonly suggested. A 100 pen bitumen with a 5 percent EVA content was found to be equivalent in terms of components of resistance to internal movement to a 'standard' 50 pen mix; normally a 70 pen bitumen with a 5 percent EVA content is taken as equivalent to a 'standard' 50 pen mix.

1.0 BACKGROUND STATEMENTS AND PROJECT OBJECTIVES

1.1 INTRODUCTION

The need for evaluating asphalt workability may be clearly recognised when considering the types of failure that occur with road surfaces, particularly those associated with the embedment of coated chippings into a hot rolled asphalt wearing course. Two different cases are frequently seen with road surfaces: firstly chipping loss, which could be as a result of fretting of the surface mortar removing the support for chippings; secondly, plucking out of chippings which are inadequately embedded in the asphalt. Both cases result in poor surface quality and surface durability. The cases of road failure are commonly blamed on the demand for laying bituminous material during the winter months, with the consequent likelihood of premature failure occurring because of inadequate compaction. Inadequate compaction of bituminous material will reduce the intimate contact of the constituent material and where this occurs and voids remain, those voids that are inter-connected permit the intrusion of air and water through the material layer. The circulation of air and water through a bituminous mixture will result in the oxidation of the binder films. and lead to early hardening and embrittlement of the pavement layer (1, 2, 3, 4).

Material ingredients and mix temperatures are the main factors which influence the workability of asphaltic mixes, which is a function of the materials resistance to internal movement. The components of hot rolled asphalt consists of highly frictional material, the mineral aggregate, and adhesive material, viscous and temperature susceptible bitumen. The bitumen is responsible for imparting the cohesion and viscosity to a mix but at the same time working as a lubricant to the mineral aggregate reducing the frictional resistance. The filler also, to some extent, reduces the frictional resistance of a mix at the same time enhancing the stiffness of the material at low temperature.

As a consequence of there being no accepted method for evaluating the workability of bituminous materials, the majority of researchers have concentrated on the method of measurement of workability to the detriment of the influence of material ingredients. One of the methods of measuring the workability of bituminous mixes is with the use of a triaxial cell, which is the only fundamental method capable of evaluating the components of resistance to internal movement: angle of internal friction, mix cohesion and mix viscosity.

In this study four different series of mixes were tested by the high temperature triaxial cell, and by a full scale roll to define the effect of: bitumen type and content;

filler content; and, the mineral aggregate content, including mixes using extreme sharp sands and extremely soft sands. Four commercial mixes prepared with difficult sand types were also included in the investigation.

1.2 MIX WORKABILITY

The term workability is commonly used to describe the ease or otherwise of mixing, laying and, most importantly, compacting a bituminous material.

During the rolling process, less workable mixes will consolidate less than more workable mixes, whilst highly workable mixes will deform and move readily under the roller rather than consolidate. This understanding is particularly important when chipped hot rolled asphalt is used where the rolling process embeds coated chippings into the surface of the layer and compacts the wearing course simultaneously. Satisfactory chipping embedment is very difficult to achieve without defining mix workability and in many cases will lead to loss of the surface texture which is increasingly required for skid resistance. Also, less-workable mixes are liable to lift the screed plate of the paver when laying thin layers such as the wearing course on curved horizontal alignment, leaving the surface of the rolled asphalt with longitudinal ridges (5). Transverse surface cracking is also a form of distress often associated with less workable mixes.

Unlike the design of structural concrete or pavement quality concrete the design of wearing course hot rolled asphalt takes no account of the ability of the material to be placed and compacted. Structural concrete is required to be workable enough to flow around reinforcement and allow the escape of entrapped air when agitated; allowance is made for this in a mix design. Wearing course hot rolled asphalt is required to be workable enough to be spread evenly on a substrate and to allow the controlled embedment of coated stone chippings into the surface of the layer during layer compaction; no allowance is made for this in a mix design.

The workability of a hot rolled asphalt, or with structural concrete, is a function of the physical properties of the mineral aggregate. But, with hot rolled asphalt, unlike structural concrete, the lubricating medium to enable the mineral aggregate to pack, is temperature dependent. The resistance to internal movement of an asphalt mix at any point in time during the compaction process depends on how a mix stiffens with decreasing temperature. The consequence can be the lack of adequate densification and chipping embedment.

At present no accepted fundamental measure of asphalt workability exists, in particular no accepted measure exists as to how the resistance to internal movement of a mix changes with temperatures or, and possibly more importantly, how plant variation of mix ingredients influences the resistance to internal movement of a hot rolled asphalt mix at any particular temperature.

1.3 RESEARCH ON ASPHALT WORKABILITY

Many researchers have tried to find a measure of workability through non-fundamental methods, or by employing indirect procedures or irrelevent temperatures. However, an initial research programme has been carried out at Heriot-Watt University to define a fundamental measure of the workability, or resistance to internal movement, of wearing course hot rolled asphalt. AL-Nageim (6) developed a high temperature closed system triaxial cell. The cell allows the measurement of three fundamental components of resistance to internal movement of an asphaltic mix. The three fundamental components are: angle of internal friction, mix cohesion and mix viscosity. It is believed that the evaluation of these components at different degrees of compaction may allow the definition of the workability of a mix through the evaluation of the components of resistance to internal movement at temperatures and voids content relevant to that of the construction stages of a pavement surface. Possibly there is no single relationship which can accommodate all the components of resistance to internal movement. However, AL-Nageim (6) found a correlation between a workability ratio at 3 percent mix voidage with the compaction level of the material layer under chippings at the cessation of compaction, indicating that triaxial test data can be correlated with minimal compacted mix voidage.

AL-Nageim's workability ratio was given by the quotient, mix viscosity (η_m) over limiting initial resistance (LIR). Limiting initial resistance is given by the expression

$$\mathrm{LIR} = \frac{4c}{1 - \sin\phi} \sqrt{\frac{1 + \sin\phi}{1 - \sin\phi}}$$

Compaction level is given by the quotient of final void content to initial void content.

The correlation defined was for two commercial mixes, but the correlation was not found in this work to be generally applicable. Although AL-Nageim's findings, based on the fundamental parameters mix cohesion (c), angle of internal friction (ϕ) and mix viscosity (η_m) and evaluated through a fundamental tool (the triaxial test), the correlation with states of compaction within a material layer was empirical, ranking mix viscosity and limiting initial resistance in opposite order whilst they clearly act in the same order. The workability ratio is directly proportional to mix viscosity and inversely proportional to limiting initial resistance; in fact any workability relationship should be inversely proportional to both parameters. A second shortcoming with AL-Nageim's approach is with the term limiting initial resistance. The expression used to evaluate limiting initial resistance greatly reduces the influence of the parameter angle of internal resistance which is an important component in the resistance to internal movement of a bituminous material at high temperature since the lubricatng effect of the bitumen is reduced.

In AL-Nageim°s work the profile of limiting initial resistance is similar to the cohesion profile (6). This is because of the nature of the expression which allows a narrow window of variation for angle of internal friction. For example, when the temperature is increased from 60°C to 140°C, the factor $\frac{1}{1 - \sin\Phi}\sqrt{\frac{1 + \sin\Phi}{1 - \sin\Phi}}$ will increase by 30 percent whilst the value of mix cohesion (C) at low temperature is more than 4 times than that at high temperature. This means that the influence of the value of angle of internal friction will be very limited on its influence on the value of limiting initial resistance, whilst the C value of mix cohesion is decisive.

In this study mix workability is defined through the interpretation of the relationships of the components of resistance to internal movement individually. Such a procedure has proved capable of defining and highlighting many features of mix workability, which are generally applicable to mix variations.

1.4 OBJECTIVE OF THE STUDY

This study is an attempt to measure the influence of material ingredients of a wearing course hot rolled asphalt mix through evaluation of the internal resistance components, mix cohesion, angle of internal friction and mix viscosity. These components are determined over a range of mix temperatures from 60°C to 140°C at 20°C intervals; for each temperature samples are tested at four different void contents, 3 percent, 6 percent, 9 percent and 12 percent. The determination of components of resistance to internal movement over such a range of temperature and voids content is a reasonable evaluation of mix workability relevant to the compaction of a material layer. The method used to evaluate the components of resistance to internal movement was the high-temperature closed-system triaxial cell developed at Heriot-Watt University in the earlier study (6). The data from triaxial tests correlated with data obtained from the compaction of slabs of material. Slab compaction was carried out using a full scale roll, over the same temperature range, 60°C to 160°C, and with different numbers of roller passages from 1 to 18 at three pass intervals.

The correlation of the results between the type of tests used, triaxial and roller, provided important information defining many aspects concerning the behaviour of hot rolled asphalt during layer compaction, and when material ingredients are varied quantitively and qualitatively. However, due to the time available to this study the investigation of the material ingredients was limited to the effect of: bitumen content, filler content, bitumen to filler ratio, bitumen grade, EVA as a modifier to the bitumen and sand type. These varients were organised into four test series, each consisting of three to five mixes, and which can be described as follows.

1. A series of five mixes prepared with different bitumen content, keeping the proportion of filler and mineral aggregate constant. This series offered an opportunity to study the influence of the volume of film thickness.

2. A series of five mixes made with different filler to bitumen ratios, maintaining a constant volume of film thickness and consequently the volume of mineral aggregate was held constant.

Test series 1 and 2 were made with the same range of bitumen content with one of the mixes being a control mix, which is a Marshall design mix with the ingredients used. The combination of the two series was found to be useful in comparing pairs of mixes made with the same bitumen content but with different filler content.

3. A series of three mixes made with the same proportion of bitumen, filler and mineral aggregate but the type of bitumen used was different. Three different nominal penetration grades were used: 50, 70 and 100. The mixes of this series were prepared in the same proportions to that of the control mix, with the objective of highlighting the influence of the bitumen grade on mix workability.

4. A series of three mixes similar to those described in test series 3 above, but each grade modified with 5 percent replacement of the bitumen by ethylene vinyl acetate, EVA. This additive is often described as a workability aid.

All the above series were prepared in the laboratory, and each mix was tested at four voids content and five different temperatures in the triaxial cell. Also, samples of each mix were compacted by using the full scale roll with six different numbers of roller passages and at six different temperatures.

In an attempt to study the influence of sand type - which forms the bulk of a hot rolled asphalt mix - four commercial mixes were used in site trials. Material was brought to the laboratory and tested in the triaxial cell and compacted using the laboratory roller. This supplementary series exemplified the role of the fine aggregate in the performance of hot rolled asphalt, particularly at high temperature when the skeleton of sand particles is responsible for load distribution.

The data accumulated from triaxial cells and rolling rigs with such variety of material ingredients provides a useful picture of mix workability or, in other words, the performance of hot rolled asphalt during its compaction stage.

The study has provided an explanation for the behaviour of hot rolled asphalt when subjected to the actions of a steel smooth wheeled roller. This has led to the construction of a simple physical model to describe the performance of the micro structure of hot rolled asphalt. At high temperature the role of the mineral aggregate increases in determining the resistance to internal movement of a mix, and that comes from the increasing role of internal friction. The role of the bitumen decreases at high temperature, this leads to a decrease in the viscous resistance of a mix. The filler plays an important role in stiffening the film thickness at low temperature, but this material was found to work in an opposite manner at high temperature, when it acts as a lubricant to the fine aggregate.

The physical model proposed has been translated into a mathematical model which allows the quantification of the components of internal resistance to movement of an asphalt mix. The model introduces the effect of material ingredients.

In the following chapters a detail of the theoretical background, the method, material, equipment and test data is reported.

2.0 A MEASURE OF WORKABILITY AND MATERIAL FACTORS INFLUENCING THIS MATERIAL PARAMETER

2.1 INTRODUCTION

It is generally recognised that the performance in practice of hot rolled asphalt wearing course is influenced by a variety of factors. The more prominent of these factors are the properties and proportions of the ingredients, the bituminous-based binder, mineral aggregate, filler and air. Most of the research on the performance of wearing course hot rolled asphalts has, until now, concentrated principally on the service performance of the material, although the laying of the material is critically important to subsequent service performance. The durability of a hot rolled asphalt wearing course and its mechanical properties are all influenced by the way the material is constructed. A principal factor influencing the performance of hot rolled asphalt in the provision of a material layer is its workability. Although this is recognised little fundamental research has been conducted into mix workability.

There have been a limited number of studies carried out to evaluate the workability of bituminous materials using different techniques, some of them empirical, such as the Marshall test and the screed test, others of them fundamental, such as the triaxial test. Few of the empirical trials were employed to study the influence of material ingredients on a comprehensive basis, nor were they able to explain some of the phenomena observed and related to mix composition at the temperature and voidage relevant to the compaction process. It is a fact that all previous studies have investigated workability from a test methodology point of view, and there is only a limited amount of work reported on the effects of mix ingredients on this important material property. A full study of the different methods used to evaluate mix workability support the need for a fundamental measure of mix workability in the temperature range relevant to mix compaction. It is understood that the method for defining workability of bituminous materials comes through the definition of the components of internal resistance to movement which are: cohesion resistance, frictional resistance and viscous resistance. A high temperature triaxial cell development at Heriot-Watt University has proved capable of defining the three components of internal resistance to movement at temperatures relevant to the laying of asphaltic mixes. In this chapter a brief review of the methods used for the definition of mix workability, including triaxial stress methods, are provided along with a theoretical background for the evaluation of mix cohesion (C), angle of internal friction (ϕ) and mix viscosity (η_m). Furthermore, the definition of mix cohesion, angle of internal friction and mix viscosity, and the factors which influence them are reviewed. Special attention is paid to highlight the influence of material ingredients on the three fundamental parameters through a review of published research work carried out on bituminous materials other than hot rolled asphalt, such as asphaltic concrete and sandsheet at service temperatures.

2.2 EMPIRICAL METHODS FOR EVALUATING WORKABILITY

Many investigators have used empirical methods for evaluating the workability of bituminous material following direct and indirect methods.

Many studies have used specially manufactured apparatus as tools for assessing workability, such as: the workability meter, the tripod penetrometer and the screed test. These methods are considered direct methods for evaluating workability. Other researchers have used indirect methods for evaluating workability, such as: the Marshall test, the Gyrator testing machine and wheel tracking test.

The studies, using direct and indirect methods, can be categorised into three temperature ranges at which the measurements were carried out. The gyratory testing machine, tripod penetrometer and screed test can be used at a temperature range similar to that of material layer compaction. The Marshall test can only be used at temperature significantly below that of material layer compaction; the test is relevant to service temperatures rather than laying temperatures. The third temperature range is higher than that for material layer compaction, the workability meter is used at a temperature 160°C and more.

Further, these tests may be classified into different groups when the manner of the workability is evaluated. The gyratory test machine uses the void content concept, the penetrometer is based on punching shear, the workability meter and screed test are dependent on pure shear force and the Marshall test relates to stability and flow as well as void content. However all the test equipment and test procedures are non-fundamental and fail to provide a comprehensive procedure to assess workability. The most important failure is the ability of the tests to evaluate the relevant temperature range and range of voids content consistent with layer compaction. Although the above studies have been reviewed in detail elsewhere (6) it is useful here to highlight reported data from those methods on the effect of material ingredients on material workability.

2.2.1 The Gyratory Testing Machine - as Simulation of Field Compaction

The development and assessment of the gyratory testing machine is discussed and reported in detail in many references (7-17). The machine is used to prepare asphaltic samples of specific voids content by applying different states of compaction. Also, it is used to simulate traffic compaction. The concept of the machine is the compaction of asphaltic material by a combination of static axial pressure and gyratory kneading action. Although most of the studies were conducted at service temperature Hassan (16) investigated the effect of different factors on the workability of hot rolled asphalt within the temperature range 75°C to 150°C, which is relevant to material layer compaction. He suggested a workability index for an asphalt mix; he defined the workability index as the reciprocal of the initial voids content of the mix, which comes from the extrapolation of the relationship between the number of revolutions and the mix voidage. This empirical index represents only the stage before rolling and ignores the workability trend during the compaction process when voids content and temperature are both changing.

In his findings Hassan reported that the optimum temperature for compacting a hot rolled asphalt mix is 150°C for mixes containing crushed limestone filler. However, and surprisingly, mixes compacted at ranges 75°C to 125°C showed very small improvement in voids content with all bitumen contents used, whilst extremely high reductions in voids content were found in mixes that were compacted at 150°C. Mixes compacted at 125°C with 30 revolutions showed voids contents ranging from 15.6

percent to 12.9 percent when the bitumen content varied from 6 percent to 8 percent respectively.

On the other hand with mixes compacted at 150°C and at the same number of revolutions, the voids content dropped considerably to around 6.6 percent, for mixes with a bitumen content of 6 percent, and to as little as 1.16 percent, for mixes with 8 percent bitumen content. This appears to be in disagreement with many other investigators' findings who reported a curvilinear relationship between the voids content and temperature when a full scale roller and other compaction equipment were used (6, 18, 19, 20, 21). And, in particular, the literature shows that for such a temperature range (125°C-150°C) the curve is flat (6, 20). This makes the data from the gyratory testing machine, as it has been defined by Hassan, unreliable for evaluating workability.

2.2.2 The Tripod Penetrometer

The tripod penetrometer is a convenient instrument for measuring the resistance to penetration of hot bituminous mixes. The test was developed as an assessment of the resistance of an asphaltic mix to the embedment of coated stone chippings. A full description of the test procedure and the penetrometer can be found in reference (21). The penetrometer is designed to be used on semi-compacted material (specifically, the state just before rolling) with a voids content relatively high and temperature range between 60°C to 130°C. This test is empirical and cannot be considered to measure any fundamental property related to mix workability. Further, data using this test showed, surprisingly, that a reduction in voids content gave an increase in penetration. This finding may seem inconsistent owing to the fact that low voidage may be thought to lead to high resistance to the embedment of coated chippings, but such behaviour is consistent with results from the Marshall test. Triaxial test data may offer an explanation for this behaviour.

2.2.3 The Workability Meter

The workability meter consists of a chamber connected to a rigid frame into which the test mix is introduced; a speed controller drives a blade through the mix. Marvillet and Bangauit (22) applied the term workability to the reciprocal of the resistance moment produced in the shaft by the mix. The workability meter has been used only within the temperature range 150°C to 200°C, which is well above the temperatures commonly used for layer compaction. Also, it appears from the extrapolation of the trend of the relationships between temperature and workability for mixes using three different binder contents that there may not be significant differences in the workability of these mixes at 140°C, and, at still lower mix temperatures, the relationships suggest that the mixes with highest binder content will have the lowest workability. For the above phenomena, Marvillet, in his discussion, stated that the workability meter can be used at temperatures lower than 160°C, but as temperature decreases the rigidity of the mix increases in such a way that the test measures become inaccurate because the increase in stiffness of the mix causes it to cluster around the blade. If extrapolation of data is not valid the use of this procedure to appraise the workability of asphalt mixes at the temperature range relevant to layer compaction is not a practical possibility.

2.2.4 Marshall Test

Many investigators have attempted to use the Marshall test to provide some understanding of bituminous material during laying process. Although stability and flow values are not a direct measure of mix workability or mix compactibility, some investigators have used stability and flow values to infer the workability of a mix (23-26). This is based on experience rather than a comprehensive study. Other investigators have linked Marshall parameters (stability and flow values) with voids content by using different relationships (2, 18, 27), whilst other researchers have reported relationships between stability, voids content and different numbers of Marshall compactor blows in an attempt to evaluate bituminous mixes during the compaction stage (27-30).

Other researchers have used the compactor of the Marshall test as a method of simulating the compaction process (3, 31-34). However, different relationships have been established between the density, or the voids content, and the number of blows of the compactor, using mostly asphaltic concrete. Type of binder, coarse aggregate percentage, effect of the particles, their shape and grading, have been investigated. The differences in results suggested by the studies remains discordant with results from site trials. This is because the Marshall test, which is a rational, non-fundamental test, fails to evaluate the resistance of bituminous material to deformation (35-38). Mixes of equal stability and flow values show different resistance to deformation when they are subject to trafficking (35). In addition, Brown et al (39) have shown that the Marshall test is not able to differentiate between types of bituminous mixes, nor is it able to rank mixes in order of their resistance to deformation.

The following points indicate some of the (intriguing) behaviour exhibited by mixes in the Marshall test.

(a) Marshall test results indicate that mixes with higher stiffness are those with better compaction results (34). Mixes with higher volumes of film thickness exhibit less voids content during compaction. Neither result is surprising. Increased bitumen content fills more of the voids in the total mineral aggregate structure, which includes the filler. For mixes with higher filler content, they are stiffer at the Marshall test temperature (60°C) which is low enough to make the mastic film stiffer when the filler content increases, whilst at higher temperatures the bitumen viscosity reduces freeing the filler to work as a lubricant in a moving aggregate system, as occurs during compaction; this leads to higher states of compaction. In addition, the filler theoretically has the effect of filling some of the voids within the fine aggregate structure.

(b) When the air voids were varied over the range 2.5 to 5.5 percent they had very little effect on Marshall stability, and more surprising, the paving mixture with 2.5 percent air void was the most easily compacted (2). This is consistent with the penetrometer result when low voidage mixes exhibited higher embedment. As commented earlier this phenomenon may be explained in light of triaxial test results obtained in this study, as will be seen later.

(c) Varying the percent content of the coarse aggregate over a range of 20 percent when air voids, filler to bitumen ratio and particle index were held constant had negligible effect on Marshall stability (33).

(d) Different asphaltic concrete mixes subjected to a range of blows (10-60) showed stability values increasing with number of blows, whilst flow values exhibited a variable trend with some mixes showing only slight changes and others showing an increase in flow value with increase number of blows. Some mixes indicated a concave upward relationship over that increasing range of blows (32).

The shortcomings of the Marshall test as a measure of mix workability arose from the sample size, as a consequence of: the wall effect on the moulds and arching action of the testing plate; the rate of determination of the sample during testing; and, test temperature (40-45).

2.2.5 Spreadability or Screed Test

The apparatus and testing procedure, as described by Please and Hardman (46), are essentially as follows. An uncompacted asphaltic specimen, 165mm in diameter at the base, 114mm in diameter at the top and 89mm high, rests on a trolley and butting up against a 25mm high stop at the rear. A small electric motor pulls the trolley containing the specimen at a speed of 30.5 mm/sec beneath the edge of a horizontally aligned blade. The height of the blade is such that as the trolley passes beneath the fixed blade the top 25mm of the specimen is screeded off. The blade is fixed to a torsion bar; the torsion is measured when the specimen is pulled beneath the screed blade. The apparatus has some similarity with the shear box. The equipment exhibits the ability to compare between mixes at different temperatures, different types of sand and different bitumen content. But, the use of uncompacted specimens provide a measure for the stage before layer compaction only, and fails to provide a measure of changing mix workability during different stages of compaction. As far as material ingredient variations are concerned Please and Hardman reported that sand-filler-binder mortars made with coarse sand were found with the screed test to be less easily spread than corresponding mortars made with fine sand, despite the fact that coarse sand has a smaller surface area than fine sand, resulting in greater film thickness with a consequently higher lubricating effect.

This may be explained due to the role of filler which is trapped between the sand skeleton and assists in the sliding and rolling of sand particle with fine sand; this may be of a marginal influence with coarse sand. A similar behaviour was found when Heukelom (47) studied the role of filler in bituminous mixes and used the screed test as well. However, in chapter five samples of sand and filler blends tested triaxially showed a decrease in angle of internal friction when filler content increased in the blend with some types of sand, whilst other sands indicated unstable behaviour.

2.3 THE TRIAXIAL TEST FOR MEASURING WORKABILITY

All the tests described so far are empirical, the stress distribution in the specimen being non-homogeneous and largely unknown from the start of the load application. The triaxial test sets out to give information of a more fundamental nature. It has been used in testing bituminous materials to determine the conditions of stress for which a cylindrical specimen is just in equilibrium, the major principal stress being applied axially and the two minor and equal principal stresses being developed by the deformation of the specimen compressing the surrounding fluid in a cell enclosing the cylindrical surface of the test specimen.

Triaxial compression theories have been discussed extensively in the literature (42, 48-51) and triaxial testing equipment has been employed since the 1930's in testing bituminous materials. The three parameters of internal resistance to movement of bituminous material can be determined by triaxial test: angle of internal friction, , mix cohesion, c, and mix viscosity, η_m . Many researchers have reported that the internal resistance of an asphaltic mix when exposed to triaxial loading conditions will be the summation of frictional resistance, cohesion resistance and viscous resistance (38, 41, 44, 52-57).

For most engineering materials the components of internal resistance to movement are friction and cohesion, but the presence of a bituminous binder imparts a viscous resistance component and that raises the need for its measurement. Pfeiffer (41) and Nijboer (52) succeeded in establishing a methodology using a triaxial cell to measure the viscosity of an asphaltic material within the temperature range of 5°C to 40°C.

The main factors influencing the internal resistance components of an asphaltic mix during the compaction process are mix temperature and the voids content of the material, both factors influencing the rate of strain of the material. These factors reflect greatly on the values of the components of resistance to internal movement. Nijboer (44, 59) used mix cohesion and mix viscosity data obtained within the temperature range of 5°C to 40°C (which he extrapolated to 130°C) to investigate the compaction of asphaltic road mixes during rolling. The validity of the extrapolation of test data is a point of concern with Nijboer's approach, in spite of his valuable and fundamental study.

At Heriot-Watt University a triaxial cell was fabricated to determine mix viscosity, mix cohesion and angle of internal friction at temperatures similar to those obtained in the compaction process (6). The cell is a modified design of the closed system procedure for measuring mix cohesion and angle of internal friction, a development of that reported by Smith (60-64). The test procedure employed for evaluating mix viscosity was the same as that developed by Pfeiffer (41) and Nijboer (52).

The closed system enables a series of axial stress values (σ_1) and confining pressure values (σ_3) at static equilibrium (zero rate of deformation) and dynamic equilibrium (different rate of deformation) to be gathered to construct the relationships shown in Figure 2.1.

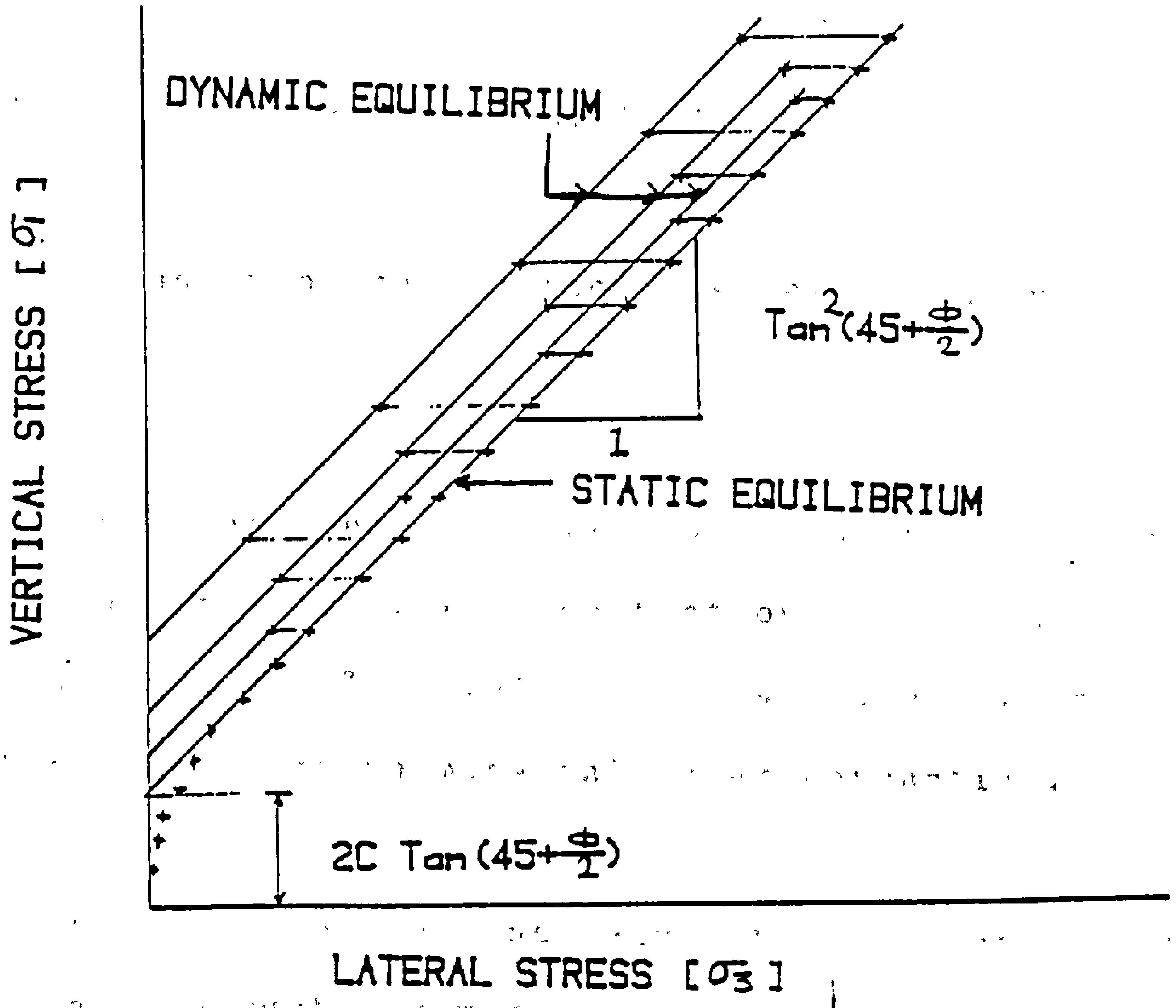


Figure 2.1: Relationship between vertical and lateral stress

The slope of the tangent to the straight line portion of the curve (static equilibrium) is equal to $\tan^2(45 + \phi/2)$, and when the tangent is extrapolated back to zero confining pressure, the interception on the axial stress axis is a value equal to $(2C\tan 45 + \phi/2)$. From these two expressions values for mix cohesion and angle of internal friction can be determined. When different rates of deformation are used (dynamic equilibrium), a series of lines are obtained and found to be sensibly parallel to the line for static equilibrium. Each line represents a specific rate of vertical deformation. The relationship inFigure 2.1 represents correspondng values for any element of material triaxially loaded (65).

2.3.1 The Heriot-Watt Triaxial Cell

This cell has important characteristics which no other cell has.

a) This cell has been proved to be capable of testing samples with different voids content over the temperature range 60°C to 150°C, which covers the range of temperatures relevant to material layer compaction.

b) The sample is located entirely within the pressurised zone so that the rubber membrane, protecting a sample from the confining oil, is attached not to the top plate of the main triaxial structure but to an upper bearing plate which is designed to operate completely within the oil bath surrounding the sample. This arrangement is quite critical to avoid any longitudinal stretching of the rubber membrane which can cause vertical stress and might prevent the development of free shear planes during a test.

c) This cell was developed to gather data for evaluating mix viscosity by allowing the sample to deform at different rates of vertical deformation.

d) The cell, using one sample, can provide sufficient data for the evaluation of all three components of resistance to internal movement. In previous cell designs a minimum of four samples were required to evaluate mix cohesion and angle of internal friction and a minimum four samples for each rate of deformation to evaluate mix viscosity. For three rates of deformation 12 samples were required to evaluate mix viscosity. The large number of samples required to define mix viscosity results from the fact that only one corresponding set of values of axial stress and confining pressure can be obtained from each test and in order to get a sensible straight line relationship between axial stress and confining pressure, a total of four points is required before mix cohesion and angle of internal friction values can be obtained. The same procedure is required when different rates of deformaton are used. A minimum of four readings are required to plot a relationship to evaluate mix viscosity.

With the present cell design a series of corresponding axial stress and confining pressure readings, usually between 15 and 20, can be obtained from one sample. In most cases this number is sufficient to evaluate the three parameters relating to resistance to internal movement. The closed-system design is not only economical and less consuming of time and material but potentially it is more accurate by avoiding the differences which might result from multiple sample preparation.

e) The sample size is 100mm in diameter and 200mm in height. The least dimension is seven times greater than the maximum size of coarse aggregate used for hot rolled asphalt, which is 14mm. Also the ratio of the height/diameter is equal to 2. This ratio makes the sample sufficiently long to permit the shear planes to form within that portion of the specimen that is free of end restraint effect (45, 61, 62).

2.3.2 Calculation of Mix Viscosity using the Triaxial Cell

Measurement of mix viscosity has been reported in detail in many studies (6, 41, 44, 52). However, there is some ambiguity in the reporting of the calculation of the rate of deformation. Although the principles and method are the same it is found important to discuss, in some detail, the manner of plotting the dynamic value of mix cohesion in relation to the rate of sample deformation.

When an asphalt sample is loaded triaxially, vertical deformation is accompanied - if no volume change occurs - by an increase in the diameter of the cylinder, as a consequence of internal shear. In this case the reduction in volume due to the vertical displacement is equalised by the lateral expansion of the sample. The system can be reported as follows:

$r^2\pi\ \Delta L = ((r + \Delta r)^2\pi - (r^2\pi))\ (L - \Delta L)$

which, by reduction, is $r^2\Delta L = (2r\ \Delta r + \Delta r^2)\ (L - \Delta L)$

$r^2\Delta L = 2rL\ \Delta r + (L\ \Delta r^2 - 2r\ \Delta r\ \Delta L - \Delta r^2\ \Delta L)$

$(L\ \Delta r^2 - 2r\ \Delta r\ \Delta L - \Delta r^2 \Delta L = 0$

Because these terms are very small and cancelling each other, then

$r^2\ \Delta L = 2rL\ \Delta r$

and

$\Delta L/L = \frac{2r\ \Delta r}{r^2} = 2\ \Delta r/r$

This can be written as

$E_1 = 2\ E_2$ ....(1) where

r = radius of the sample

L = length of the sample

ΔL = vertical displacement

Δr = radial displacement

E_1 = vertical strain

E_2 = lateral strain

In this case the vertical strain is a contraction strain, the lateral strain is an expansion strain, therefore equation (1) will be

$$E_1 = -2 E_2$$

since the lateral stresses are the same in all directions a two dimensional state of strain is the dominant case.

Figures 2.2(A) and 2.2(B) show the state of strain in a small element, the shear strain $E_{1,3}$ and $E_{3,1}$ are brought about by rotation of the sides of the element. From the geometry of Figure 2.2 (C) it follows that $E_{1,3} = E_{3,1}$ (66-68). If the element is rotated counter clockwise about 0, through an angle $E_{3,1}$ (Figure 2.2 (D) or alternatively, if the element is rotated clockwise about 0 through an angle $E_{1,3}$, then the following is obtained:

$$\gamma_{1,3} = \gamma_{3,1} = E_{1,3} + E_{3,1}$$

but $E_{1,3} = E_{3,1}$ therefore

$$\gamma/2 = \gamma_{1,3}/2 = \gamma_{3,1}/2 = E_{1,3} = E_{3,1}$$

Figure 2.3 shows the Mohr's circle of strain corresponding to the state of strain in Figure 2.2 (B). The circle of strain is plotted on a diagram with axes $\frac{\gamma}{2}$ (pure shear strain) and E_1, E_3 as a normal strain. From Figure 2.2 (B)

$$\gamma/2 = E_{1,3} = E_1 \sin\theta \cos\theta - E_3 \cos\theta \sin\theta$$

$$E_{1,3} = (E_1 - E_3) \sin\theta \cos\theta$$

$$\gamma/2 = \frac{E_1 - E_3}{2} \sin 2\theta$$

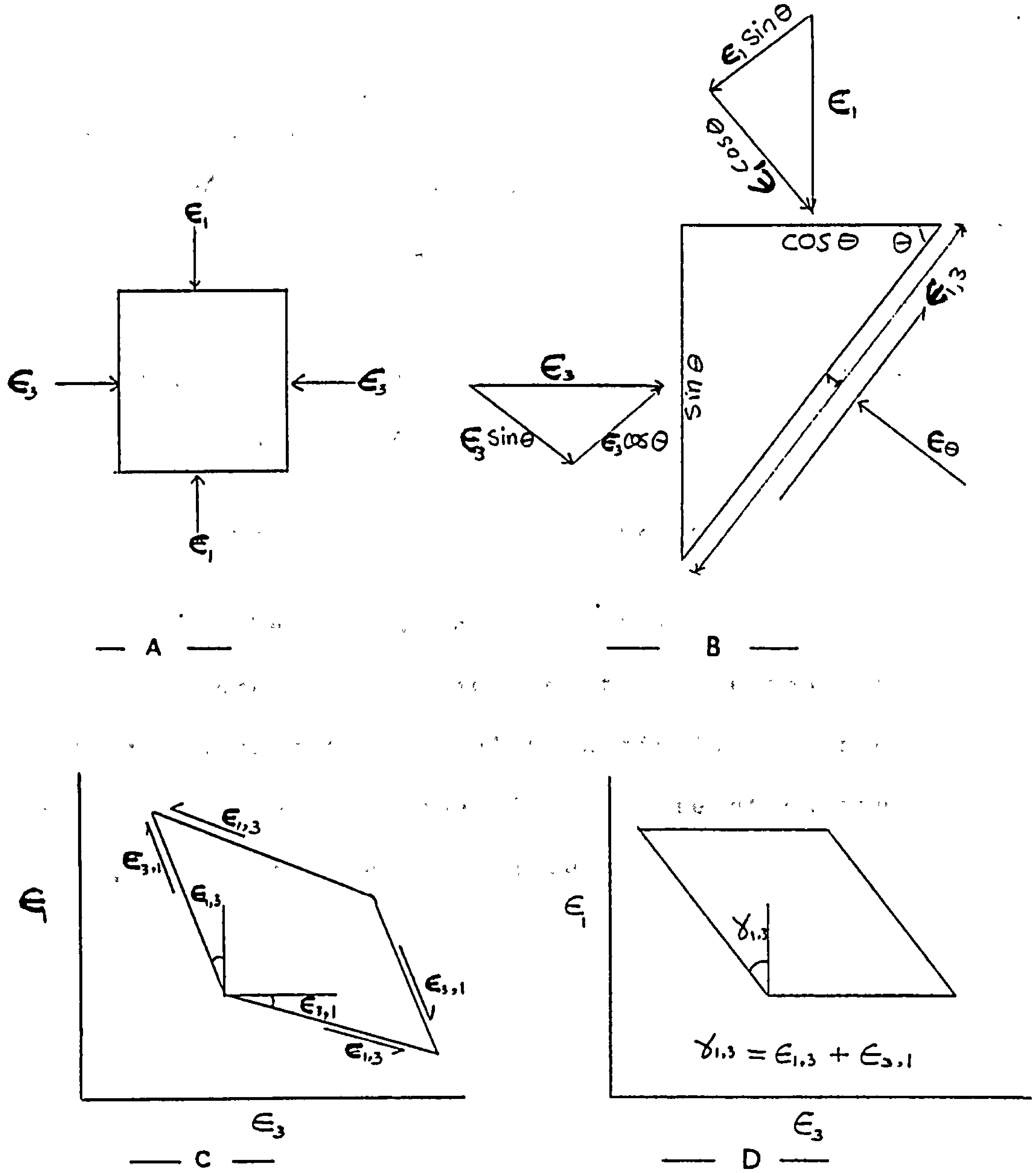


Figure 2.2: The components of shear strain

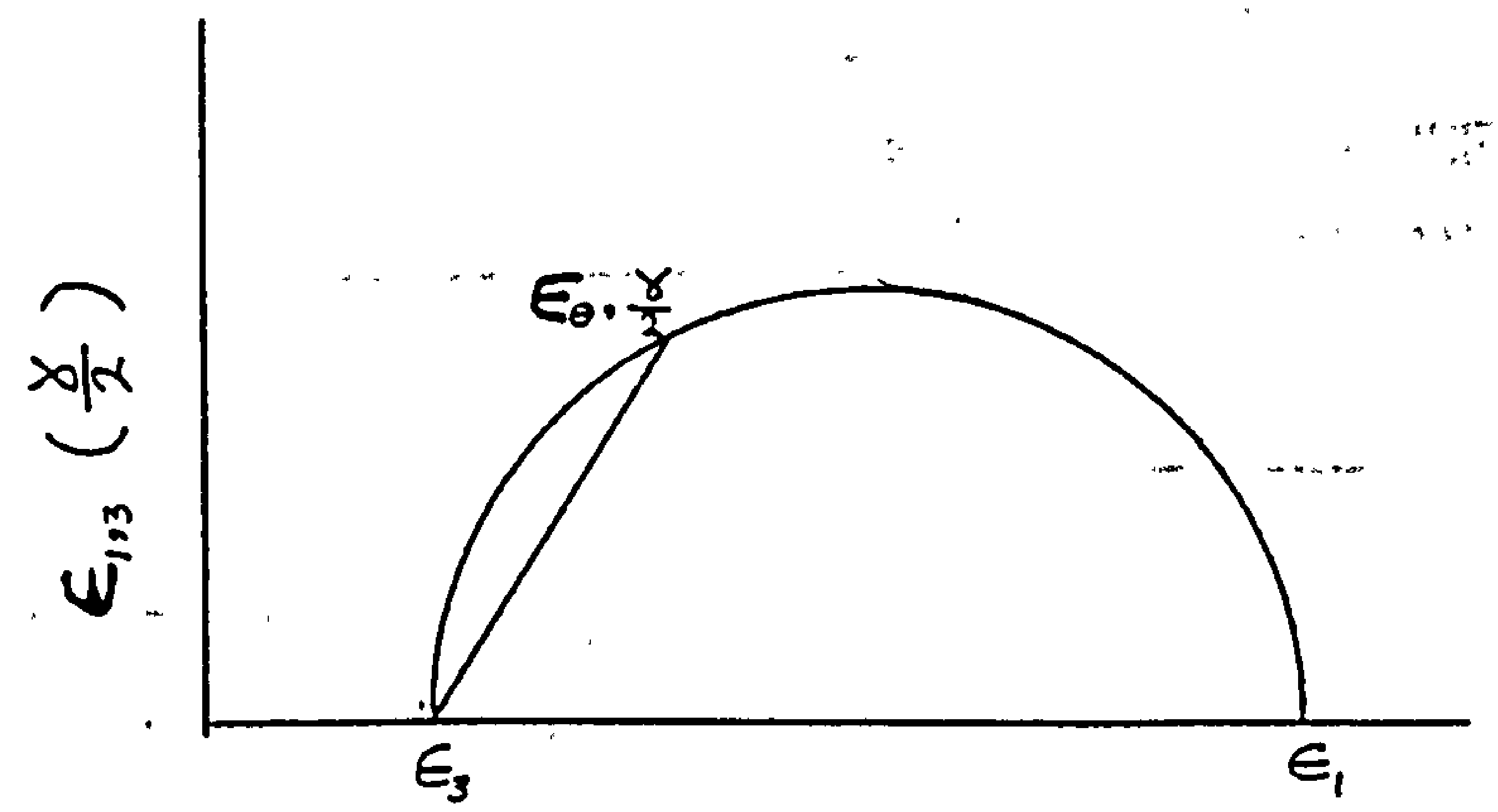


Figure 2.3: The strain Mohr circle

but $E_3 = -\frac{1}{2} E_1$

$$\gamma = 3/2\ E_1 \sin 2\theta$$

$$\frac{d\gamma}{dt} = \frac{3}{2}\frac{dE}{dt}\sin 2\theta$$

where $d\gamma/dt$ = rate of shear strain (rate of deformation

$$\theta = 45° + \frac{\phi}{2}$$

ϕ = angle of internal friction

When the cohesion values at the state of dynamic equilibrium are plotted against the corresponding values of $d\gamma/dt$ a straight line relationship is obtained and mix viscosity will be the slope of this relationship (6, 41, 44, 56), as can be seen in Figure 2.4.

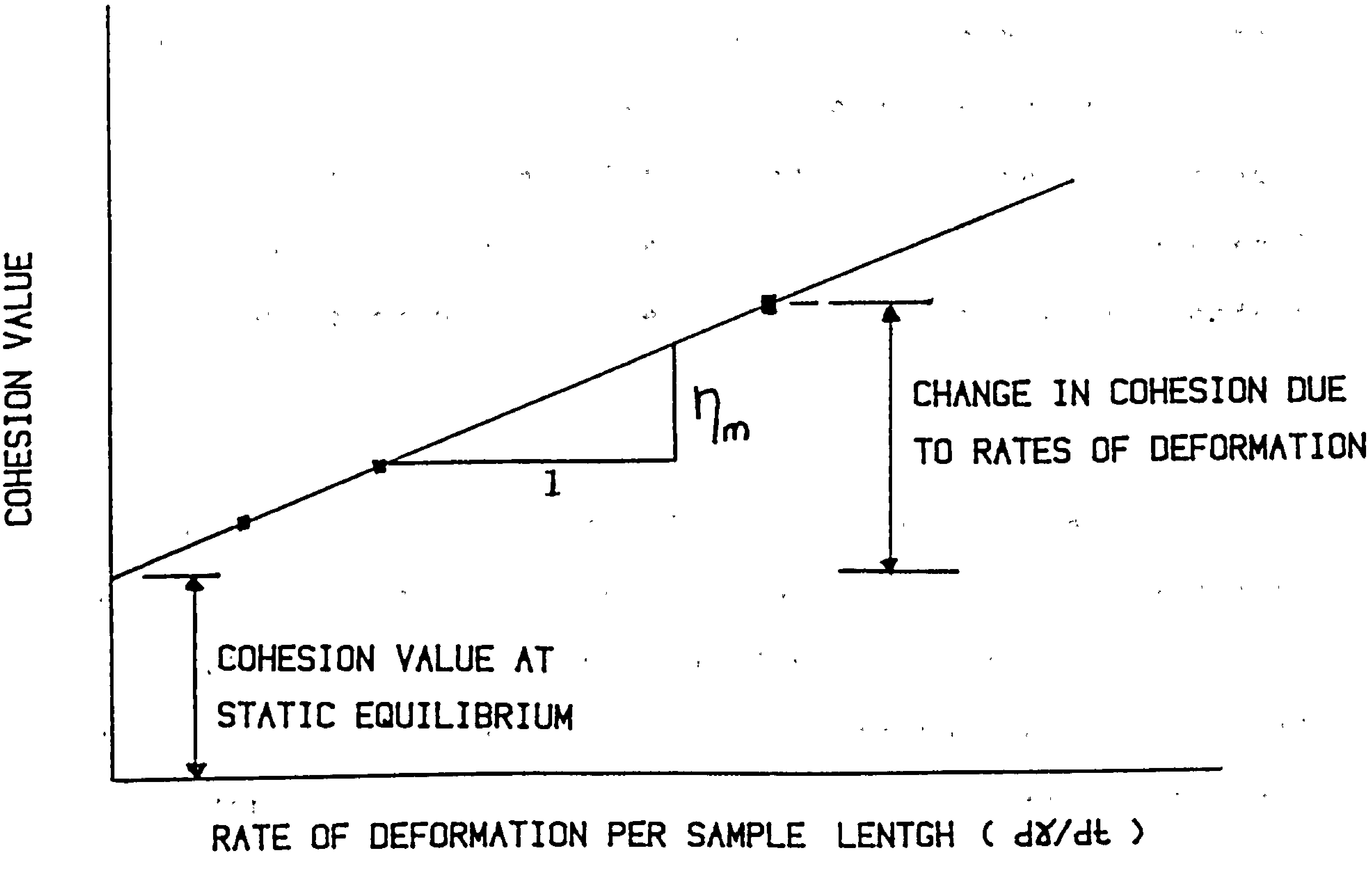


Figure 2.4: Evaluation of mix viscosity (η_m)

2.4 THE PARAMETERS OF INTERNAL RESISTANCE

The triaxial test offers a fundamental method for the evaluation of the three components of resistance to internal movement of hot rolled asphalt. These components are very much temperature and void content dependent. The changes in voidage state and temperature may be used to explain material layer compaction. With low stone content asphalt the three components are a function of the complex interaction between the binder, filler and fine aggregate; they are also a function of the temperature of the material, through its influence on the viscosity and volume of the bituminous binder.

2.4.1 Angle of internal friction

When two solid bodies move over one another a certain resistance to movement must exist and be overcome. The resistance to movement of the bodies with respect to each other is found to be directly proportional to the normal stress existing between the bodies and to be independent of the rate of movement (44).

The angle of internal friction of hot rolled asphalt is a measure of the friction within the mineral aggregate particles, which in turn is a function of the packing of the mineral aggregate, the surface texture of the mineral aggregate, the grading of the mineral aggregate particles, the binder volume in relation to the voidage available within a packed aggregate system and the viscosity of the binder. Nijboer (44, 52) found that angle of internal friction of dry aggregate increased slightly when water was added whilst it reduced noticeably when a lubricant, oil or bitumen, was used as a binder.

Binder volume and its viscosity influences the physical separation of the mineral aggregate particles and therefore the effect of the interlocked pattern and surface texture of the mineral aggregate. It is found from low temperature research work that a reduction in angle of internal friction occurs when the bitumen content is increased in spite of the source of mineral aggregate used (45, 69-72). Also, the viscosity of the bitumen has some influence on the value of angle of internal friction when a different grade of bitumen is used at low temperature, a marginal increase in value of angle of internal friction was found as the penetration value of the petroleum bitumen was increased (46, 69, 70). Filler content is no less important than the binder. Lottman and Goetz (73) investigated the influence of the filler content on the internal resistance to movement of bituminous materials. A conflicting result was obtained when a different percentage of crusher dust was used in asphaltic concrete and sand sheet asphalt. In the case of asphaltic concrete, angle of internal friction increased when the content of crusher dust increased, but in the case of sand sheet, angle of internal friction decreased when the percentage of crusher dust increased. In an attempt to explain the inconsistency in data Lottman and Goetz carried out extraction tests on the asphaltic concrete to determine the distribution of bitumen between the fine and coarse aggregate fractions. The results indicated that the amount of bitumen coating the coarse aggregate decreased when the percentage of crusher dust increased. Lottman and Goetz ascribed the increase in value of angle of internal friction to the reduction in the percentage of bitumen coating the coarse aggregate, and they recommend more work to develop a complete explanation. However, the coarse aggregate is responsible for the value of angle of internal friction and any reduction in the bitumen coating of this aggregate fraction will lead to an increase in the chance of interparticle contact and therefore an increase in value of angle of internal friction.

Nijboer (44, 52) carried out an extensive study on the influence on the internal resistance components of a bitumous mix as a result of mix ingredients, including the filler content. However, he did not report any change in angle of internal friction when ingredients changed. The neglect of the value of angle of internal friction might be the consequence of the fact that Nijboer carried out test programmes at low temperature at which the value of angle of internal friction is low and the other two components of the internal resistance are high. The avoidance of the frictional resistance has occurred in spite of the fact that the study showed that the value of angle of internal friction increased when mix temperature increased, and Nijboer extrapolated his data for high temperature conditions when there is a reduction in the influence of mix cohesion and mix viscosity accompanied by an increase in the effect of the angle of internal friction. Later, Herkenhoff (74) also found that the value of angle of internal friction at 60°C was higher than that at 43°C when he tested bituminous mixtures by using tension and unconfined compression tests.

The author (19) in this study found that the angle of internal friction increased steadily with temperature until maximum value was reached when a fall in value was exhibited. Furthermore the profiles of values of angle of internal friction were found to be consistent with the profiles of mix compaction as a result of rolling. This data indicates the importance of frictional resistance as high temperature and an important factor in the workability of a bituminous mix.

It is reasonable to expect that the value of angle of internal friction of hot rolled asphalt may be more influential at high temperature. Fine aggregates possess high values of angle of internal friction and form the skeleton of an asphalt. At elevated temperatures the fine aggregate skeleton is likely to be the principal stress distributing system, whilst the mastic which is responsible for mix cohesion and mix viscosity will be marginalised at high temperature. This is the opposite case at low temperature.

2.4.2 Mix Cohesion

Mix cohesion is a part of the total shear resistance between material ingredients and is independent of the normal stress across shearing planes. This means that even when the normal stress is decreased to zero there is still measurable shear resistance. In such a case many researchers (41, 44, 52) have reported various causes for this resistance, which can be divided into three parts: true cohesion, apparent cohesion and interlocking resistance.

True cohesion is due to the interaction of mineral aggregate particles as a consequence of Van Der Waals' forces which these particles exert on each other and multilateral pressure is thereby caused. True cohesion is greater with finer aggregates than with coarse aggregates such as used with bituminous mixtures (44).

Apparent cohesion is ascribed to the force exercised by liquid-gas menisci which pull grains of aggregate toward each other. This is proportional to the water-air interfacial tension in soil mechanics, and bitumen-air interfacial tension in the case of bituminous materials. This will depend on the void content, and more likely to diminish at low void content.

Interlocking resistance is due to the angularity of the aggregate. This property by definition is a part of cohesion. It is believed the interlocking resistance may reach a considerable magnitude when the aggregate is formed of crushed stone or angular particles (41, 44). This is likely to take place when the particles are in contact and trap each other. However, the presence of the bitumen as an adhesive material in asphalt enhances the cohesion value, as well as the shear resistance and mix viscosity.

Mix cohesion is an important component of the internal resistance to movement of an asphalt. In contrast to the belief of some engineers in the soils field who regard frictional behaviour as the normal situations for soil and cohesive behaviour as the exception (75). The cementation role of the bituminous binder dominates the true cohesion in terms of internal resistance to movement. Nijboer (44, 52) stated that the apparent cohesion in bituminous materials is very small and considered negligible. This may be true when the void content is very low, otherwise the apparent cohesion has some influence on the total value. Nijboer called mix cohesion "initial resistance", initial resistance being the summation of bituminous and interlocking resistance. Pfeiffer (41) stated that the three types of cohesion work together to form the initial resistance.

The cohesion value of a bituminous mix is likely to be influenced by the volume of the binder within an asphalt and the boundary effects between the mineral aggregate and the binder. It is reported that when asphaltic concrete is tested triaxially it is found that the cohesion value shows a maximum value at a certain bitumen content and there is a drop in cohesion value both before and after that value, and the drop in value of cohesion increases as the bitumen content moves away from that optimum value. This data has been confirmed by many researchers (45, 69-72) when they tested asphaltic concrete at service temperature. The optimum value of bitumen content depends on the type and the grading of the mineral aggregate used. The value is found to be between 4 percent to 7 percent. This seems largely dependent on the packability of the aggregate particles. For more pactable aggregates the optimum value is more likely to be low, whilst for less packable aggregate the value is more likely to be high. However, the bitumen content in hot rolled asphalt is generally higher than that of asphaltic concrete. This means that the cohesion value is more likely to fall as the bitumen content increases. The type of the bitumen will logically influence the cohesion value. It is found that cohesion values noticeably decrease when the penetration value of the bitumen increases (45, 69, 70). There are other factors influencing the cohesion value related to the type of mineral aggregate and filler contents. Mixes made with crushed limestone show higher cohesion value than corresponding mixes made from gravel. Other tests revealed that an increase in filler content led to an increase in cohesion value with asphaltic concrete and sand sheet asphalt mixes (73).

The cohesion of an asphalt mix is temperature dependent. The important part of cohesion comes from the adhesive force of the bitumen; this is greatly influenced by the viscosity of the bitumen and is temperature dependency. All the reported literature relating to mix cohesion is low temperature, except AL-Nageim (6). It is shown that a rise in temperature certainly will reduce cohesion value (44, 53, 74). A full explanation of all factors influencing mix cohesion, angle of internal friction and mix viscosity are discussed in chapter five.

2.4.3 Mix viscosity

The presence of the bitumen in bituminous material imparts the mix viscosity component of resistance to internal movement. When some soils are tested triaxially, and tested with contained moisture (which has a low viscosity) the rate of deformation is of little concern. But, with mixtures of bitumen and mineral aggregate the rate of shear of samples is important because of the rheology of the bitumen.

In ashaltic mixes the voids within the mineral aggregate skeleton are (partly) filled with a material which has a measurable resistance to shearing. Mix viscosity is dependent on the viscosity of the bitumen and the rate of applied shear. Pfeiffer (41) was the first researcher to define a method of determining the viscous resistance of an asphaltic mix. He found that mix cohesion (true cohesion, apparent cohesion and interlocking resistance) increases proportionally as the rate of deformation in a rectilinear manner; he called this component viscous resistance. Friction, as with cohesion, is not lost when a material is subject to a rate of deformation. Nijboer (44, 52) called the slope of the line through the corresponding points of the internal shear stress at zero normal stress and rate of deformation, mix viscosity.

The three components of mix cohesion ('true', apparent and interlocking) will represent the case of zero rate of deformation.

The concept of mix viscosity is conceived as a plastic flow taking place in planes which pass through the contact points between the aggregate particles. Pfeiffer (41) explained that during the deformation of bituminous mixtures the particles slide over each other, but they will also try to roll over each other and turn. When the particles turn over and shift in the mixture it makes all the difference whether there is a layer of air between the moving particles, or there is a viscous mass which is bound to the mineral aggregate by adhesive forces (the bitumen). This means harder binders lead to higher resistance to movement, and subsequently higher viscous resistance. Nijboer (44) went further in his understanding of this phenomenon. He considered that the coarser particles within a material arranged themselves in layers parallel to the sliding planes. The finer aggregate might be supposed to fill the pores between the coarser aggregate. When flow takes place these layers of coarse aggregate will move with respect to each other, taking with them the finer aggregate. Under these circumstances the flow gradient will be highest in the neighbourhood of the contact points between the particles, so the viscous resistance must be considered to be located near these contact points where the layer of bitumen is very thin. This can explain why the mix viscosity increases when the volume of the binder, or volume of film thickness decreases - as will be seen in chapter four. Thus the thinner the layer of flowing bitumen, the higher the viscosity obtained. However, mix viscosity is a function of the angularity and service texture of the mineral aggregate, the viscosity of the binder, the volume of the binder and the volume of film thickness. High mix viscosity is expected with rough, angular particles and/or hard bitumen and low bitumen content.

Many investigators have reported the work of Nijboer since the 1940's and acknowledged the method of determining mix viscosity (53-58), but no attempt has been made to extend the work particularly to temperatures relevant to material layer compaction until presently when the high temperature triaxial cell has allowed tests to be carried out at compaction temperatures (6).

3.0 MATERIALS AND EQUIPMENT

3.1 TEST MATERIALS

In this study four mix variants were investigated. The mix variations were bitumen grade, bitumen content, bitumen rheology and filler:bitumen ratio. For each mix variation a range of mixes were prepared in the laboratory: 'low' to 'high' pen grade of bitumen; low to high bitumen content; 'low' to 'high' pen grade of bitumen with 5 percent EVA replacement; and, low to high filler to bitumen ratio. The control mix (a commercial Marshall design mix) lay in the middle of the mix variant ranges.

The first series of mixes was chosen to highlight the influence of bitumen content, and subsequently the influence of volume of film thickness (mastic volume); the film thickness was taken as the summation of the volume of bitumen and filler. The proportion of mineral aggregate and filler was held constant and the same as the control mix for this test series.

The second series of mixes was chosen to study the effect of filler to bitumen ratio, keeping the volume of film thickness and the volume of the mineral aggregate constant and similar to that of the control mix. The first and second test series provided a comparison between mixes having the same bitumen content but different filler content. These mixes highlighted the role of the filler in mix workability.

The third and fourth series of mixes focussed on the influence of the rheological properties of the bitumen. The third series covered three different penetration grade bitumens having measured pen values of: 46 pen, 68 pen and 99 pen. The fourth series used the same grades of bitumen used in the third series but the bitumen was modified with an inclusion of 5 percent by weight of EVA. The proportion of mineral aggregate, filler and bitumen with both series (3rd and 4th) was the same as that of the control mix.

The raw materials used in preparation of the four series was supplied from the quarry which produced the control mix. The quantities of coarse aggregate, sand, filler, bitumen of different grade and EVA additive were each brought to the laboratory in mass to avoid any differences between batches. The materials purchased were: four tonnes of crushed limestone 14mm coarse aggregate; seven tonnes of natural fine aggregate; and, one ton of crushed limestone filler. Six drums of bitumen with 200 litre capacity each were purchased, four of these were nominal 50 pen bitumen, one was nominal 70 pen bitumen, the third was nominal 100 pen bitumen. Twelve kilogrammes of Ethylene Vinyl Aestate (EVA) was used as a modifier to the three bitumen grades. The control mix as a commercial mix was designed using a 50 pen bitumen.

3.1.1 Aggregate and Filler Properties

Standard tests were carried out to define the mineral aggregate and filler properties. The tests were: sieve analysis, specific gravity and water absorption. Materials were tested in accordance with relevant British Standards (76, 77). The average of four determination with each test were recorded, the values are reproduced in Table 3.1. The fine aggregate grading exhibited 2 percent material retained on the 2.36mm sieve and 2.9 percent passing the 75μm sieve. Crushed limestone filler was added to provide the required filler contents. It was found that 6.5 percent of the added crushed limestone filler was retained on the 75μm sieve.

Table 3.1: Properties of Mineral Aggregate and Filler

sieve size	Passing Percentage		
	coarse aggregate	fine aggregate	filler
20 mm	100	-	
14 mm	95.78	-	
10 mm	19.48	-	
2.36 mm	0.00	98.0	
1.18 mm		94.76	
0.600 mm		88.83	
0.300 mm		60.71	
0.212 mm		41.3	100
0.075 mm		2.9	93.5
specific gravity:			
(oven dry)	2.734	2.696	2.675
(SSD)	2.879	2.706	-
Absorption	0.88%	0.37%	-

3.1.2 Bitumen Properties

The properties of the three pen grade bitumens used in this study were tested in accordance with BS 2000 (78, 79). The tests consisted of penetration, softening point and viscosity temperature profile. Penetration and softening point tests were regularly carried out throughout the research programme to check the stability of the materials. The test data for the pure bitumen and the modified versions are shown in Table 3.2.

Table 3.2: Penetration and Softening Point of Binders used in the Research Programme.

nominal penetration	penetration		softening point (R&B)	
	without EVA	with EVA	without EVA	with EVA
50	46	34	54.0	71.5
70	68	51	50.5	67.5
100	99	75	44.0	59.0

Viscosity measurements were made on pure bitumen samples and EVA modified bitumen samples using a modified British Standard procedure; the modification related to the oil bath and density measurement. The specific nature of modifications is as follows.

Viscosity measurements were made using a standard BS/IP Cannon reverse flow viscometer. The test method was based on IP specification IP 319/74, the kinematic viscosity was recorded directly from the test; dynamic viscosity (commonly referred to as 'viscosity') was determined by multiplying kinimatic viscosity by the mass density of the sample at the particular test temperature. The coefficient of thermal expansion for the bitumen of all three pen grades was provided by Shell Bitumen U.K. The value quoted did not vary with grade, being 0.00054 per degree Centigrade. It does not appear reasonable that different grades of bitumen have the same coefficient of thermal expansion. However, the binder density at any temperature was calculated using the density at 25°C and applying the thermal expansion factor as follows;

$$D = D_{25} [1 - (T - T_{25}) C]$$

where D = density at required temperature

D_{25} = density at $(T = 25°C)$ = 0.9935 g/cm^3

T = temperature in degrees Centigrade

C = thermal expansion coefficient = 0.00054/C°

giving the expression,

$$D = 1.007 - 5.365 \times 10^{-4} T$$

The viscosity test was carried out within the temperature range 60°C to 160°C. The test was performed by using a constant temperature oil bath, the heat being supplied by a hot plate which in turn was controlled by a rheostat. Specific details of the oil bath used and its calibration can be found elsewhere (80). The testing procedure was carried out according to BS 2000 part 71 (81). The viscosity result for all six types of bitumen and modified bitumen were plotted on a Bitumen Test Data, as shown in Figure 3.1. The bitumen grades 46 pen, 68 pen and 99 pen exhibited a straight line relationship linking penetration, softening point and viscosity measurements. For the modified bitumen a discontinuity was evident between penetrations and softening point measurements and viscosity measurements made at elevated temperatures.

3.1.3 The Control Mix

The control mix was a local Marshall design wearing course hot rolled asphalt using a nominal 50 pen bitumen. The design mix proportions were as follows:

coarse aggregate (retained on 2.36mm sieve) = 31.8 percent
fine aggregate (passing the 2.36 sieve and retained on the 75μm sieve) = 51.8 percent
filler (passing the 75μm sieve) = 8.2 percent
bitumen = 8.2 percent
total =100.0 percent

The proportions are by mass of material. In relation to the total aggregate, including the filler the aggregate proportions are: coarse aggregate 34.65 percent, fine aggregate 56.43 percent and filler 8.92 percent. The combined grading of the crushed limestone coarse aggregate, fine aggregate and filler to maintain the above percentages after carrying out the necessary calculation is shown in Figure 3.2; the grading passes down the centre of the grading limits defined in BS 594 (82). The control mix was described by the suppliers as "good" in response to roller action during laying and compaction. A Marshall test carried out on replicate samples of control mix prepared in the laboratory exhibited a stability value average of 10.35 kN and flow value average of 3.4 mm.

3.1.4 The Test Mixes

The research programme studied four series as specific mix variants, all mixes being prepared in the laboratory and covering a wide range of mix workability. The mix variables selected included material ingredients that influence the components of resistance to internal movement, and therefore the workability of hot rolled asphalt. In addition four commercial mixes were tested in a supplementary research programme which included variations in sand type. The details of the laboratory prepared mixes are as follows:

a) Test series 1. This test series consisted of five mixes designed to keep the proportions of coarse aggregate, fine aggregate and filler constant and in the same proportions as the control mix. However, five different percentages by mass of nominal 50 pen bitumen content, ranging from 7.0 percent to 11.8 percent, were added to the aggregate and filler. The all-in mix proportions of aggregate and filler consequently changed to accommodate the added bitumen and to ensure their proportions were maintained constant. This test series explored the effect of bitumen content on the components of resistance to internal movement, and in turn explore the effect of the volume of binder film thickness (bitumen + filler). As the mastic volume increased the volume of the mineral aggregate and its surface area decreased.

b) Test Series 2. This test series consisted of five mixes which were designed to study the influence of filler to bitumen ratio but keeping the volume of the mastic film thickness (filler + bitumen) constant. The volume of the total aggregate was kept constant, the proportions of coarse aggregate to fine aggregate were kept the same as for the control mix. This series covered the same range of bitumen content as that of Series 1, but the filler content varied in an inverse proportion in order to maintain the same volume of binder film thickness. For mixes with 7 percent bitumen content the filler content was 10.9 percent. As the bitumen content increased the filler reduced, so that for mixes with 11.8 percent bitumen they had only a very small filler content, as little as 0.12 percent. The extremely low filler content was as a result of washing the fine aggregate on a 75μm sieve, and no filler was added. For other mixes amount of crushed limestone filler was added to that already in the fine aggregate. The range of filler to bitumen ratio ranged from 0.01 to 1.56, covering all possible ranges of mastic stiffness used in design or recipe mixes. The volume of the mastic with these mixes was 27 percent and the aggregate volume was 63 percent. It is convenient for the percentage of aggregate to vary in spite of their constant volume, that is because the density at any specified void content is variable, resulting from the variability of the filler and bitumen. This test series showed the effect of filler to bitumen ratio (quality of the mastic) whilst the surface area of the mineral aggregate (coarse and fine) was kept constant. The percentage of each ingredient with each mix in both test series and other properties of the mixes are shown in Table 3.3. The control mix is naturally also represented in each series, which is seen in Table 3.3 denoted as mix No.2 in Series 1 and Series 2. The two series, 1 and 2, cover many variables, such as:

- changing bitumen content whilst the filler and mineral agregate proportions remain constant.
- changing bitumen and filler content whilst the mineral aggregate volume remains constant.
- changing the filler content whilst the bitumen content is constant.

The wide range of bitumen content used covers a range of mix workability; the range overcomes the internal friction resulting from the angularity of the mineral aggregate, particularly the fine aggregate particles.

Table 3.3: The mass percentage of ingredients and other properties of each mix used in the four test series

Criteria	Mix Number	Ingredient percentage by mass				Type of Binder	Filler to Bitumen ratio	Volume percentag of mastic
		Coarse agg.	Fine agg.	Filler	Binder			
Series 1								
changing bitumen content keeping the proportion of filler and mineral aggregate constant	1	32.22	52.48	8.3	7.0	46 pen	1.19	24.68
	* 2	31.8	51.8	8.2	8.2	46 pen	1.0	27.00
	3	31.39	51.13	8.08	9.4	46 pen	0.86	29.26
	4	30.98	50.45	7.97	10.6	46 pen	0.752	31.43
	5	30.56	49.77	7.87	11.8	46 pen	0.667	33.53
Series 2								
Changing filler to bitumen ratio keeping the volume of film thickness constant	1	31.23	50.88	10.89	7.0	46 pen	1.56	27.00
	* 2	31.8	51.8	8.2	8.2	46 pen	1.00	27.00
	3	32.37	52.72	5.51	9.4	46 pen	0.59	27.00
	4	32.94	53.65	2.81	10.6	46 pen	0.265	27.00
	5	33.50	54.58	0.12	11.8	46 pen	0.01	27.00
Series 3								
Changing the Rheology of the bitumen	* 1	31.8	51.8	8.2	8.2	46 pen	1.00	27.00
	2	31.8	51.8	8.2	8.2	68 pen	1.00	27.00
	3	31.8	51.8	8.2	8.2	99 pen	1.00	27.00
Series 4								
Changing bitumen Rheology by adding EVA	1	31.8	51.8	8.2	8.2	46 pen +5% EVA	1.00	27.00
	2	31.8	51.8	8.2	8.2	68 pen +5% EVA	1.00	27.00
	3	31.8	51.8	8.2	8.2	99 pen +5% EVA	1.00	27.00

* The control mix

c) Test Series 3

The three mixes in this test series used different penetration grade bitumens. The control mix included the 46 pen straight-run bitumen, the other two mixes included a 68 pen and 99 pen straight-run bitumen. The proportions of the mineral aggregate and filler were held constant with all three mixes and the same as the control mix. This series covered a range of bitumen penetration grades (46 pen to 99 pen), which currently represent the permitted range of penetration grades used for road construction. This series tested the changing stiffness of the mastic, but keeping the volume of mastic and mineral aggregate constant.

d) Test Series 4.

This test series appraised the effect of EVA as a modifier to the bitumen. The proportion of aggregate and filler used with the mixes in this series was the same as the control mix. The base bitumen binders are also the same as series 3, but partially replaced by EVA. The binder in each mix consisted of 95 percent by mass of bitumen with 5 percent EVA. EVA replacement is used in the U.K. presently to enhance the service performance of hot rolled asphalt. Such a modifier, it is claimed, has a measurable influence on proprties of a mix, particularly cohesion and viscosity.

Full details of Marshall tests carried out on all mixes with the four test series is shown in Appendix A. The data consists of the values of stability, flow and void content for each individual mix used.

Chapter seven includes a site study to measure the influence of the nature of the fine aggregate on mix workability. Four commercial mixes were tested. The mixes used two different fine aggregate blends, both different to the fine aggregate used with the four laboratory based test series.

3.2 LABORATORY EQUIPMENT

The study was carried out using equipment built and assessed in a previously reported study (6). The equipment includes

- a high temperature, closed-system triaxial cell for the determination of mix cohesion, angle of internal friction and mix viscosity at elevated mix temperatures.
- a rolling rig with a full scale roll for slab compaction.
- a vibrating compactor used to prepare samples for both the triaxial work and rolling rig.

. other basic equipment, such as corer, rock saw and Marshall apparatus.

3.2.1 High Temperature Triaxial Cell

The most important feature of the cell is its ability to use only one test sample to define the three components of resistance to internal movement within the temperature range 60°C to 150°C. The cell is unique in its ability to test samples statically and dynamically over the temperature-mix voidage combinations which are likely to occur during layer compaction.

Because the cell is non-standard it is important to provide an outline description of its characteristics and details of the modifications to equipment and procedures made as a result of this study. The general arrangement of the cell is shown in Figure 3.3 and Plate 3.1.

General description of the cell

The cell consists of a double lined mild steel cylinder. The outer annulus wall of diameter 300mm is filled with a standard heat transfer oil and contains a heating coil. This detail is capable of providing a uniform temperature distribution around the sample. The sample is located within the inner cylinder that has an internal diameter of 200mm and is filled with the same oil as the outer annulus. The oil has a flash point above 200°C. Temperature of the oil is adjusted by two thermostats, within the inner cylinder and within outer annulus.

The cell is insulated externally with rock wool which is held in contact with the outer wall of the outer annulus by a P.V.C. cover. The cell body and top plate is a single unit, see Plate 3.2. Two safety valves are connected through the top plate to the inner cylinder and outer annulus, which open automatically at an oil pressure of 1000 kN/m . Two thermostats are fixed to the top plate and connected to the heating oil circuit. The outer annulus and inner cylinder also have holes through the top plate for oil filling.

The cell base is 25mm thick mild steel. It is fitted with four connections, to perform the following functions.

1. Measure the confining pressure using a bourdon gauge with range 0 to 60 psi.

2. Control the rate of vertical deformation of a sample through the efflux of pressurised inner cylinder oil by using a valve manufactured with a scale to control the opening size of the valve. This valve was modified by adding a special sleeve designed to ease the control of the oil bleed rate.

3. Provide an inner oil cell pressure supplied by an oil pump used to increase the pressure around the sample between static and dynamic testing.

4. Provide access to the sample to monitor sample temperature; this consists of three 0.6mm diameter insulated thermocouples located at three points along the length of the surface of the sample and one point within the sample, as shown in Figure 3.3 and Plate 3.3. The thermocouples are connected to a six-way channel selector and in turn connected to a digital thermometer.

The pedestal on the base, on which the sample sits, is a machined cylinder which has two grooves on the face to locate two o-ring providing an oil tight seal with the rubber membrane protecting the sample. The cell has a set of 8 rods to connect the top plate to the base plate and provide an oil tight steel to the inner cylinder and outer annulus.

The load is applied to a sample through a steel shaft passing through the top of the inner cylinder. The steel shaft is located on a circular steel platen lying on the upper face of a sample. A cantilever arrangement applies the load to the steel shaft. A dial gauge (80mm travel reading to 0.01mm) was used to measure the vertical movement of the shaft, which is the vertical deformation of the sample.

The rubber membrane

An asphalt sample is protected by an easily deformed silicon rubber membrane 300mm in length and 100mm inside diameter. The membrane was designed for high temperature application; it is held against the steel platens at both ends of a sample by four rubber o-rings.

A correction for the strength of the rubber membrane is made in the calculation of (actual) axial stress applied to a sample. The correction expression was reported in a previous study (6) as

$$\sigma_r = 31.8\ E(1 - E)$$

σ_r = correction stress (kN/m^2)

E = axial strain of the sample

The correction is small, of the order of $5kN/m^2$ at maximum axial strain of the tested sample ($E = 0.2$). The correction stress is a negative quantity.

Calibration of loading system

Although the cell is calibrated prior to any testing programme recalibrations are made during the programme to eliminate any error which may arise from using the cell. Precalibration is carried out following the same procedure used during the commissioning of the cell and which is reported in the earlier study. The load cell used in recalibration was itself calibrated first, the data for which is shown in Figure 3.4; the cell calibration is shown in Figure 3.5.

The data in Figure 3.4 and Figure 3.5 provides the relationship between the applied load on the lever arm and the load on the sample; this relationship is as follows.

$$Y = 0.261 + 0.555x$$

where y = the axial load on the sample in (kN)

x = the dead load on the lever arm in (kg)

This relationship is marginally different from that reported by AL-Nageim.

Calibration of the oil pressure gauge

The calibration of the oil confining pressure gauge was carried out prior to and during the research programme. A linear relationship was found between the dial gauge reading and the data view readings as shown in Figure 3.6. By substituting the 'black box' value from Figure 3.4, the actual confining pressure relationship can be defined as follows.

$$\sigma_3 = -5.873 + 6.6\ G$$

where σ_3 = the continuing pressure surrounding the sample in kN/m^2

G = the oil gauge pressure reading in psi

Preparation of sample for triaxial testing

As identified previously the cell measures mix viscosity in addition to mix cohesion and angle of internal friction. The sample to be tested is fitted with three thermocouples at the three locations shown in Figure 3.3, the thermocouple wires passing through the cell base. The silicon rubber membrane is fitted to the sample which is then placed on the top of the pedestal on the cell base plate. A paper disc is placed at both ends of the sample to prevent any adhesion between the sample and the pedestal or the top bearing plate. After locating the rubber membrane and fitting the rubber o-rings the upper and lower halves of the cell are assembled; the cell is then filled with oil. The loading piston is then passed through the top of the cell and the cell lifted by mini-lifting machine onto the testing frame. The loading shaft is then connected to the loading piston and enough room for the dial gauge movement is made to ensure the maximum deformation of the sample can be measured. Finally, the thermostats are set to the required testing temperature.

When the required sample temperature is achieved and the confining pressure is stabilised, the bleed valve is opened to reduce the gauge pressure to 2 psi (14 kN/m^2); this value is the initial pressure used to ensure the rubber membrane is in continuous contact with the sample and the testing head is seated on the sample (6, 62, 83).

Sample testing procedure

A static load of between 1 kg and 5 kg is applied to the weight hanger (Figure 3.3). The amount of initial load depends on the stiffness of the sample. When the rate of vertical movement of the sample falls below 25 x 10^{-3} mm/min, or when the confining pressure stabilises, whichever occurs first, the confining pressure is read; the axial load and strain gauge reading are also recorded. This sample condition is defined as static equilibrium. Further increments of static load are added and readings taken at static equilibrium until no further load can be sustained, or the total deformation of the sample is equal to 20 percent of the initial vertical length of the sample. Loads were applied in increments of 5 kg with most mixes, but with mixes which deformed easily, particularly at high temperatures, the increment was reduced. In some cases the increment was reduced to 1 kg to prevent any sudden collapse of the sample, or high rate of strain.

Data from the conditions of static equilibrium defined mix cohesion and angle of internal friction. In order to measure mix viscosity conditions of dynamic equilibrium are required. Conditions of dynamic equilibrium were interspersed between conditions of static equilibrium. The initial dynamic equilibrium test was made when the confining pressure had reached a value of about 10 psi (70 KN/m^2), enough to cover any possible drop to zero pressure during bleeding of the oil from around the sample. The bleeding valve was opened marginally to drain oil from the inner cylinder surrounding the sample. The valve opening was such as to give the desired constant rate of sample deformation. When the confining pressure became constant, under the desired constant rate of deformation, the load on the lever arm hanger and lateral pressure were recorded. The valve was then closed and the loading shaft locked; the strain gauge noted to record the total strain of the sample. The confining pressure was then raised to its level before the loading valve was opened. The procedure was repeated after an incremental load was placed onto the lever arm hanger, but a different rate of deformation was applied on replication of the procedure. Three rates of sample deformation were used, nominally 2.5mm/min, 5.0mm/min and 10mm/min. The conditions of dynamic equilibrium were repeated in order to record at least four readings for each rate of sample deformation. Figure 3.7 shows a typical record of data for a sample.

Staggering the rate of sample deformation is a useful technique in that data for each rate of deformation is separated by a wide interval in values of vertical stress and confining pressure, which, it is believed produces a more accurate relationship for different sample strain rates. This test procedure enables data to be gathered from the sample for mix cohesion, angle of internal friction and mix viscosity.

Calculation of vertical stress and confining pressure

In order to determine the axial stress at any state of sample deformation the corected cross-sectional area of the sample has to be calculated. The recorded value of axial stress is that calculated, but adjusted to take account of the effect of the rubber membrane and confining pressure.

$$\sigma_1 = \frac{Y}{A} + \sigma_3 \, \frac{A - a}{A} - \sigma_r$$

σ_1 = recorded value of axial stress (kN/m^2)

σ_r = $31.8\,E\,(1 - E)$ (kN/m^2)

Y = $0.261 + 0.0555x$ (kN)

X = dead load on level arm hanger (kg)

a = the leading piston cross-sectional area (m^2)

A = $\dfrac{Ao}{1 - E}$

Ao = initial sample cross-sectional area (m^2)

E = axial strain = $\Delta L/L$

ΔL = sample axial deformation (mm)

L = initial length of the sample (mm)

σ_r = the correction stress due to the effect of the rubber membrane (kN/m^2)

σ_3 = $- 5.873 + 6.6\ G$ (kN/m^2)

G = the oil gauge pressure readings (psi)

A computer program was used to calculate the axial stress. The values of axial stress and confining pressure are used to establish the relationships shown in Figure 3.7. The mix properties of angle of internal friction and mix cohesion are then determined, as shown in Figure 3.7.

Mix viscosity is defined by constructing the relationship between mix cohesion and rate of sample deformation, as shown in Figure 3.8 and described in section 2.3.2.

Specific details of the cell construction and method of testing can be found in the report on the previous study (6).

Modifications to the triaxial test procedures

1. Sample Temperature

In this study special attention was paid to setting the sample temperature in order to minimise the temperature differences between the upper and the lower part of the sample. It is naturally the upper part of the oil surrounding a sample in the inner cylinder that is hotter than the lower part, and that is reflected in the sample temperature. This effect was minimised by drawing oil from the bottom of the cell and pouring it in at the top of the cell prior to a test and the cell being pressurised. This circulation of the oil homogenises the temperature and reduced the difference in temperature over the length of the sample to about 1°C in the case of sample tested at 60°C and to around (3 to 4°C) for testing at 140°C.

There are two important factors concerning sample and oil temperature which should be acknowledged. The sample temperature influences the values of components of internal resistance to movement; the surrounding oil temperature controls not only the sample temperature but also the confining pressure. Any temperature fluctuation in the oil bath will influence the confining pressure. It is important to stabalise the temperature in the oil bath to ensure an accurate measure of confining pressure, but at the same time ensuring any sample temperature fluctuation during the test is minimised to ensure accuracy in the values of the components of resistance to internal movement.

In this study the temperature was monitored through its effect on the confining pressure; when the sample reached the required temperature within 2 to 3 degrees Centigrade the confining pressure was monitored carefully. When the confining pressure stabilised the pressure was set to the initial pressure (14 kN/m^2) and the test started.

2. Definition of static equilibrium

In the triaxial test the measurement of the vertical deformation of the sample is important because it will define the amount of increase in the cross-section area of the sample and enable the calculation of the true vertical stress. In soil mechanics the deformation of a sample is read when the dial gauge stabalises (i.e. the condition of static equilibrium reached). For bituminous materials the case is different. The presence of the bitumen imparts a viscous property. This means the dial will take some time to stabilise, the rate decreasing with time. In some cases the gauge may not stabalise to zero. This is due to the continuous deformation of the sample when subject to loading. Within a closed system any deformation of a bituminous sample will lead to an increase in confining pressure. The deformation of a sample may reach a rate so small that is has no definable effect on the measured confining pressure. Smith (62) assumed with bituminous materials that static equilibrium was defined when the rate of vertical deformation of a sample became less than 0.025 mm/min. Smith's assumption has a wide acceptance, enough to be adopted by the Asphalt Institute (63, 64). They also recommend this rate of vertical sample deformation when acknowledging Smith's method for the evaluation of btuminous materials. Other researchers have either followed Smith's method or have avoided acknowleging this situation, or they tested the materials at different rates of vertical sample deformation and extrapolated back to zero rate of vertical sample deformation (41, 44).

The rate of vertical sample deformation is based on tests carried out at service temperatures and for asphaltic concrete; the temperature and material is different from the high temperature testing of hot rolled asphalt. With high temperature testing the rate of vertical deformation of a sample is faster and it may take longer for the rate of vertical deformation to settle and this depends, to a large extent, on the stiffness of the material. In the previous reported study, AL Nageim (6) followed Smith's criteria, but he only used two commercial mixes. In this study a variety of mixes were used having material proportions beyond the limits quoted in Standards. Here it was found difficult to adopt Smith's limits of rate of vertical deformation with all mixes, particularly the soft workable mixes tested at high temperatures. In this study static equilibrium was assumed to occur when confining pressure stabalised, at this point vertical sample deformation was recorded even although the rate of vertical deformation of the sample was greater than 0.025 mm/min. As any increase in the rate of sample vertical deformation may lead to an increase in the calculated value of mix cohesion, this was checked by using the data to calculate mix viscosity, which uses different rates of vertical sample deformation. Extrapolating the relationship between cohesion and rate of deformation back to zero (rate of vertical deformation) defines the true static equilibrium state. It was found with this check that when the rate of vertical sample deformation increased to ten times Smith's rate, the influence on mix cohesion values was nil.

It was found that 'soft' mixes had limiting rates of vertical sample deformation about ten times Smith's rate of 0.25 mm/min per 200 mm of sample height. This can be explained by example:

The softest mix in the programme from series 1 had bitumen content of 11.8 percent. At a voids content of 3 percent and temperature of 100°C, mix cohesion, C was measured as 13340 N/m^2, mix viscosity, η_m was measured as 1.23×10^7 $Ns.m^{-2}$ and angle of internnal friction, ϕ was measured as 30.75 degrees.

For a rate of vertical deformation ten times Smith's rate of 0.025 mm/min per 200 mm height then

$$\frac{d\gamma}{dt} = \frac{3}{2}\frac{dE}{dt} \sin 2\theta \quad \text{(see section 2.3.2)}$$

$$\frac{d\gamma}{dt} = \frac{3}{2} \times \frac{10 \times 0.025\text{mm}}{\text{min}} \times \frac{\text{min}}{60\ \text{sec}} \times \frac{1}{200\ \text{mm}}$$

$$\times \sin 2(45 + \frac{30.75}{2}) = 2.686 \times 10^{-5}\ \text{Sec}^{-1}$$

$$\text{cohesion} = 1.23 \times 10^{7}\ \text{NS/m}^{2} \times 2.686 \times 10^{-5}\ \text{sec}^{-1} = 330.3\ \text{N/m}^{2}$$

Hence the percentage change in cohesion value for rate of vertical deformation ten times that of Smith $\frac{330.3}{13340} \times 100$ = 2.4 percent. This is low and lies within generally accepted experimental error. It is believed that Smith's rate cannot be justified for high temperature testing, particularly for soft mixes.

3. Calculation of rate of deformation

The calculation of rate of sample vertical deformation is shown in section 2.3.2, and determined by the following equation.

$$\frac{d\gamma}{dt} = \frac{3}{2}\frac{d\epsilon}{dt} \sin 2\theta$$

The E term is the strain value of vertical displacement which is equal to the ratio of amount of deformation to the total height of the sample. Mix viscosity is based on a different rate of deformation. Each time the rate is applied to a sample the height of the sample is different; the height is reduced. Furthermore, each rate of vertical sample deformation is applied four times to a sample, each ratio is applied at a different sample height. In the present study the average sample heights for each rate of vertical sample deformation was used when the value of E was calculated. This is more accurate than assuming the height of a sample is equal to its original height, as was the case with Nijboer (52), or the height of sample before the first reading in each rate of deformation, as was the case with AL-Nageim (6). Therefore the term $\frac{dE}{dt}$ is equal to the average of the ratios at the rate of deformation corresponding to the height of the sample for all readings of that rate.

4. Arrangement of rate of sample deformation

In the present study the determination of each rate of vertical sample deformation is spread over the test sequence in order to ensure a more accurate relationship between vertical stress and confining pressure. This is different from that of AL-Nageim who measured four rates of sample vertical deformation consecutively.

5. Load Application

The static load application was not fixed at intervals of 5 kg, as was the case with AL-Nageim. It was found important to maintain the rate of strain approximately constant between mixes to avoid any possibility of overvalueing the stresses. In the present study the load increment was reduced as the workability of the mix increased, the bitumen content increased or filler bitumen ratio decreased. For example, with mixes with a bitumen content of 7 percent the load increment was 5 kg whilst for mixes with a bitumen content of 11.8 percent the load increment was 1 kg.

All above modifications were made to ensure a high level of accuracy and to build the required confidence in the testing procedure and in the declared results.

3.2.2 The Rolling Rig

The rolling rig used for this research programme was constructed for the previous study. The roller is a dead-weight roll, 295 mm wide and 1200 mm in diameter with a static linear load of 53 N/mm; the linear load relates directly to the specification for the rear roll of an 8-10 tonne dead-weight smooth wheeled steel roller used in practice (6, 84, 85). The roller was constructed from 25mm steel plate, the drive shaft for the roll supports a steel cradle which in turn houses two drive chains. The roll is shown in Plate 3.4. The roll is driven by a quick acting reversible and adjustable speed motor. The rolling speed was set to 0.5 m/sec, the rolling speed commonly reported as used on site (6, 86, 87). The rolling track is 7 metres long by 300 mm wide by 100 mm deep, constructed from two side plates welded to a 46 kg/m channel. A water tank is mounted over the roll to deliver a controlled amount of water through an outlet pipe to the face of the roller to prevent adhesion of the mix to the face of the roll.

The sample temperature was monitored during the compaction through four thermocouples positioned 10 mm, 20 mm, 30 mm, from the top of the sample and a fourth at the interface between the slab and a bituminous substrate. The thermocouples were connected to an amplifier which in turn was connected to a BBC microcomputer. More information on the roll and related accessories are reported elsewhere (6).

3.2.3 Compaction Apparatus

Cylinders for the triaxial test and slab for roller compaction were prepared using a vibrating hammer shown in Plate 3.5. A kango pneumatic hammer with a 26-60 Hz frequency was used to apply vibrating compaction to samples through a specially designed compaction plates. The use of a vibrating hammer is not new and has been shown to give satisfactory results, as reported by a number of investigators (6, 88); it is also used as a method of compaction in Standards (89, 90).

3.2.4 Mechanical Mixer

A mechanical mixing unit of 16 litre capacity was used to make the asphaltic mixes in this project. The mixer was capable of combining up to 16 kg of aggregate, filler and binder speedily and thoroughly without loss of material.

3.2.5 Modified Binder Mixer

The fourth test series consisted of three mixes with different grades of EVA modified bitumen. A mixing system was designed to blend the bitumen with EVA at a controlled temperature. The mixing system consists of a brass bowl, 250 mm diameter and 145 cm deep filled with standard heat transfer oil with a flash point above 200°C. The bowl is seated on a variable switch hot plate. A cauldron 150 mm diameter and 140 mm depth made of brass was used for mixing the binder; the cauldron was fabricated with an insulated handle and 4 brass feet, 20 mm high, to prevent direct heating from the hot plate. The cauldron was placed inside the bowl, the surrounding oil provided the heat required to maintain the binder at the required temperature. Two stirrers were used, one for circulating the oil around the cauldron and the other for mixing the binder. Both stirrers were supplied with variable speed motor. A safety jacket was designed to surround the hot plate and bowl to stabalise the system. A schematic diagram of the setup is shown in Figure 3.9.

3.2.6 Moulds

Two types of steel mould were used. For the triaxial samples 4 prisms 150 mm by 350 mm base by 150 mm height and which is shown in Plates 3.5 and 3.6 were used to prepare prismatic samples; the prismatic samples were subsequently cored to provide cylindrical samples as shown in Plate 3.7. For the slabs used in the rolling rig 20 moulds, 300 mm by 300 mm base size by 40 mm height were used as shown in Plate 3.8. Both moulds were supplied with collars for filling and compacting the samples.

3.3 SAMPLE PREPARATION

All aggregates and fillers were oven dried for 24 hours at a temperature of 105±5°C before being weighed individually. The three ingredients were stored in one container and returned to the oven which was set to a temperature of 170°C.

The bitumen was supplied in barrels of 200 litres. Each barrel was cut and the bitumen stored as chippings in a freezer cabinet at a temperature of -18°C to keep the bitumen as discrete chippings. The bitumen was heated in metal cans of 2.5 litre capacity. All bitumens were heated according to their grade to a temperature of 110+3°C above their softening point, as stated in BS 598 Part 3 (91), using thermostatically controlled ovens.

In the case of modified binders, the bitumen was poured in the mixing cauldron the amount of bitumen determined by difference. The exact amount of additive was added, mixed with a flat blade stirrer for a continuous 15 minutes - as recommended by the manufacturer - to ensure a homogeneous solution was achieved.

The heated aggregate was discharged to the mixing bowl, mixed thoroughly with a spatula and a crater was formed to receive the binder. The heated binder was weighed to the nearest gram by weight difference by pouring it into the mixer. The asphalts were mixed for two minutes then checked by spatula to ensure they were thoroughly and evenly mixed.

3.3.1 Sample Preparation for Triaxial Test

The rectangular prisms were used to produce triaxial samples. After mixing the materials were scooped hot into pre-heated moulds; the moulds were filled in three approximately equal layers. Each layer was rodded with a 10 mm steel rod, the tamping ensured a fair distribution of the material inside the mould. The material was then compacted either by applying a vibrating pressure to one face of the sample in the case of samples with a target voids content of 6 percent, 9 percent, 12 percent, or a vibrating pressure was applied to two opposite faces 150 mm x 350mm in the case of samples with a target voids content of 3 percent. The compaction of both faces was achieved with the use of a special mould base. The prisms were cored on cooling, the samples then being sawn to remove their outer ends as shown in Plate 3.9. The ends were cut again to provide two discs for density calculation. Sample density and voidage were determined according to the specified British Standard procedure (91).

3.3.2 Sample Preparation for Roller Compaction

Material for two samples were mixed at the same time. After mixing the weight of the material to provide slabs of 12 percent voids content was weighed out. The void content was taken at 12 percent to represent the voidage achieved on site subsequent to paver laydown (92). The material was added hot to the assembled and pre-heated moulds with the tufnol block holding the thermocouples located 20 to 30 mm inside the mould. The material was then distributed uniformly in one layer in the mould, rodded with a pre-heated 10 mm diameter steel rod and then hand tamped with a laboratory spatula. The tamping action was to ensure the asphalt mixture was distributed uniformly in the mould. The material was then compacted by the vibrating compactor.

3.4 THE TESTING PROGRAMME

The test programme was carried out to evaluate the workability of hot rolled asphalt, through the assessment of the internal resistance parameters angle of internal friction, mix cohesion and mix viscosity. The values measured were intended to cover material conditions in increments during the whole process of pavement compaction. This was achieved by testing samples at different voidage, simulating the case of material placed by the paver to material at a state after rolling. Furthermore it was important to determine the internal resistance parameters over the range of temperatures relevant to material compaction. These conditions required the testing of each mix ingredient variation at four voids content and five temperatures.

The rolling performance of the asphalts was determined by the material being compacted using one, three, six, nine, twelve and eighteen passes of the roll at the same temperatures as the triaxial tests. Each roller test and slab temperature required a separate slab.

The programme consumed 4 tonnes of coarse aggregate, 7 tonnes of fine aggregate, 500 kg of filler and more than 1 ton of the binder.

3.4.1 Triaxial Testing Programme

The four series of mixes resulted in 16 mixes to be tested: the control mix is common to the three test series therefore reducing the number of mix variations to fourteen. Each mix was prepared at four nominal voids contents; 3 percent, 6 percent, 9 percent and 12 percent. And, with each voids content samples were tested at five different temperatures, 60°C, 80°C, 100°C, 120°C and 140°C. For each mix variant 20 samples were required. At the beginning of the programme mixes were made to ensure consistency was achieved with the procedures described in this section, even so each triaxial sample was tested for voidage content and those not complying were rejected.

A variation of 1.0 percent in sample voidage was the criterion adopted for triaxial sample acceptability; it was found that 80 percent of the samples were within ±0.3 percent of target voidage. The mixes causing most difficulty in testing were those with high bitumen content tested at 140°C and high void content such as 9 percent and 12 percent. Tests were replicated to ensure the accuracy of specific values.

3.4.2 The Rolling Programme

Each of the fourteen mixes was rolled at six temperatures with six numbers of roller passes; a total of 36 samples were tested for each mix variation, each prepared at 12 percent voids content. The nominal slab temperatures used were 60°C, 80°C, 100°C, 120°C, 140°C and 160°C; the roll passages used were 1, 3, 6, 9, 12 and 18. Each pass represented one forward and one reverse pass of the roll. Slab tests were replicated to ensure the accuracy of representative values. Slabs tested at temperature of 140°C or below were rolled immediately from the preparation stages, whilst for 160°C samples were heated in a pre-heated oven for 30 to 60 minutes. The compacted samples were sawn to provide 100 mm x 100 mm samples from the centre of the compacted slab; these samples were used for density measurements. Two mix variants were not rolled at a slab temperature of 160°C because they were unstable; the mixes were those having a bitumen content of 11.8 percent.

The rolling programme was carried out on unchipped slabs for the following reasons.

a) In the previous study (6) it was found that the layer under chippings was controlling the slab properties and chipping embedment. In the rolling of unchipped slabs their response to the roller through the densification process was considered to be substantially the same as with chipped slabs. This hypothesis was checked as part of this study.

A mini-programme comparing the compacted voidage with unchipped slabs with slab voidage below chippings with chipped slabs was carried out. Slabs with all mixes of test series 1 and 2 were prepared and rolled using a 70 percent area coverage of pure coated chippings with 18 passes at six different temperatures within the temperature range 60°C to 160°C. After rolling the chippings were removed carefully following the same procedure as the previous study, the centre 100 mm by 100 mm was cut out and the void content of the whole slab was measured. The sample was then cut horizontally and the voidage of both sub-layers calculated. Voidage values for the chipped slabs using the lower sub-layer was found to be consistent with unchipped samples.

b) In correlating data from the triaxial cell and the rolling rig, or more specifically between the internal resistance parameters and terminal voidage of rolled slab, it is critically important to ensure both samples are identical in terms of ingredients. The added chipping will increase the stone content within the slab below the chippings resulting in a change in the percentage of the ingredients, produce an increase in the surface area of mineral aggregate, and decrease the volume of film thickness. A direct comparison of materials is not practically possible.

c) In the voidage or density calculations with chipped slabs the slab is divided into two sub-layers; around chippings and below chippings. The upper sub-layer (between chippings) has more mastic and less stone content, and vice versa for the lower sub-layer. The density calculations consequently will be in error on the basis of the theoretical maximum density which varies between the upper and lower sub-layers. Although this error may be small, with unchipped slabs there is no such difficulty.

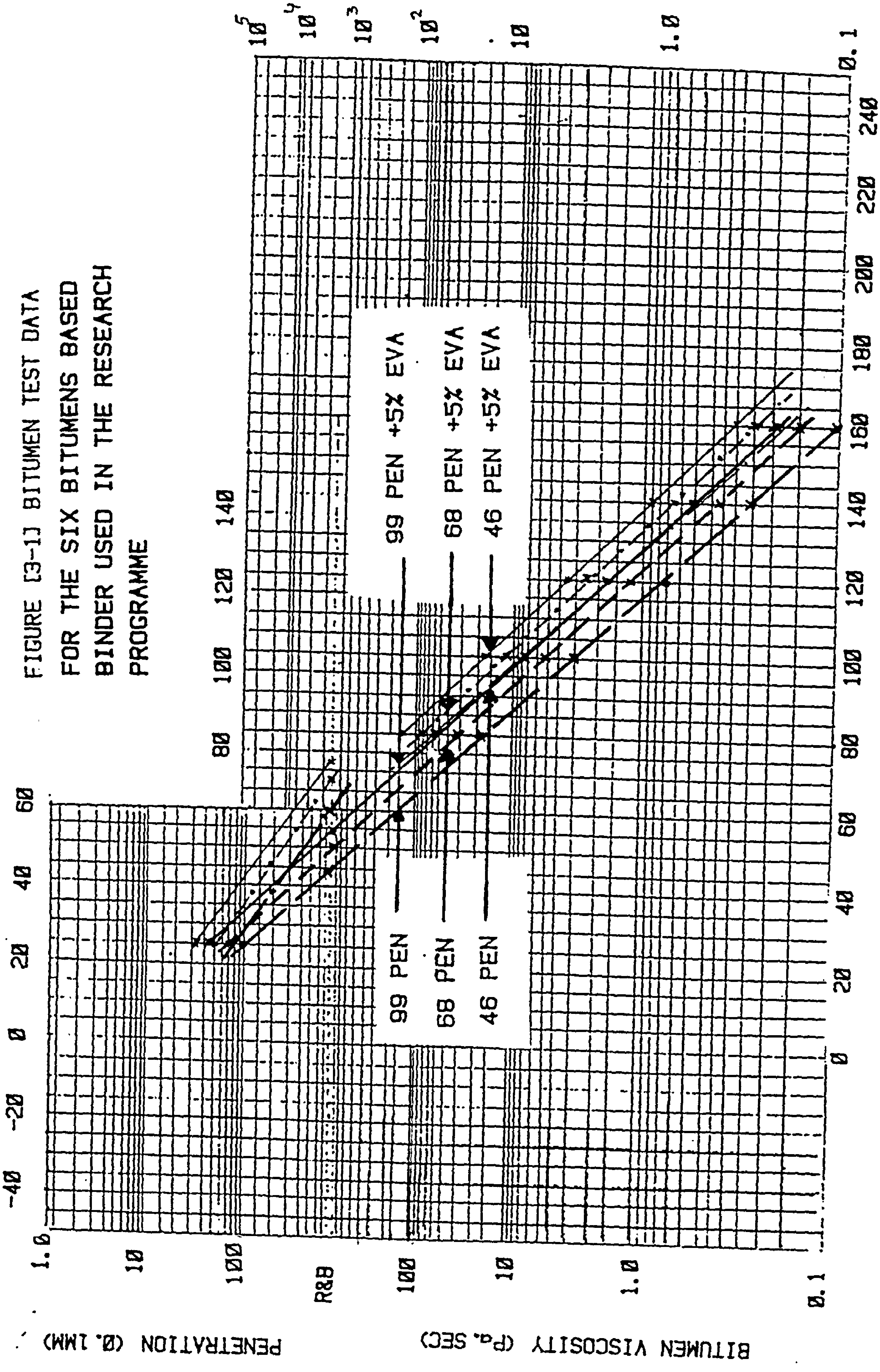


FIGURE [3-1] BITUMEN TEST DATA FOR THE SIX BITUMENS BASED BINDER USED IN THE RESEARCH PROGRAMME

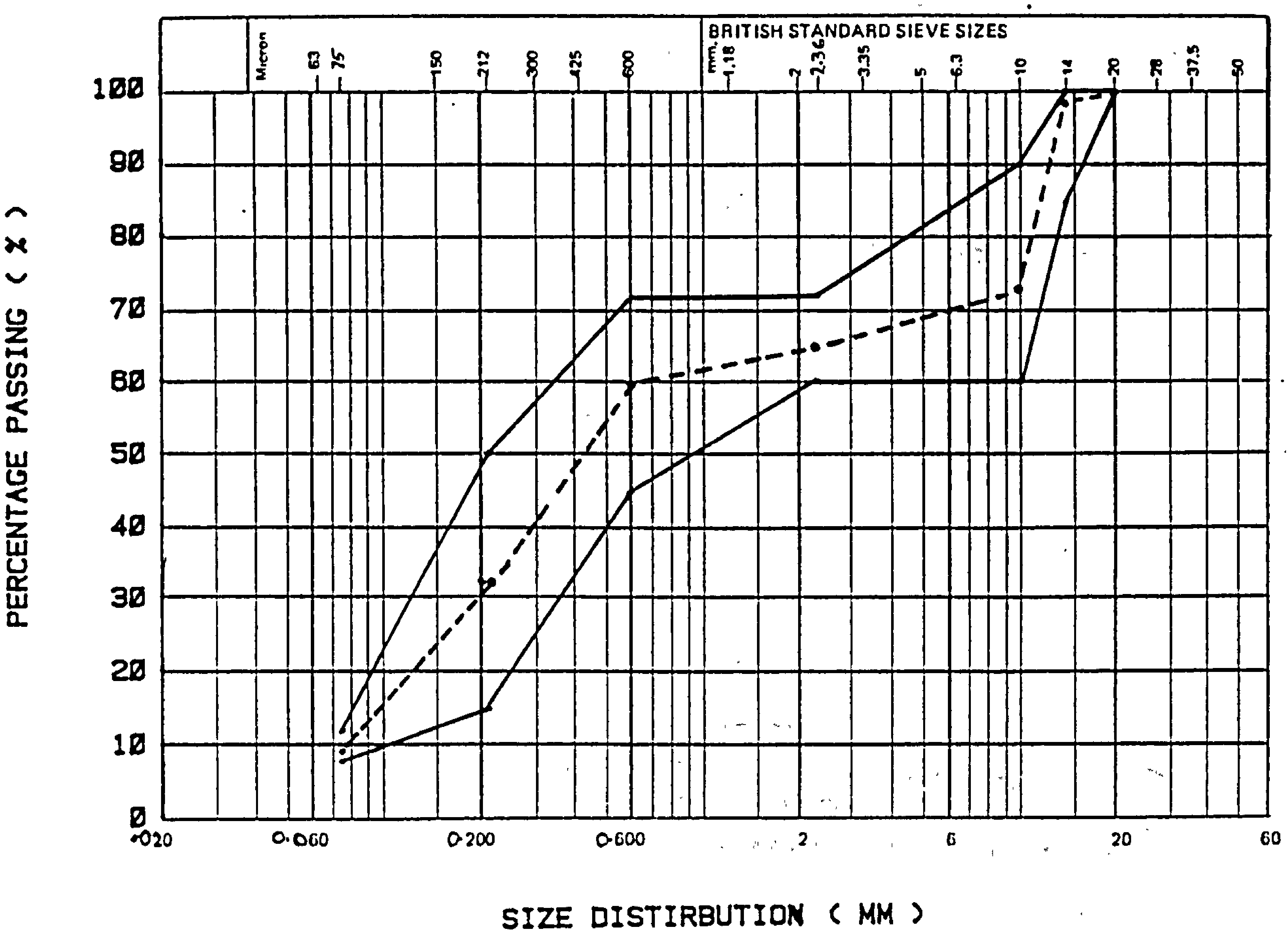
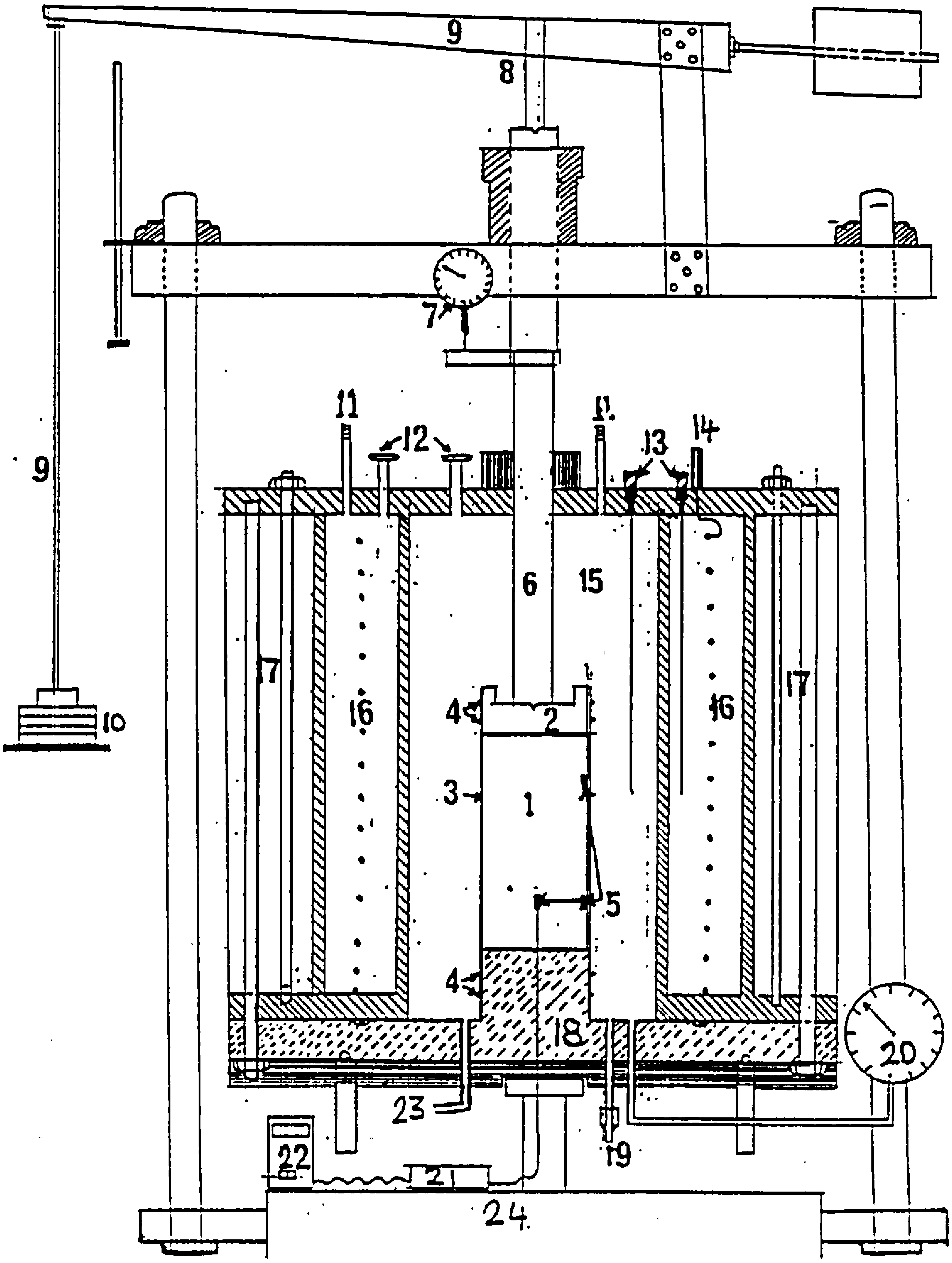


Figure 3.2: The combined grading of mineral aggregate and added filler of control mix.



1. TEST SAMPLE
2. THE LOADING PLATE
3. RUBBER MEMBRANE
4. O - RING
5. THERMOCOUPLES
6. LOADING PISTON
7. DIAL GAUGE
8. HINGE
9. LOADING LEVER ARM
10. LOADS
11. RELEASE VALVE
12. OIL FILLING HOLE
13. THERMOSTAT
14. HEATING ELEMENT
15. THE INNER CYLINDER
16. THE OUTER CYLINDER
17. INSULATION MATERIAL
18. THE CELL BASE
19. BLEED VALVE
20. OIL GAUGE PRESSURE
21. BENCH SELECTOR
22. DIGITAL THERMOMETER
23. CONNECTION TO THE OIL PUMP
24. TRIAXIAL FRAME

Figure 3.3: The High Temperature Triaxial Cell.

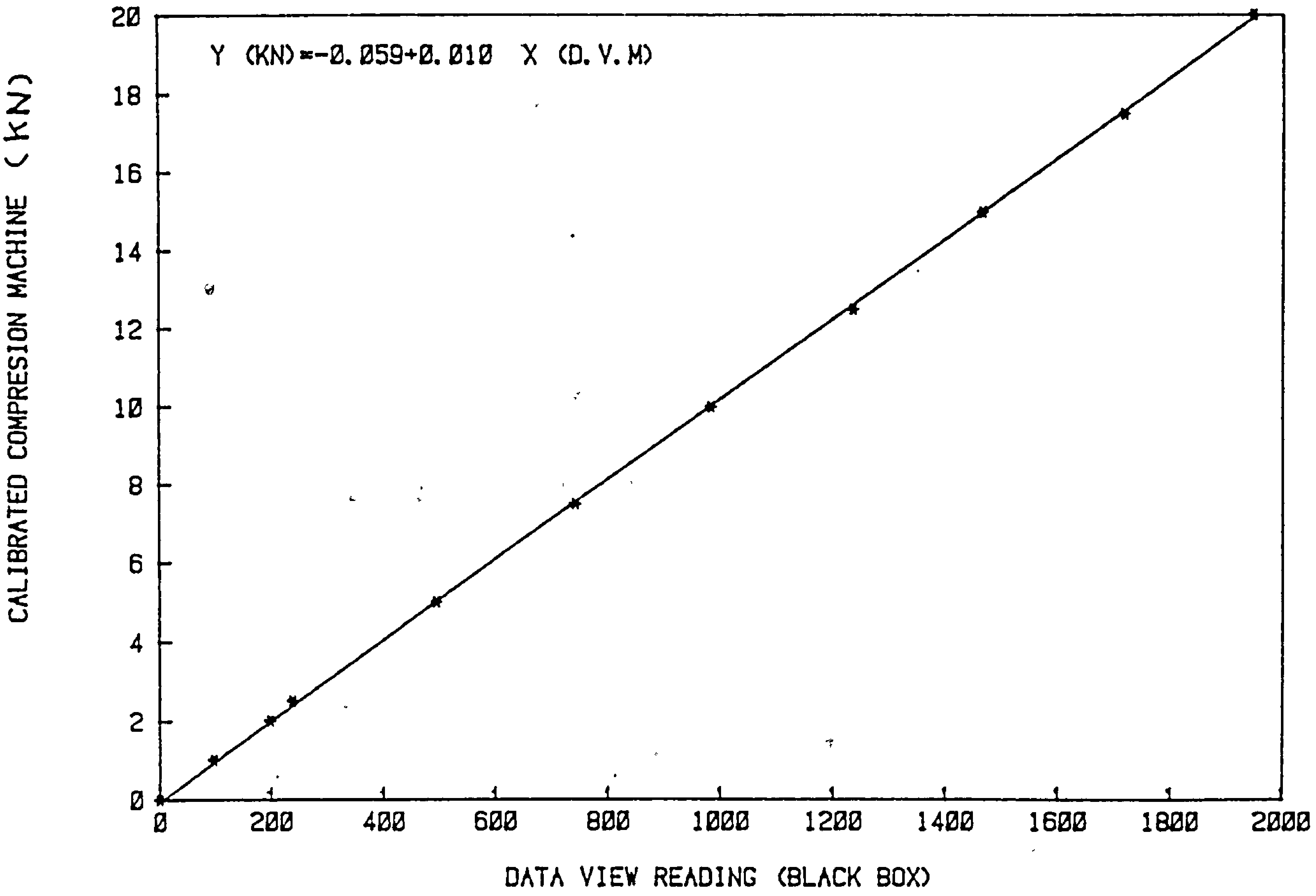


Figure 3.4: Calibration Data for the Load Cell.

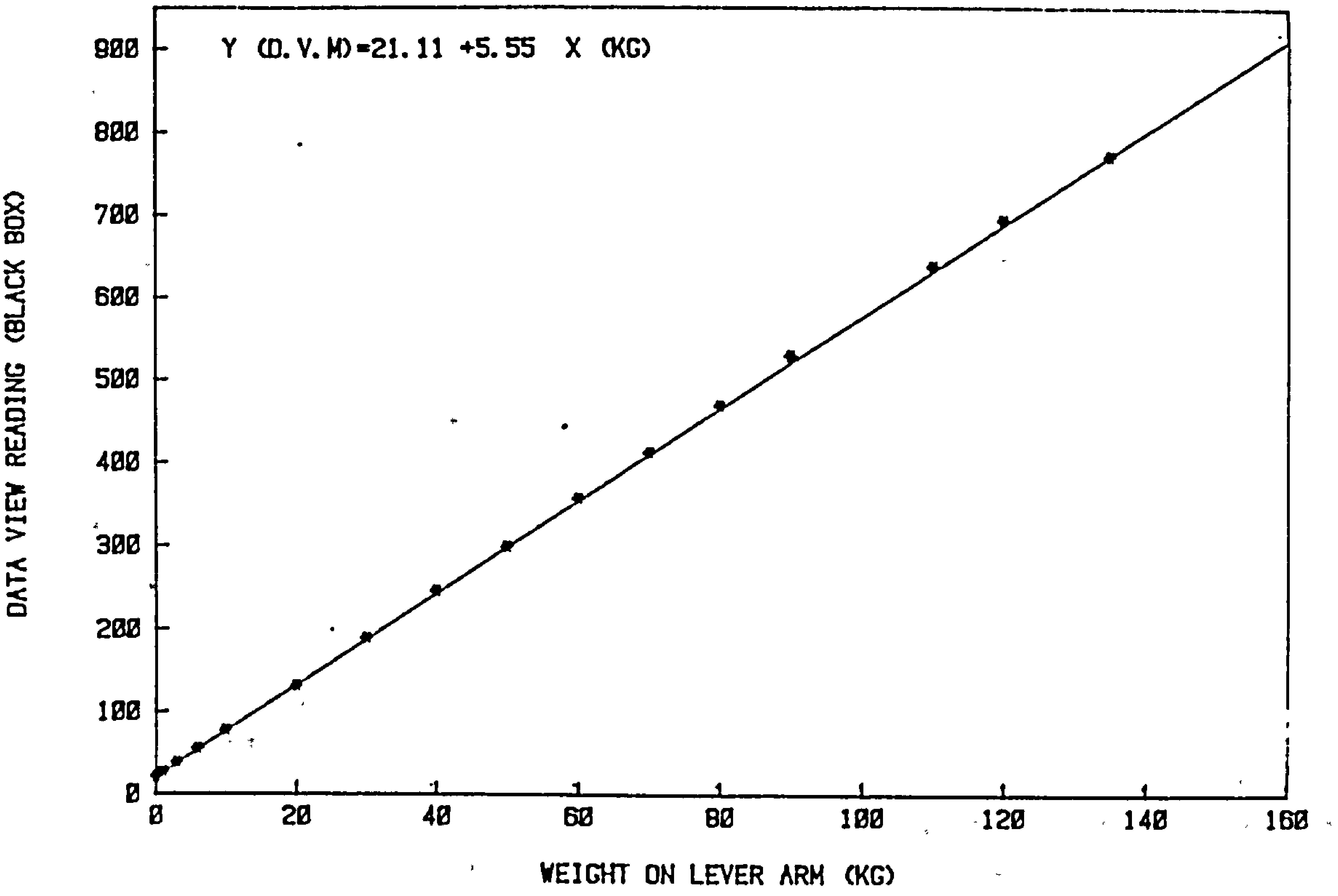


FIGURE [3-5] DATA VIEW READING VERSUS WEIGHTS ON LEVER ARM

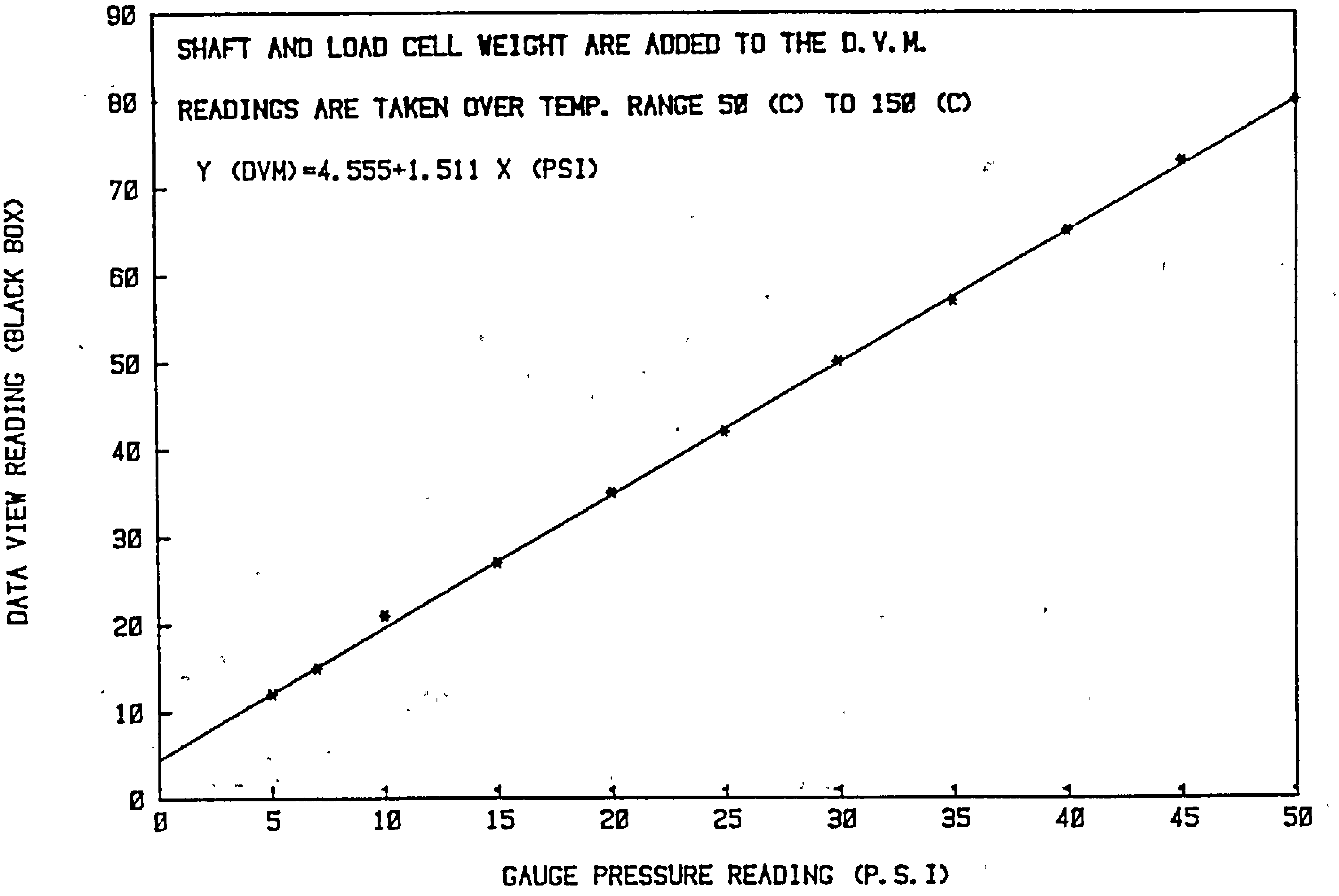
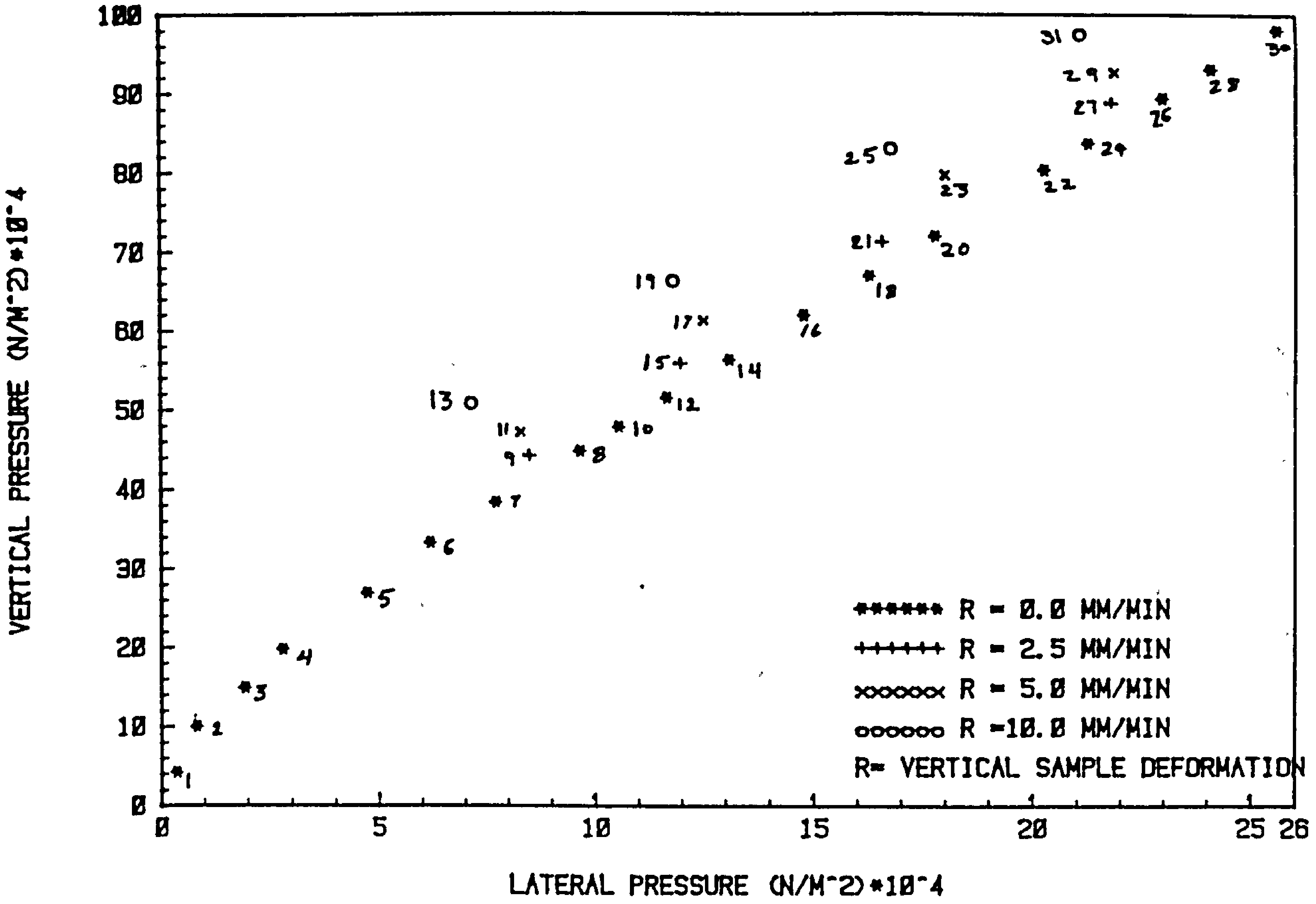
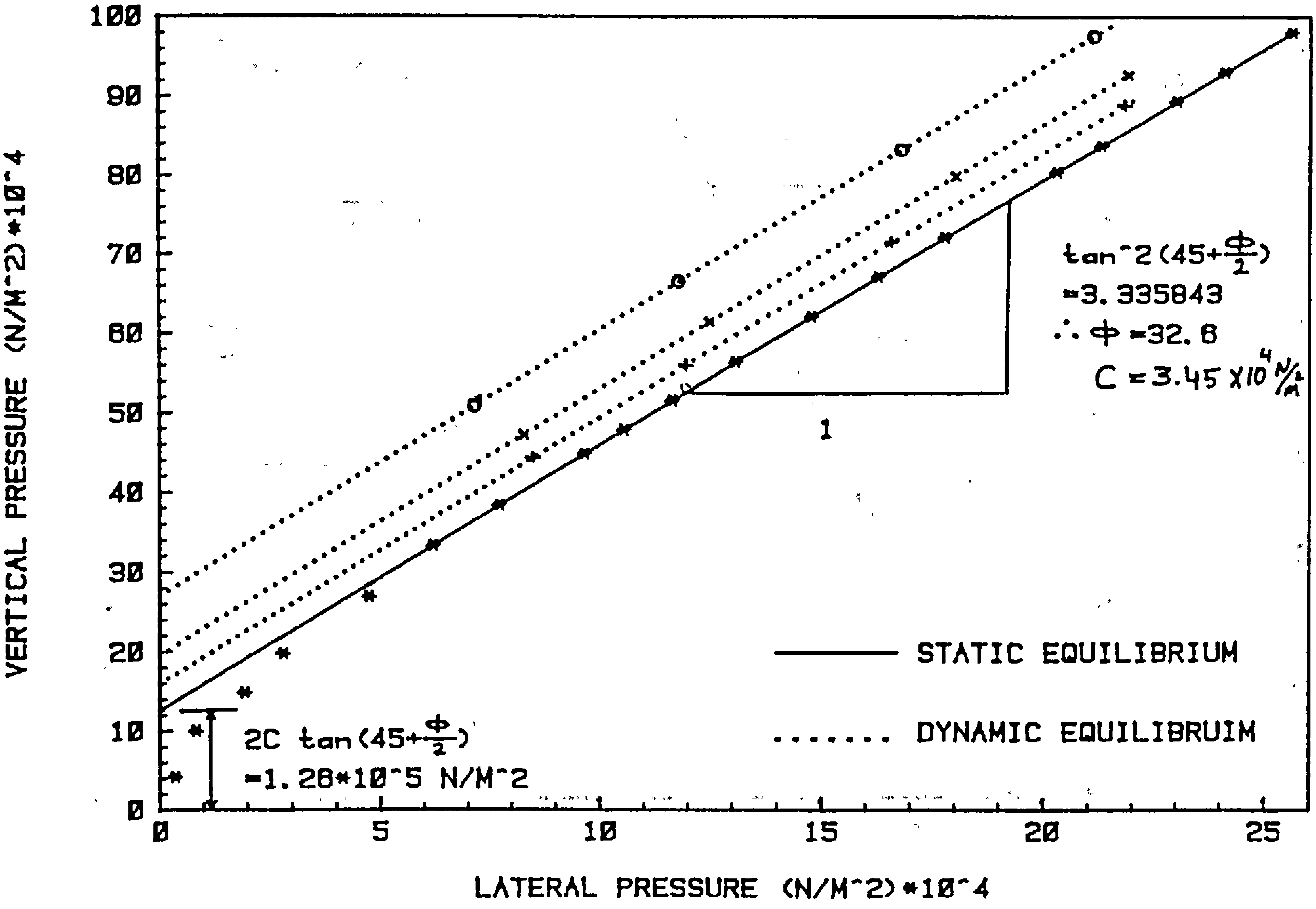


FIGURE [3-6] DATA VIEW READINGS VERSUS GAUGE PRESSURE

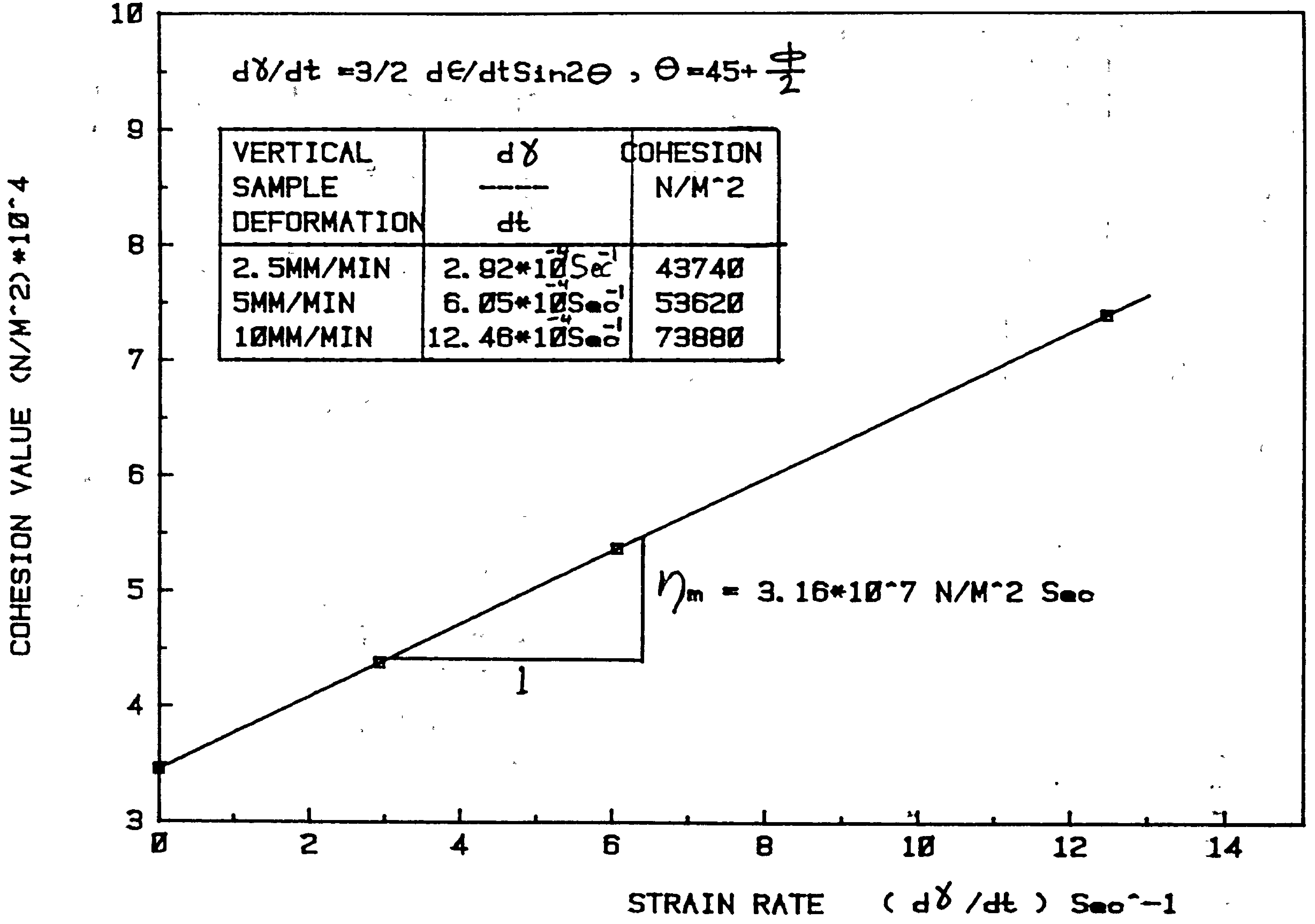


FIGURE(3-7A)



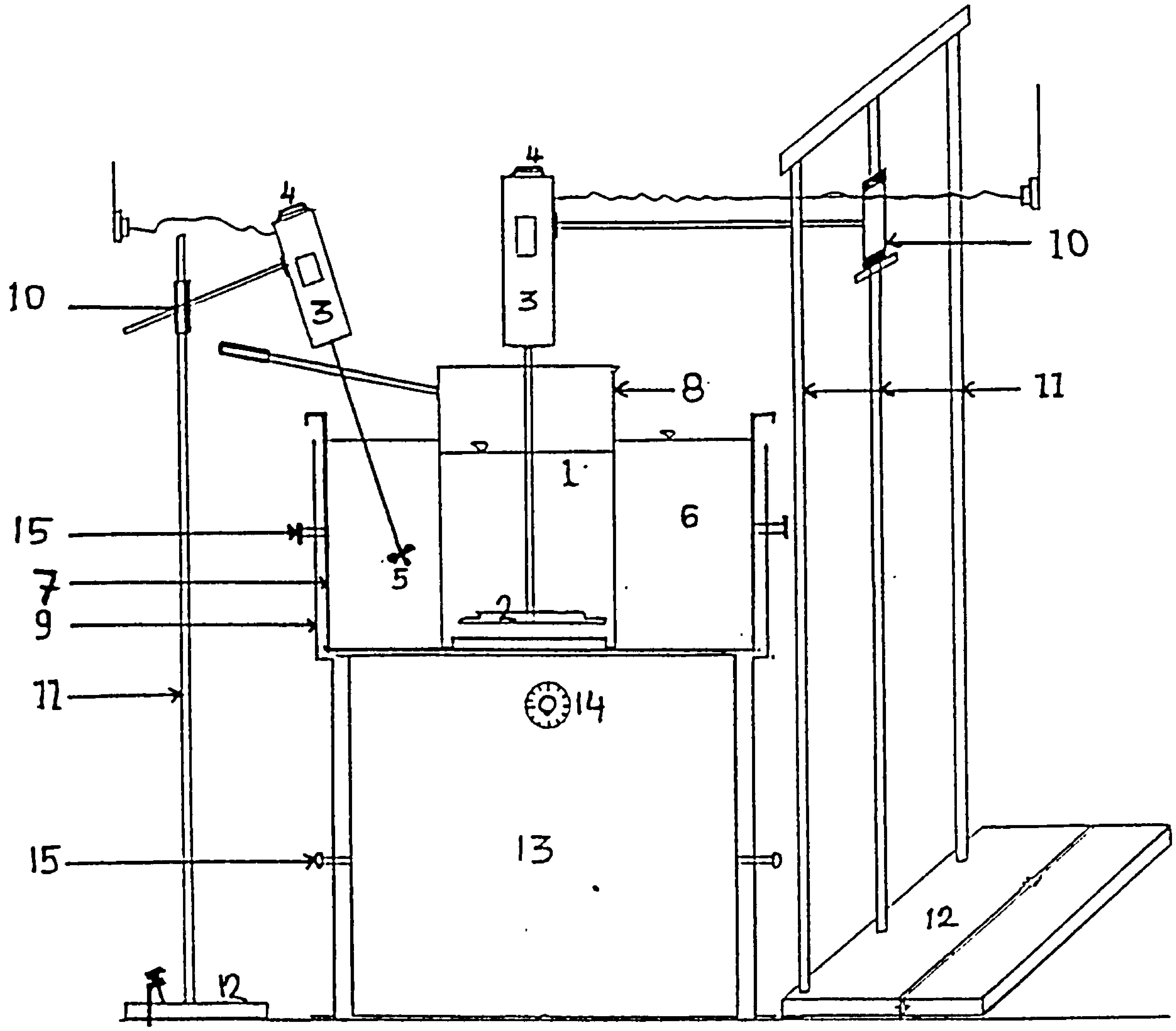
FIGURE(3-7B)

FIGURE(3-7) A- PATTERN OF TESTING, B- TYPICAL TRIAXIAL TEST DATA FOR CONTROL MIX AT TEMPERATURE = 100°C & VOID CONTENT = 3%



VERTICAL SAMPLE DEFORMATION	$\frac{d\gamma}{dt}$	COHESION N/M^2
2.5MM/MIN	$2.92*10^{-4}Sec^{-1}$	43740
5MM/MIN	$6.05*10^{-4}Sec^{-1}$	53620
10MM/MIN	$12.46*10^{-4}Sec^{-1}$	73880

FIGURE (3-8) TYPICAL MIX VISCOSITY(η_m) EVALUTION FOR CONTROL MIX AT TEMPERATURE= 100°C & VOID CONTENT = 3%



1. BINDER SAMPLE
2. BLADE STIRR
3. MOTOR STIRR
4. SPEED CONTROL
5. PROPELLOR STIRR
6. HEAT TRANSFER OIL
7. OIL BATH
8. CAULDRON
9. SAFETY WALL
10. AJUSTABLE HANDEL
11. SUPPORT
12. BASE PLATE
13. HOT PLATE
14. TEMPERATURE CONTROL
15. SAFETY CLAMP

FIG. (3-9) BINDER MIXING APPARATUS.

plate (3-1)
High temperature
Triaxial cell

plate (3-2)
The TOP and bottom part of the triaxial cell (with untested sample)

plate (3-3) The Bottom plate [with tested sample]

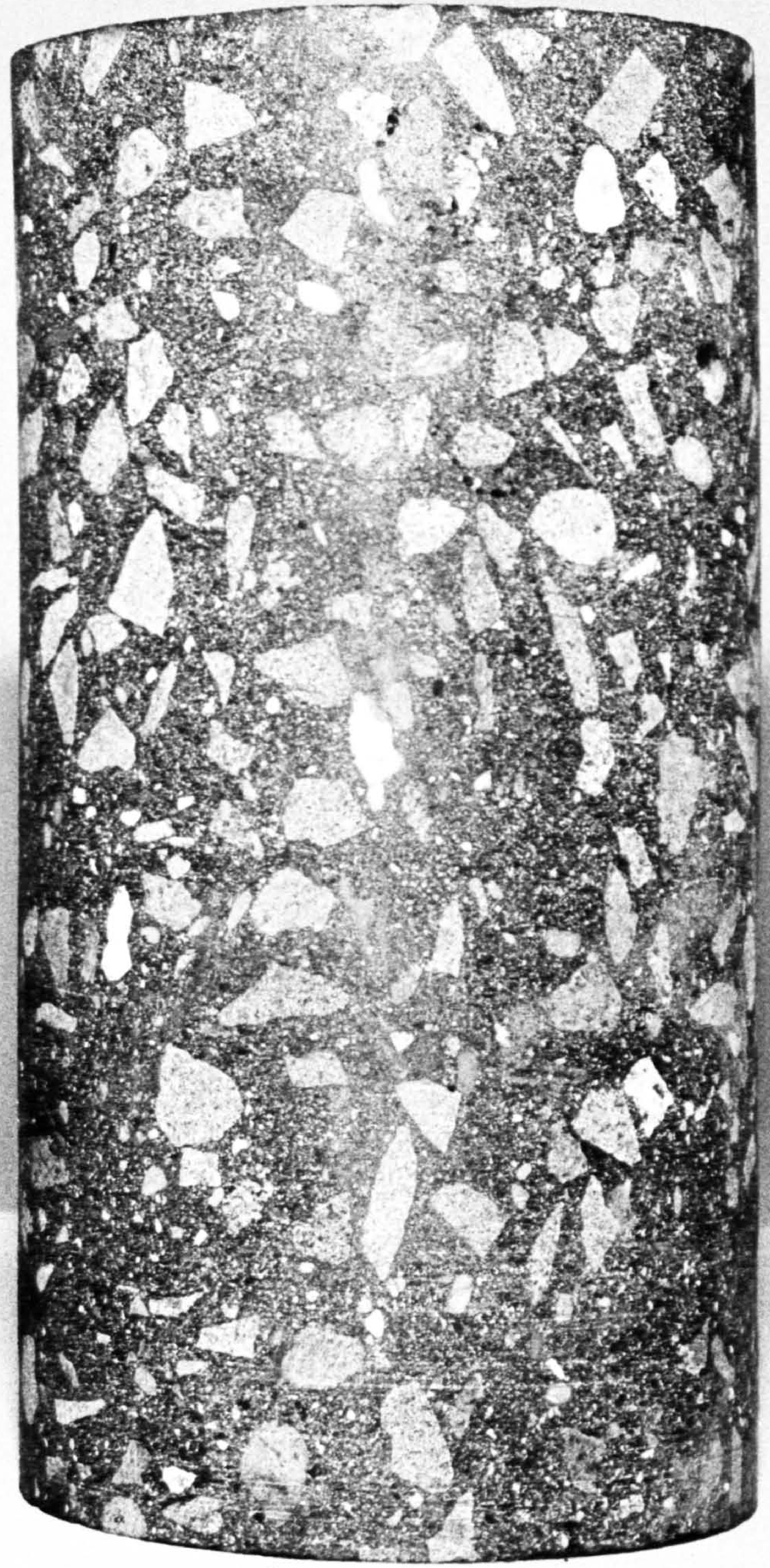
Plate (3-4) Rolling Rig

plate (3-5)

Compacting Machine

plate 3-6
Coring Machine

plate [3-7] Triaxial Sample After Test



Befor test

PLATE [3-8]

SLAB MOULD

plate [3-9]
TRIMMING
MACHINE

4.0 TRIAXIAL TEST DATA

4.1 GENERAL

The results from all mixes prepared in the laboratory, and tested triaxially, are provided in this chapter. The mixes are organised into four series as described in Chapter 3. The data from the triaxial tests are shown in the form of graphs of the three components of resistance to internal movement; angle of internal friction, mix cohesion and mix viscosity. The three components of resistance to internal movement are plotted against six parameters: mix temperature, void content, bitumen content, filler bitumen ratio and different grade of petroleum bitumen, or petroleum bitumen modified with EVA.

The source of frictional resistance is the mineral aggregate; the source of mix cohesion and viscous resistance is the petroleum bitumen, the volume of which is directly related to temperature.

4.2 DATA WITH CONTROL MIX

The control mix is a Marshall design mix. The internal resistance parameters with the control mix are plotted against temperature as shown in Figure 4.1. It can be seen that angle of internal friction increases with increasing temperature but at a reducing rate, whilst the opposite happens with mix cohesion and mix viscosity, both parameters decreasing with increasing in temperature.

The mix viscosity profile appears flatter than mix cohesion. Mix cohesion is the first resistance component overcome during layer compaction, it also provides the lateral support which restricts the mobility of a mix when subject to surface stress under the action of a roller.

4.3 DATA WITH TEST SERIES 1

The proportion of the coarse aggregate, fine aggregate and filler is constant for all the mixes in this test series; the bitumen content varies from 7 percent to 11.8 percent; the other ingredients have been modified in the same proportion to accommodate the bitumen content variations. The volume of the film thickness of mastic (bitumen + filler) varies from 24.68 percent to 33.53 percent of the total volume of the ingredients. This series highlights the effect of the bitumen content and the mastic volume on the internal resistance parameters.

4.3.1 Angle of internal friction data

Data with angle of internal friction are shown in Figures 4.2 to 4.4.

The profile of angle of internal friction with temperature is concave upward and has a turning point. The particular temperature of the turning point varies with bitumen content: higher bitumen content mixes have lower turning point temperature, as shown in Figure 4.2. The turning point may indicate an optimum internal response of a material to load application.

The profile of angle of internal friction with bitumen content exhibits three stages at 3% mix void content as shown in Figure 4.3: a flat profile was observed between 8.2 percent to 10.6 percent bitumen content; a sharp increase in angle of internal friction value below 8.2 percent bitumen content; and a noticeable drop in value of angle of internal friction above 10.6 percent bitumen content. The first stage disappears when the void content of the mix increases, this relationship reflects the effect of the bitumen in minimising the value of angle of internal friction. The relationship between angle of internal friction and voids content shows a peak value between 6 percent to 9 percent as shown in Figure 4.4. For mixes with low bitumen content, the peak friction value was at 9 percent voids content; with a higher bitumen content the peak was at 6 percent voids content. When the temperature of a mix was increased the changes in angle of internal friction value were minimised, this is particularly so with mixes of low bitumen content.

4.3.2 Mix cohesion

The relationships between mix cohesion and temperature, void content and bitumen content are concave downward but have no turning point. They show that mix cohesion reduces when temperature or/and bitumen content or/and void content increases, as shown in Figures 4.5, 4.6 and 4.7. The effect of temperature on mix cohesion is quite obvious with mixes of low bitumen content, particularly between 60°C and 80°C, but with high bitumen contents the changes are marginal, particularly at high temperature. The void content also shows little effect on mix cohesion at high temperature and high bitumen content. When the changes in mix cohesion with temperature with some mixes is very small, this reflects non-temperature sensitive mixes because their internal resistance changes marginally over a particular range of void content, as shown in Figure 4.5.

4.3.3 Mix viscosity

The relationship between mix viscosity and temperature can be divided into three stages: Stage 1, a large decrease in mix viscosity when mix temperature increases from 60°C to 80°C; Stage 2, a flat profile between 80°C to 120°C, or 140°C; Stage 3, a tendency for a non-systematic drop above 120°C or 140°C. A flat profile relating mix viscosity and temperature is, again, a likely sign of a non-temperature sensitive mix. The bitumen content has a marked effect on mix viscosity at low mix temperature, but a marginal effect at high mix temperature, as shown in Figure 4.9. Mix viscosity shows less change with void content particularly at high temperature, as can be seen in Figure 4.10.

4.4 DATA WITH TEST SERIES 2

In this series the volume of film thickness was kept constant and consequently the volume of mineral aggregate was also constant. The filler to bitumen ratio varies from 0.01 to 1.56. The result of the three parameters of internal resistance are as follows.

4.4.1 Angle of internal friction

These mixes exhibited a different ranking order of profile when temperature or void content changed. At low void content, particularly 3 percent, the relationships between angle of internal friction and temperature appeared to 'pivot' around a particular value of angle of internal friction and temperature; below the 'pivot' temperature values of angle of internal friction increased as the filler to bitumen ratio decreased, above the 'pivot' temperature the opposite happened as shown in Figure 4.11. For mixes with low filler to bitumen ratio small changes in angle of internal friction are evident; large changes in angle of internal friction are evident with mixes with high filler to bitumen ratio. The former may be non-temperature sensitive mixes; the latter may be temperature sensitive mixes. For the mixes with 9 percent and 12 percent void content, they did not show a 'pivot' point and angle of internal friction increased as the filler to bitumen ratio increased.

As in series 1 the angle of internal friction profiles exhibited a turning point at elevated temperature, the temperature of the turning point dropped as the filler to bitumen ratio decreased. A second aspect which was found to be similar to that of test series 1 was the peak in angle of internal friction value with void content. This was at 9 percent void content with low bitumen content mixes and moved to 6 percent void content with high bitumen content, as shown in Figure 4.12. The relationships between angle of internal friction and filler to bitumen ratio were linear at low voids content but curvalinear at high voids content, as shown in Figure 4.13. The change in angle of internal friction values increased with voids content showing the sensitivity of such mixes.

4.4.2 Mix cohesion

Mix cohesion profiles with low bitumen content mixes show no difference from that of test series 1, but, when the filler to bitumen ratio decreases the concave downward profile relationship changes to a concave upward profile for mixes with little filler content, as shown in Figure 4.14. These mixes show lack of progress in developing cohesion when the mix temperature is low. These mixes also show non-temperature sensitive behaviour.

The relationship between mix cohesion and voids content is concave downward and the profiles become steeper as the filler to bitumen ratio increases, as shown in Figure 4.15. A linear relationship was found between mix cohesion and filler to bitumen ratio, the slope of these relationships increased as mix temperature or/and void content decreased, as shown in Figure 4.16.

4.4.3 Mix viscosity

The relationships between mix viscosity and mix temperature exhibit again three stages, as shown in Figure 4.17. Stage 3 is a tailed profile showing a noticeable drop in mix viscosity when mix temperature is raised to around 140°C for stiff mixes, and to around 120°C or even 110°C for the more 'workable' mixes. Stage 2 is a flat profile between 120°c or 140°C downward to around 80°C; Stage 1 is a sharp increase in mix viscosity when mix temperature drops to 60°C. The tailed profile indicates potential mix instability and the readiness of the material to exhibit a high rate of deformation when responding to a surface applied stress. The relationship between mix viscosity and voids content exhibits a flat profile for most mixes of this test series, as shown in Figure 4.18. Figure 4.19 shows a linear relationship between mix viscosity and filler to bitumen ratio. It can be seen that when mix temperature increases the relationships appear to be parallel.

4.5 COMPARISON OF THE INTERNAL RESISTANCE PARAMETERS BETWEEN TEST SERIES 1 AND TEST SERIES 2

The internal resistance parameters for selected mixes from both test series and the control mix are shown in Figures 4.20, 4.21 and 4.22. The figures are the same bitumen content. Profiles of angle of internal friction for both series show a turning point at particular values of mix temperature and the presence of filler made the profiles steeper, particularly at low voids content.

The two series showed a remarkable and common phenomenon with all internal resistance parameters: the values of the parameters decreased when the volume of film thickness increased (for mixes of equal bitumen content). The implication of this phenomenon is that the addition of filler reduces the resistance of a material to internal movement; materials increase their workability. It can be seen from the figures that mixes with 7 percent bitumen content and 8.3 percent filler gave higher values with internal resistance parameters than mixes with the same bitumen content and 10.9 percent filler content. This finding contradicts the idea of higher filler content giving less workable mixes, for mixes with the same bitumen content.

The behaviour of asphaltic materials at high temperature is not necessary a linear extension of low temperature behaviour, as can be seen from the mix viscosity profile which exhibits three different stages from 60°C to 140°C.

Both series show that mixes with low filler to bitumen ratio have more temperature sensitiive profiles than mixes with high filler to bitumen ratios. Both mixes exhibited a significant reduction in internal resistance at elevated mix temperature; the consequence is that at such temperatures mixes are likely to deform excessively under the action of a roller.

4.6 DATA WITH TEST SERIES 3

Two additional petroleum bitumen grades were used in Test Series 3, in addition to that of the control mix: 68 pen and 99 pen, the control mix being 46 pen. The three mixes had the same proportion of material ingredients: filler to bitumen ratio and volume of mastic were constant.

4.6.1 Angle of internal friction

Changes in petroleum bitumen penetration grade produce a marginal difference in angle of internal friction profiles within the range of mix temperature and voids content used, as shown in Figures 4.23 and 4.24. Angle of internal friction increased in value when a softer bitumen grade was used and peaked at a lower mix temperature. The maximum angle of internal friction value was found at 9 percent void content with all grades.

4.6.2 Mix cohesion

Mix cohesion values decreased as the pen value of petroleum bitumen used increased: mixes using 46 pen petroleum bitumen had higher mix cohesion values than mixes using 68 pen bitumen, and, both had higher mix cohesion values than mixes using 99 pen bitumen. The differences in mix cohesion values reduced when mix temperature or/and voids content increased, as shown in Figures 4.25 and 4.26.

4.6.3 Mix Viscosity

Mix viscosity changed little when the grade of petroleum bitumen changed. Mix viscosity relationships with mix temperature had the same ranking order of mix cohesion value but the reverse order of angle of internal friction value, as shown in Figure 4.27 ad Figure 4.28. The bitumen is an important ingredient factor in promoting mix viscosity, nevertheless the differences in mix viscosity are greater than the differences in binder viscosity, as shown in Figure 4.29, even although the differences in mix viscosity are relatively low. This can only be as a result of the influence of the mineral aggregate and filler within the mix. It was found that the ratio of mix viscosity to binder viscosity increased as mix temperature increased, or the penetration value of the binder increased, as shown in Figure 4.30. This means that as the bitumen becomes softer, either by an increase in mix temperature or by an increase in the penetration value of the bitumen, the aggregate and filler exerts a stronger influence on the measured value of mix viscosity.

4.7 DATA WITH TEST SERIES 4

The bitumen with these mixes was modified by a 5 percent mass replacement of ethylene vinyl acetate (EVA); it was found that the viscosity increased significantly, as shown in Figure 4.29. The consequence of the use of the modified bitumen was a significant increase in mix cohesion and mix viscosity.

4.7.1 Angle of internal friction

The differences in value with angle of internal friction between the mixes of this test series is very small over the range of test temperatures and voids content. The profiles of angle of internal friction are shown 'pivoted' around the 80°C mix temperature, as shown in Figure 4.31. Above this mix temperature the ranking order of mixes is in line with test series 3; below this mix temperature the ranking order of mixes is reversed. This may reflect the chrystalisation of the EVA at this temperature. Figure 4.32 shows the angle of internal friction peaking between 6 percent and 9 percent voids content.

4.7.2 Mix cohesion

The change in mix cohesion values were far greater than changes between straight run grades of petroleum bitumen. It was found that the profiles were becoming steeper as mix temperature or/and voids content decreased, as shown in Figures 4.33 and 4.34.

Although the high values of mix cohesion were the result of the EVA replacement of the petroleum bitumen the ranking order of the profiles remained consistent with the basic bitumen grade.

4.7.3 Mix Viscosity

The profiles of mix viscosity as with the profiles of mix cohesion show steeper relationships, particularly at low mix temperature and/or voids content, as shown in Figures 4.35 and 4.36. The profiles with mix temperature did not show the 'tails' at high mix temperature that were exhibited with the other test series.

4.8 COMPARISON BETWEEN TEST SERIES 3 AND TEST SERIES 4

The addition of EVA reduced the temperature sensitivity of the parameter angle of internal friction. The changes in angle of internal friction profile with mix temperature were smaller when compared with the corresponding mixes from Test Series 3. The mix cohesion values increased about 60 percent over the whole range of mix temperatures used for mixes with modified 46 pen bitumen; with modified 68 pen bitumen mixes the mix cohesion values increased by 45 percent to 55 percent; with modified 99 pen bitumen mixes, far less improvement was shown and the improvement became zero at high temperature, as shown in Figure 4.37.

Mix viscosity results show the significant effect of EVA but the increase in value with the internal resistance parameters was reduced as mix temperature increased. Mixes using the modified 99 pen bitumen was found nearer in behaviour with 'standard' mixes using a straight run 46 pen bitumen. Furthermore the effect of aggregate and filler on mix viscosity was in the same order for both series as can be seen in Figure 4.30.

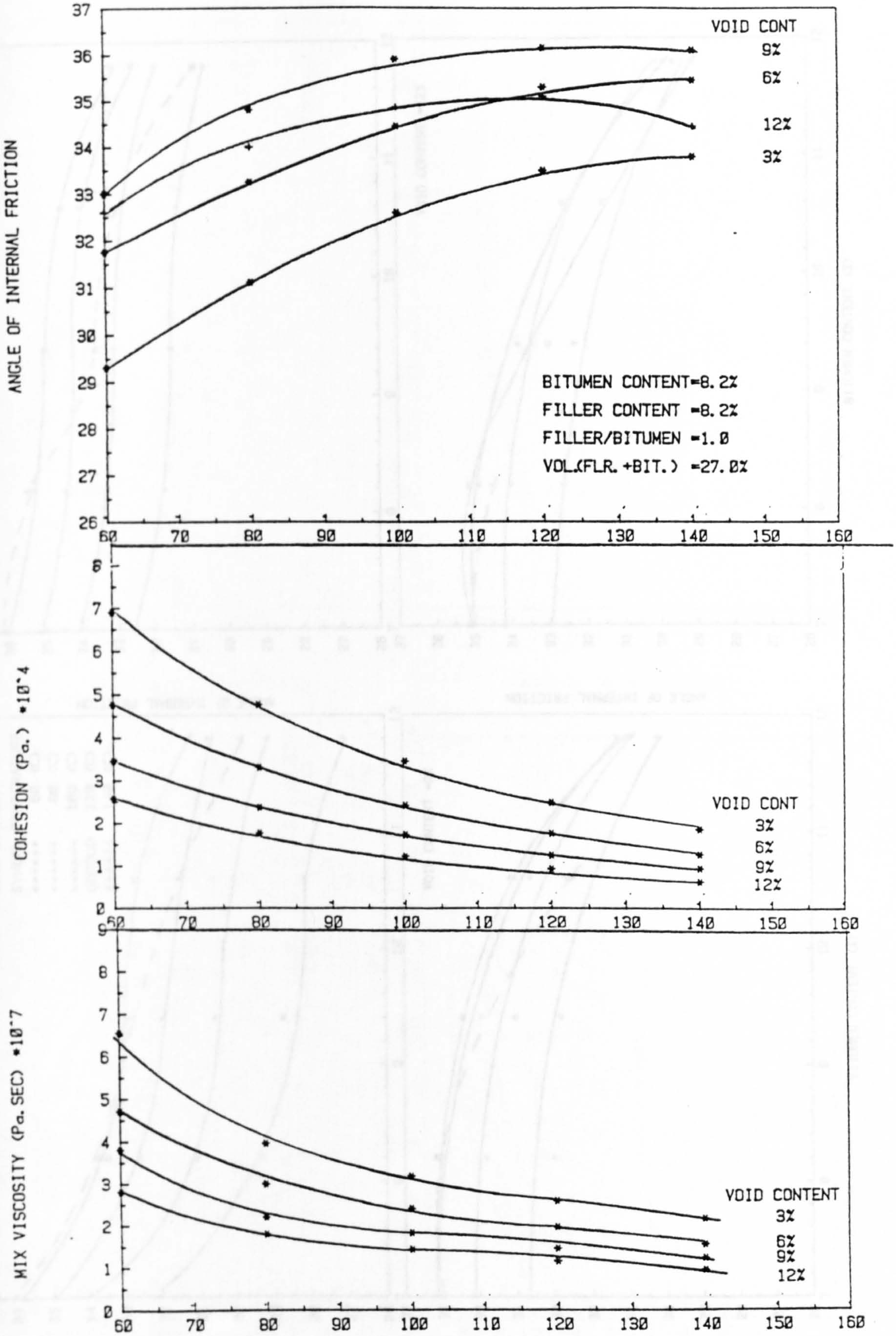


Figure 4.1: Internal resistance parameters versus temperature for the control mix.

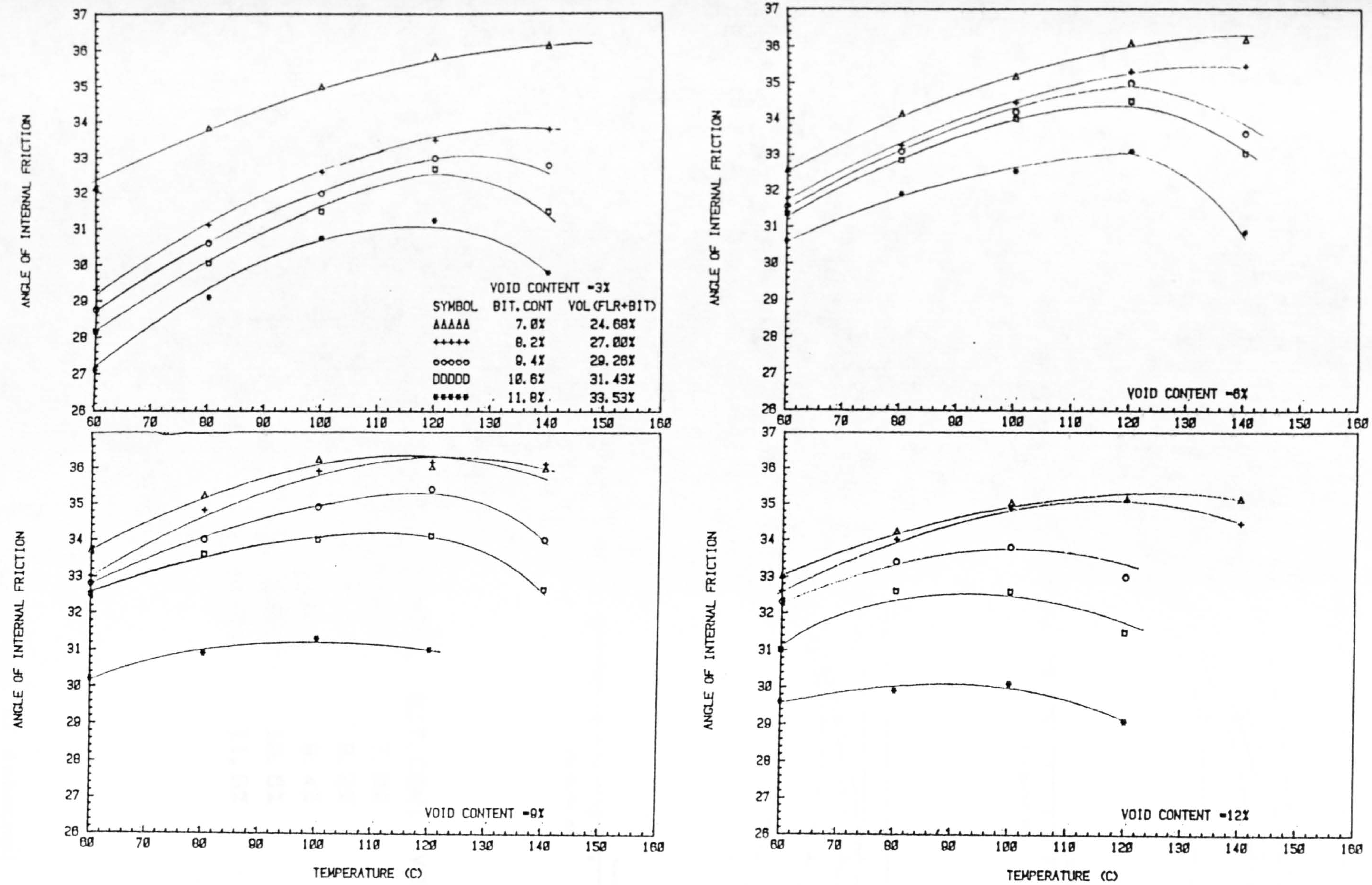


Figure 4.2: Relationships between angle of internal friction and temperature for series 1.

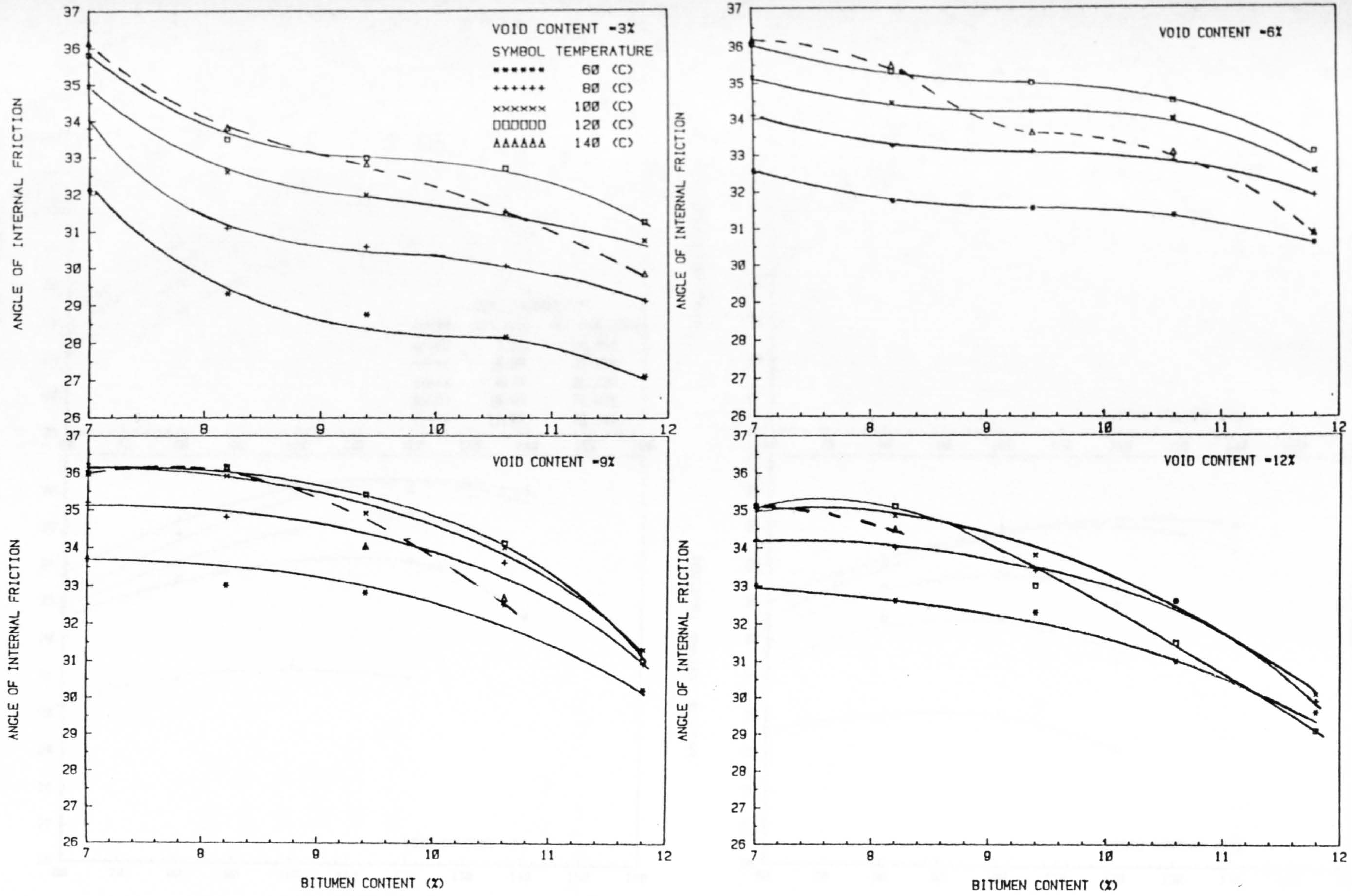


Figure 4.3: Relationships between angle of internal friction and bitumen content for series 1.

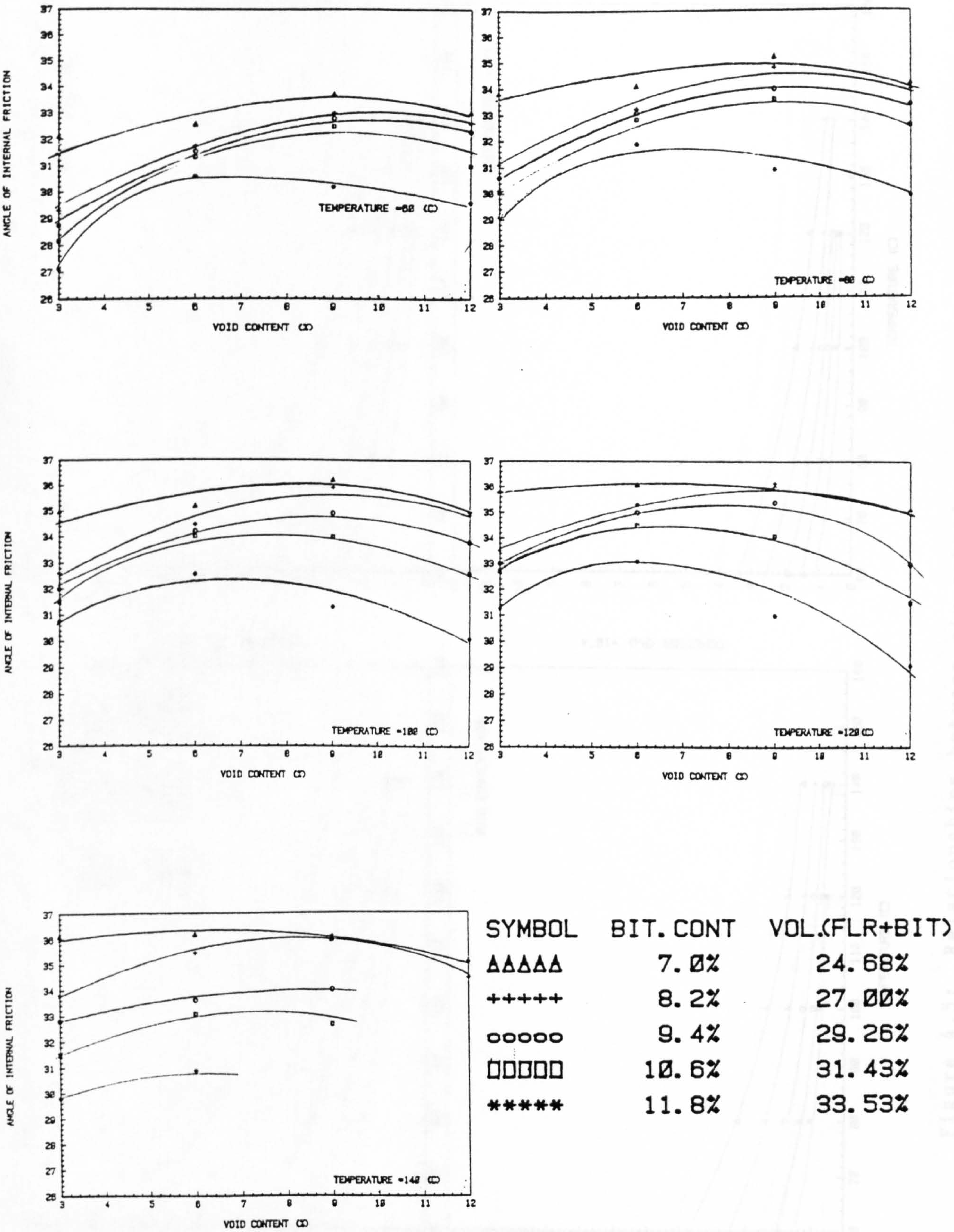


Figure 4.4: Relationships between angle of internal friction and void content for series 1.

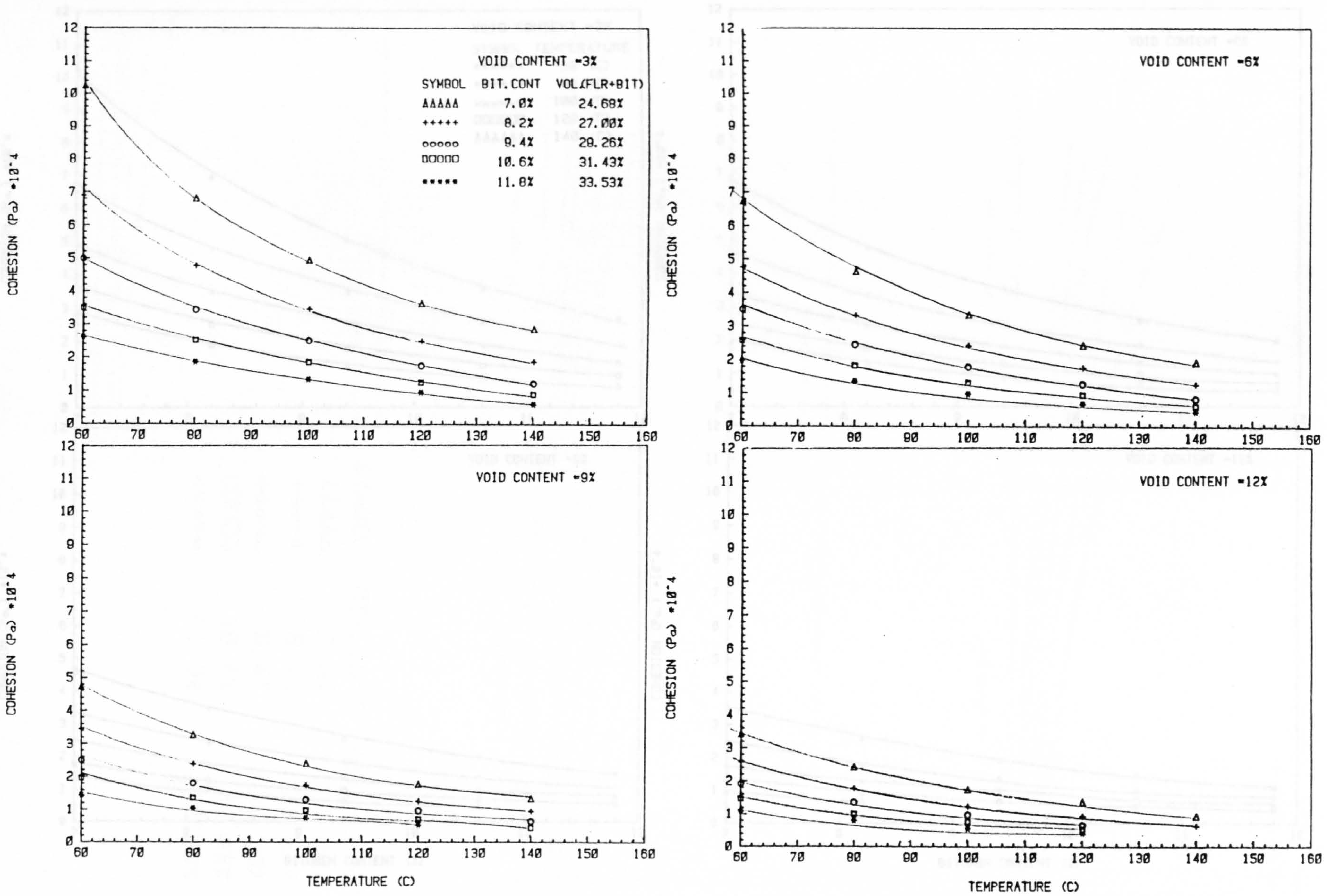


Figure 4.5: Relationships between mix cohesion and temperature for series 1.

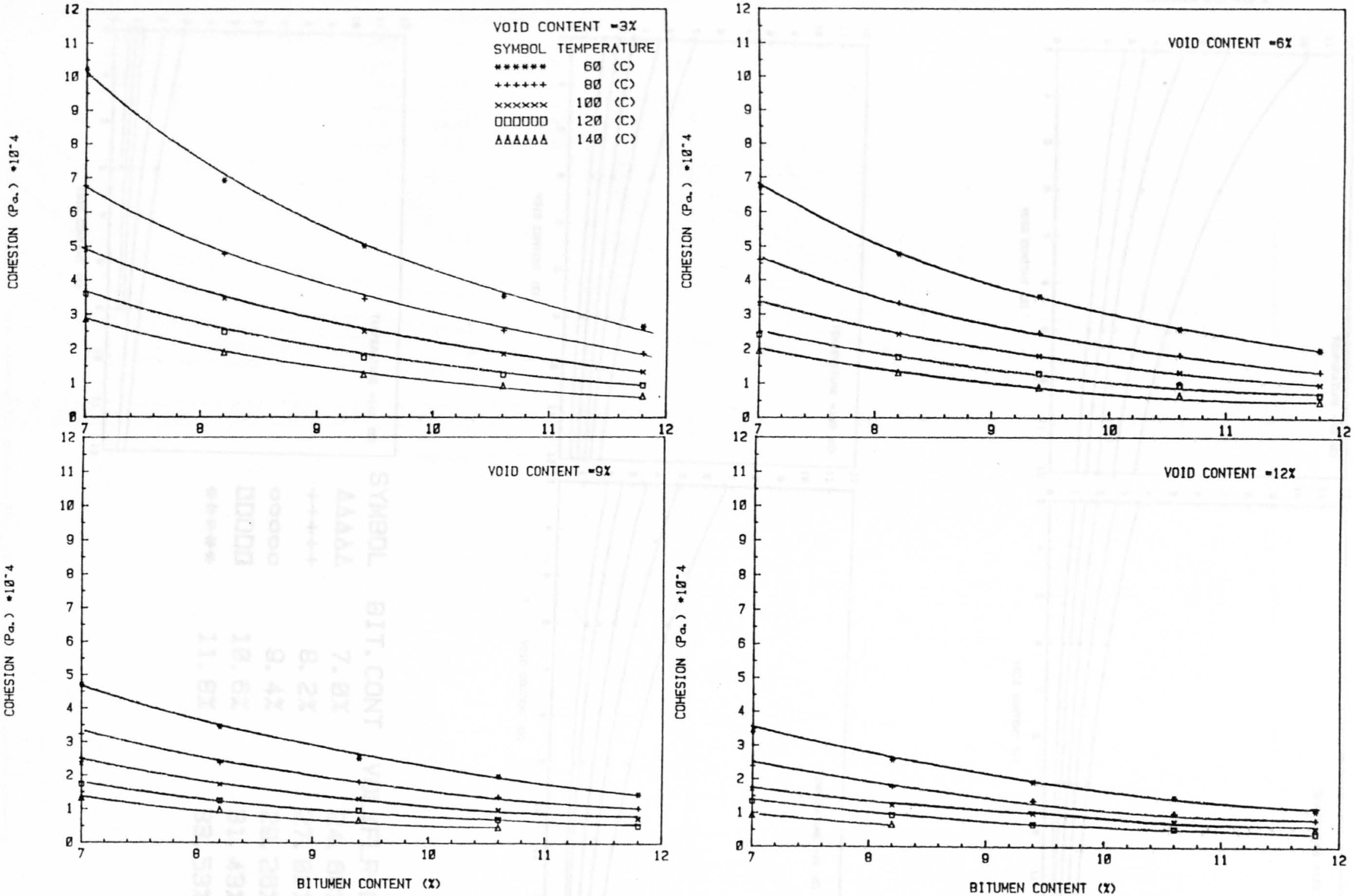
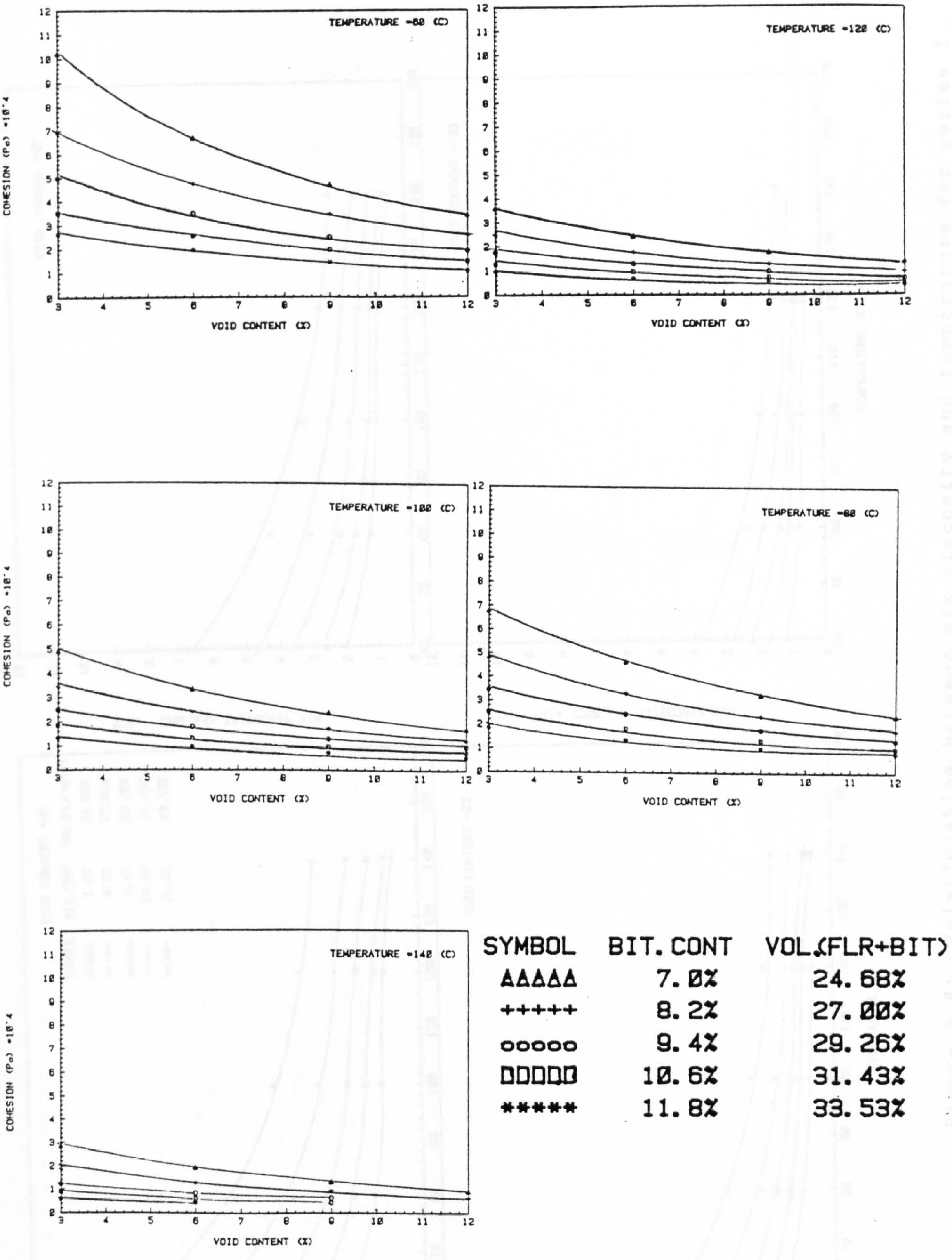


Figure 4.6: Relationships between mix cohesion and bitumen content for series 1.



SYMBOL	BIT. CONT	VOL.(FLR+BIT)
ΔΔΔΔΔ	7.0%	24.68%
+++++	8.2%	27.00%
ooooo	9.4%	29.26%
□□□□□	10.6%	31.43%
*****	11.8%	33.53%

Figure 4.7: Relationships between mix cohesion and void content for series 1.

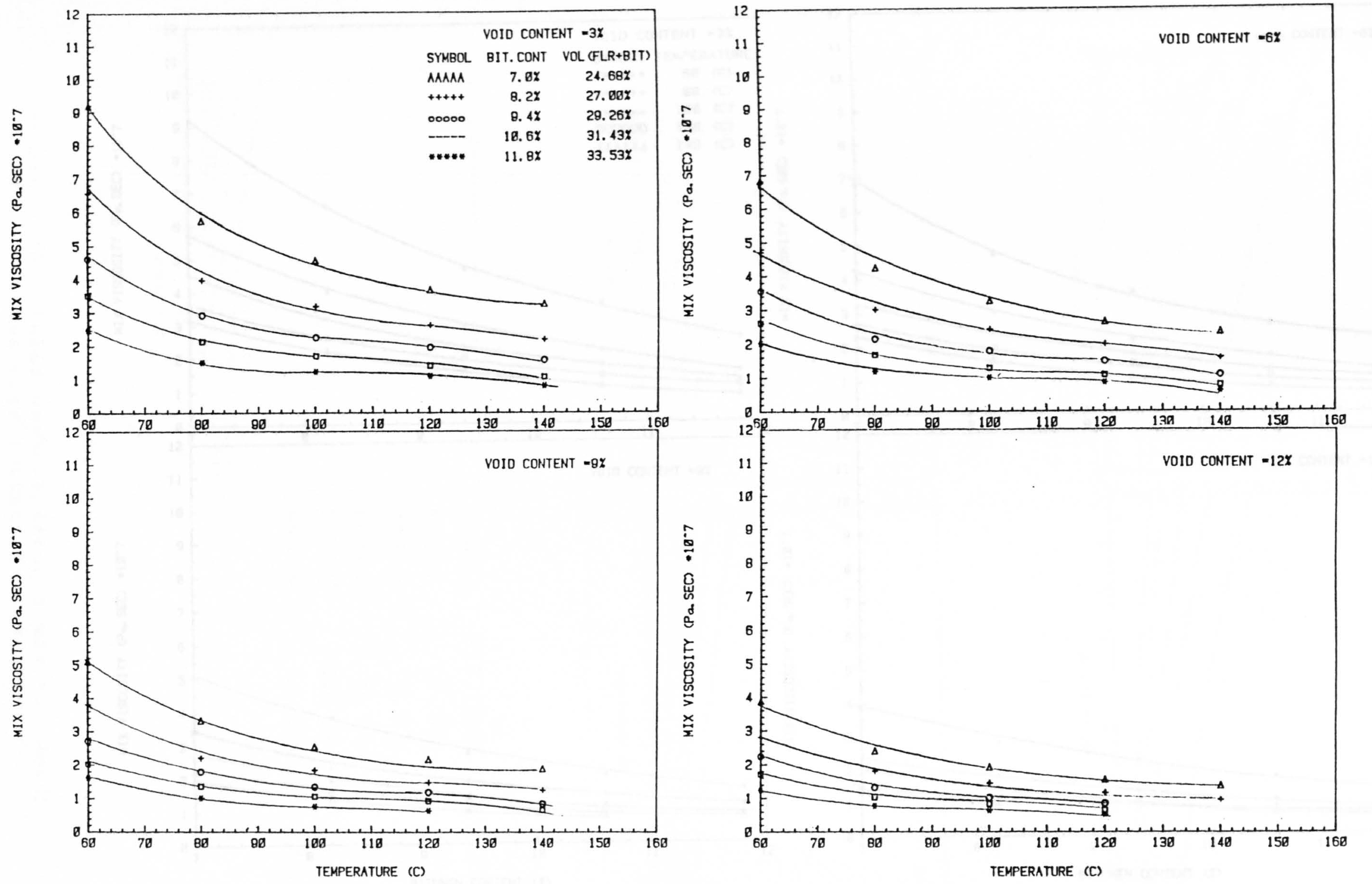


Figure 4.8: Relationships between mix viscosity and temperature for series 1.

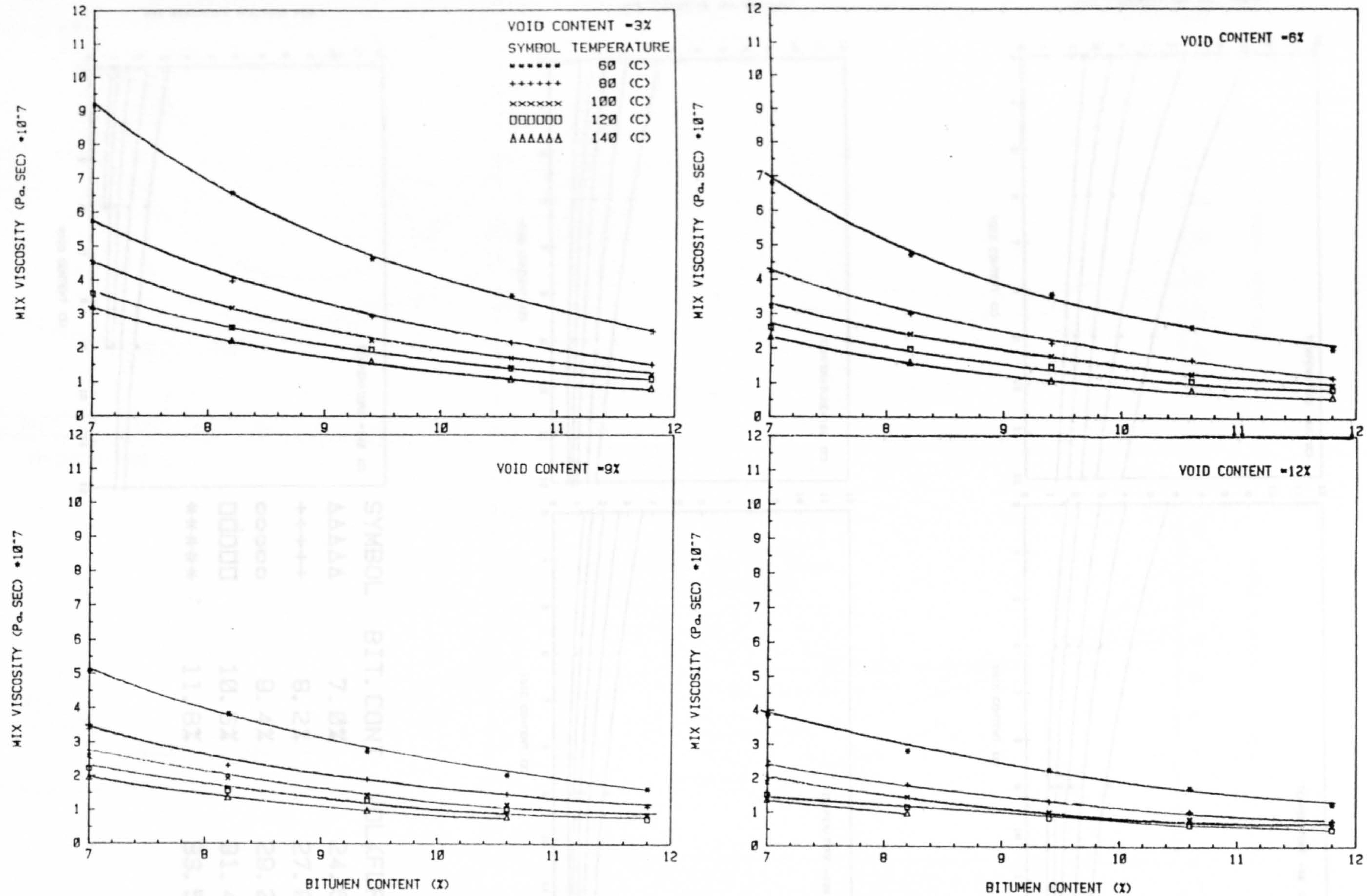
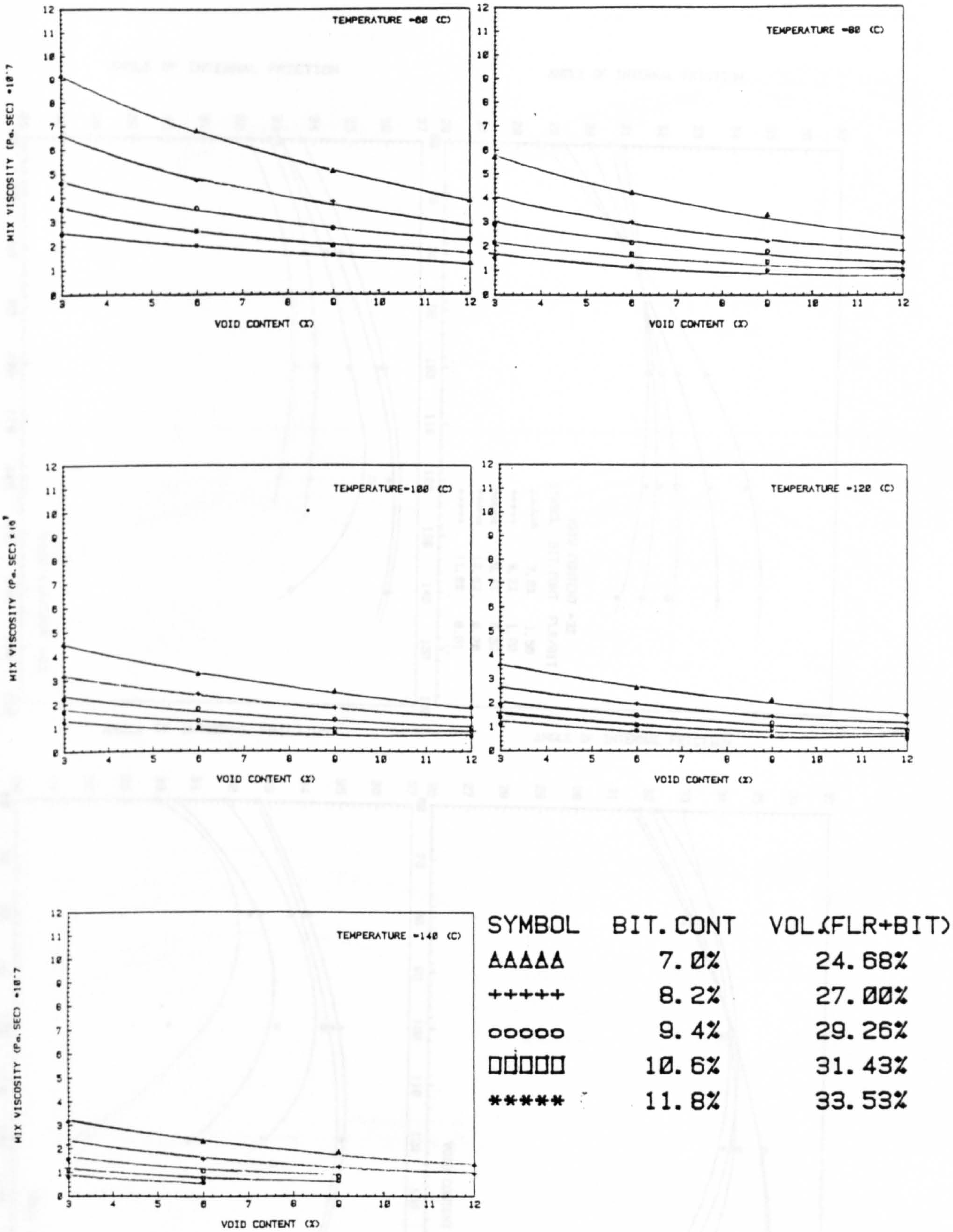


Figure 4.9: Relationships between mix viscosity and bitumen content for series 1.



SYMBOL	BIT. CONT	VOL.(FLR+BIT)
▲▲▲▲▲	7.0%	24.68%
+++++	8.2%	27.00%
ooooo	9.4%	29.26%
□□□□□	10.6%	31.43%
*****	11.8%	33.53%

Figure 4.10: Relationships between mix viscosity and void content for series 1.

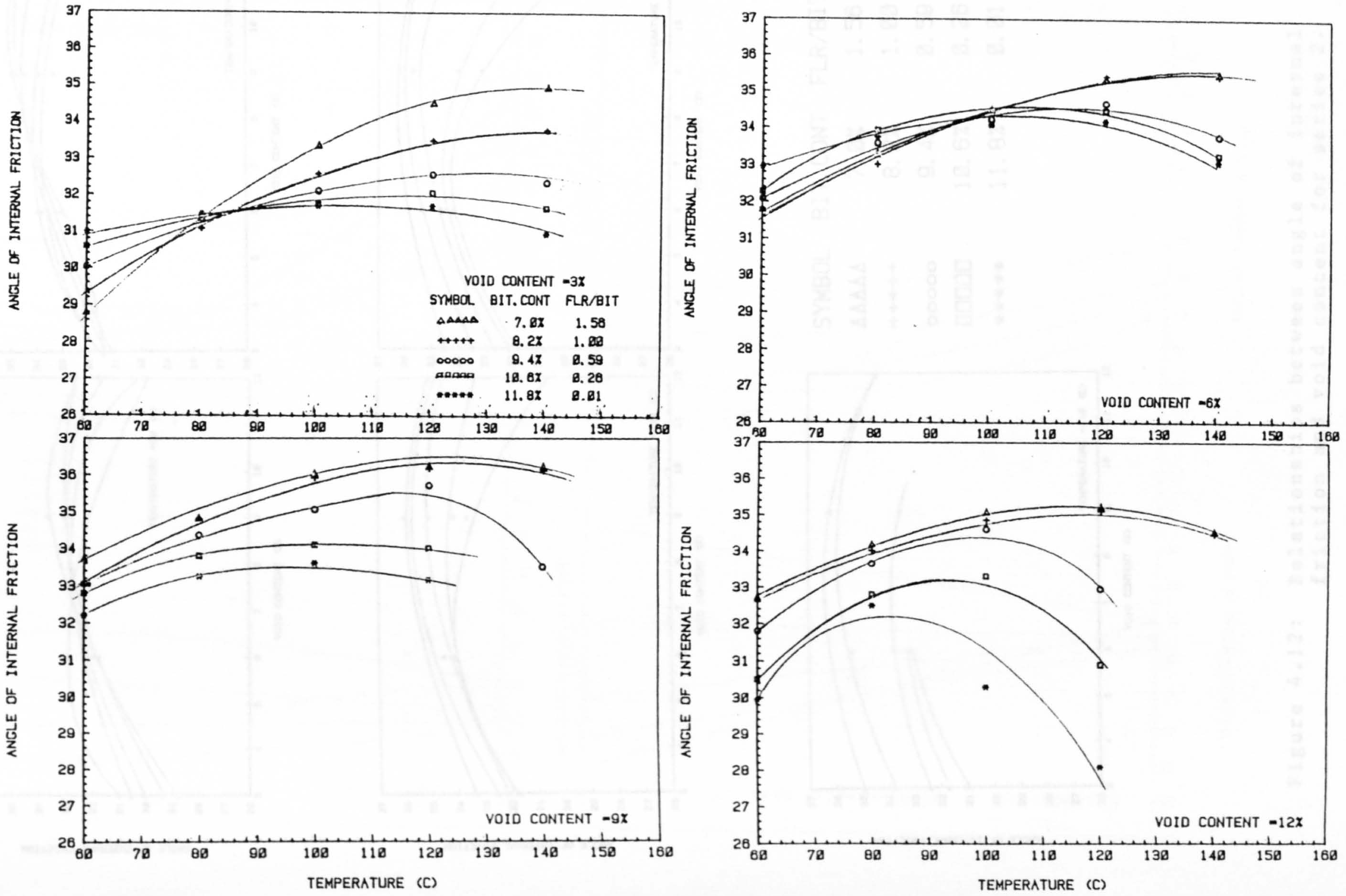
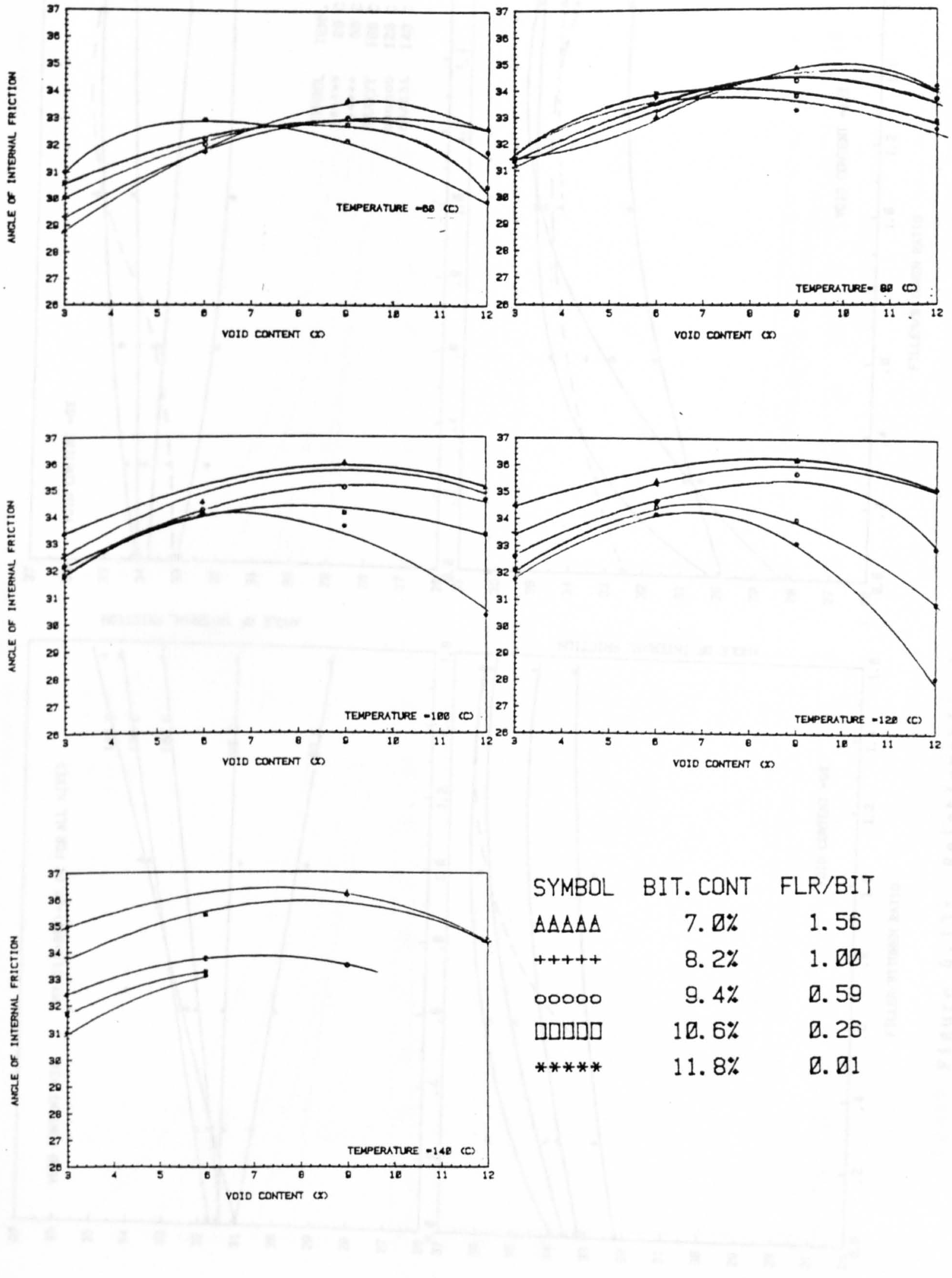


Figure 4.11: Relationships between angle of internal friction and temperature for series 2.



SYMBOL	BIT. CONT	FLR/BIT
ΔΔΔΔΔ	7.0%	1.56
+++++	8.2%	1.00
ooooo	9.4%	0.59
□□□□□	10.6%	0.26
*****	11.8%	0.01

Figure 4.12: Relationships between angle of internal friction and void content for series 2.

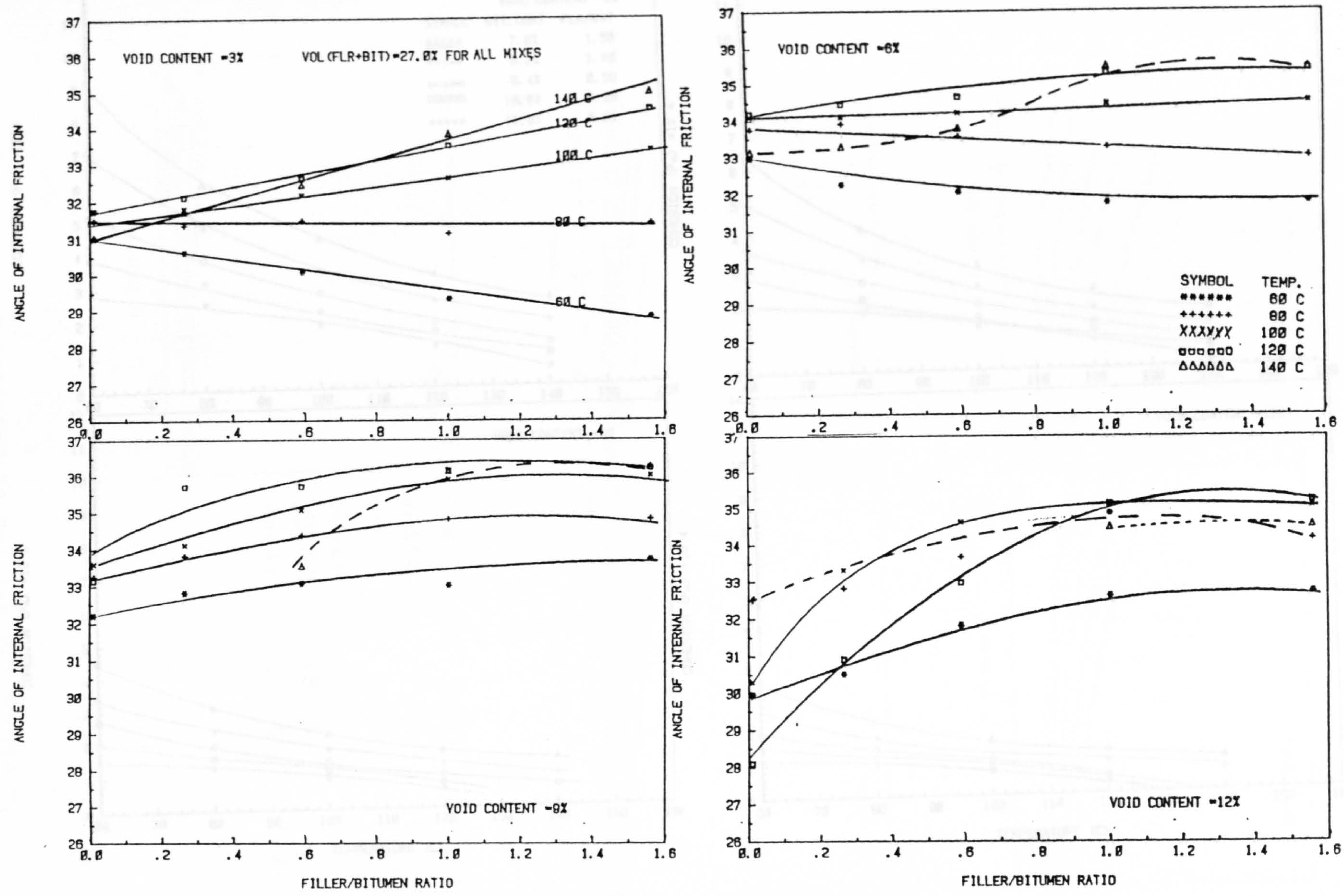


Figure 4.13: Relationships between angle of internal friction and filler to bitumen ratio for series 2.

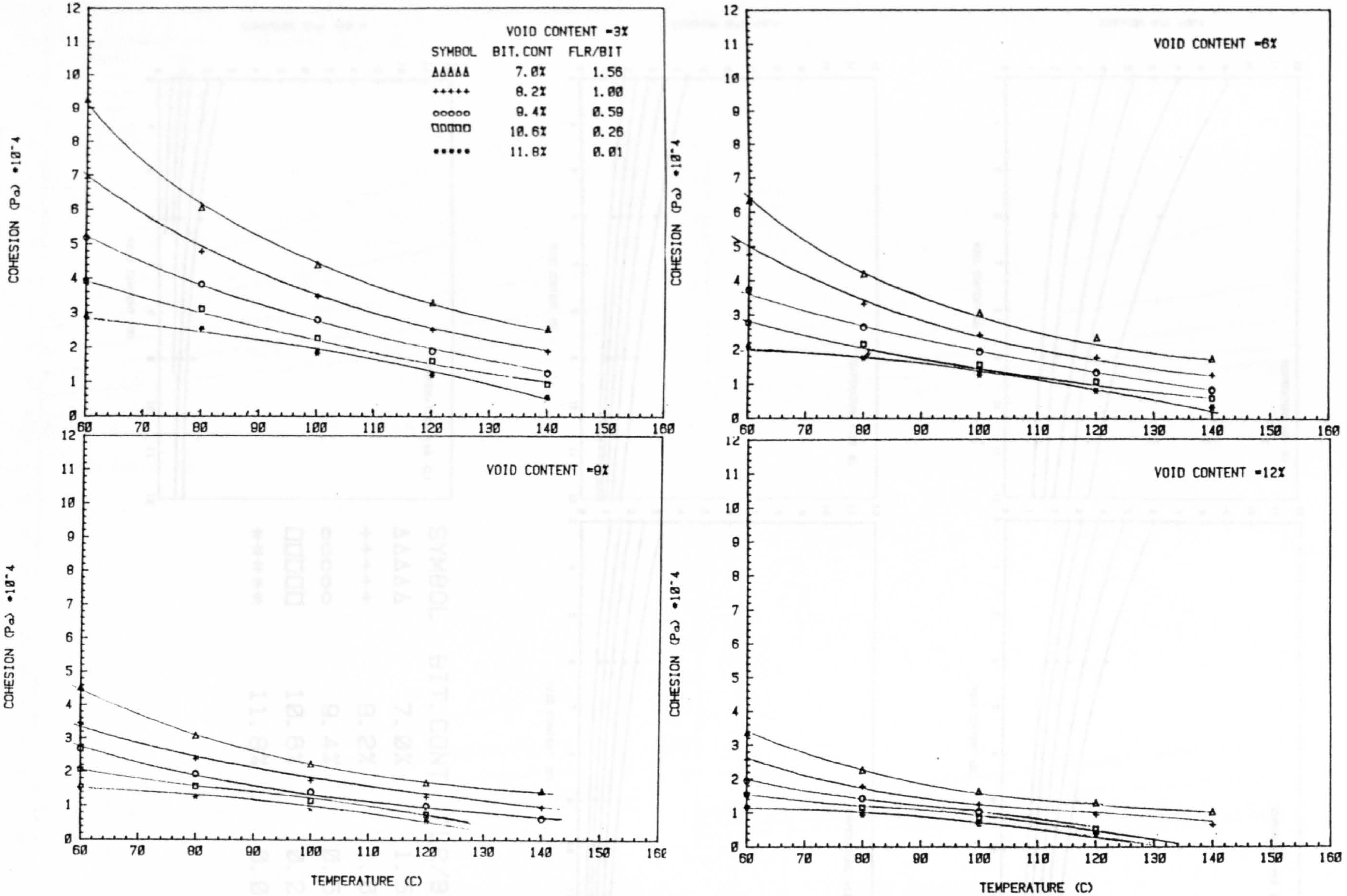
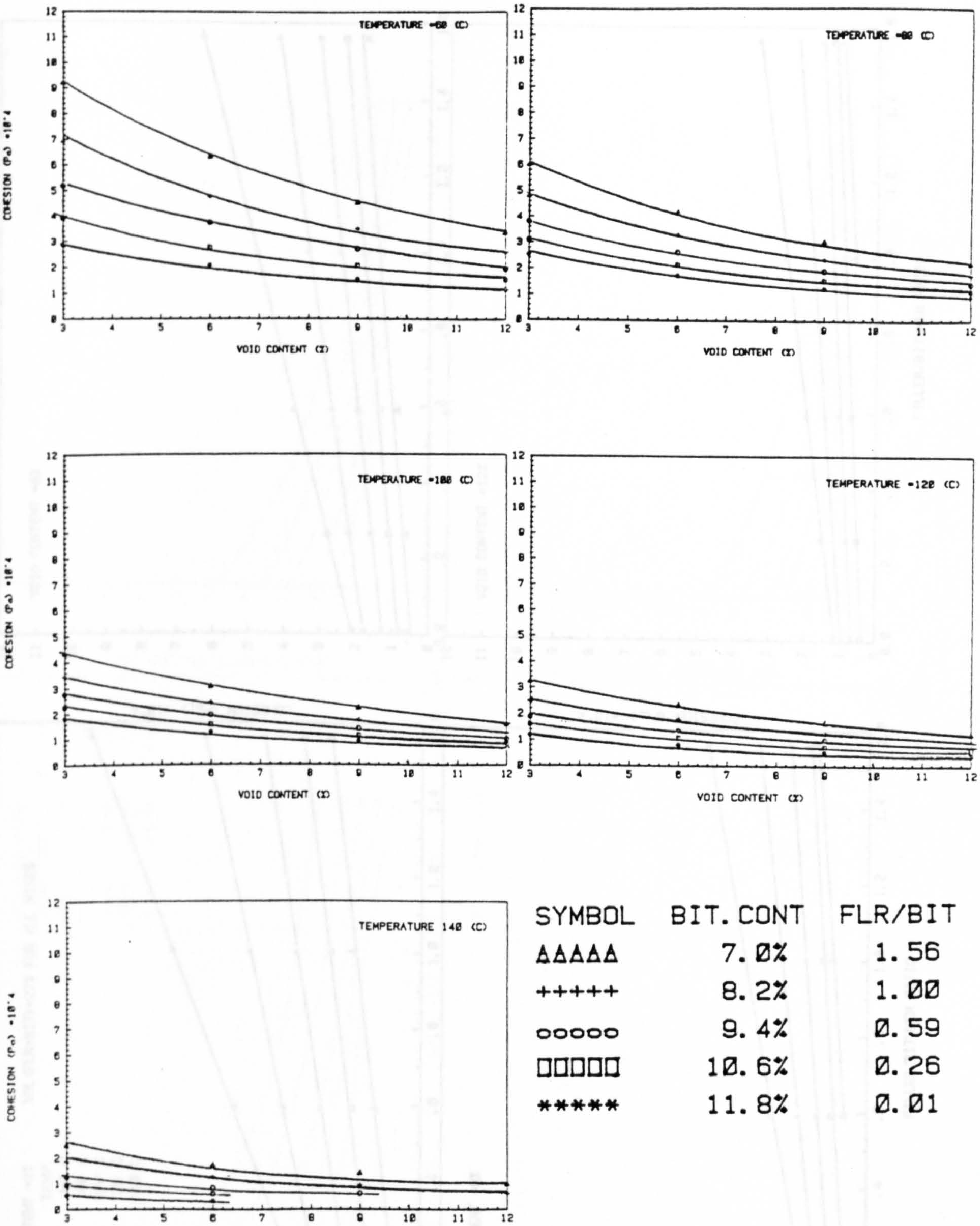


Figure 4.14: Relationships between mix cohesion and temperature for series 2.



SYMBOL	BIT. CONT	FLR/BIT
▲▲▲▲▲	7.0%	1.56
+++++	8.2%	1.00
ooooo	9.4%	0.59
□□□□□	10.6%	0.26
*****	11.8%	0.01

Figure 4.15: Relationships between mix cohesion and void content for series 2.

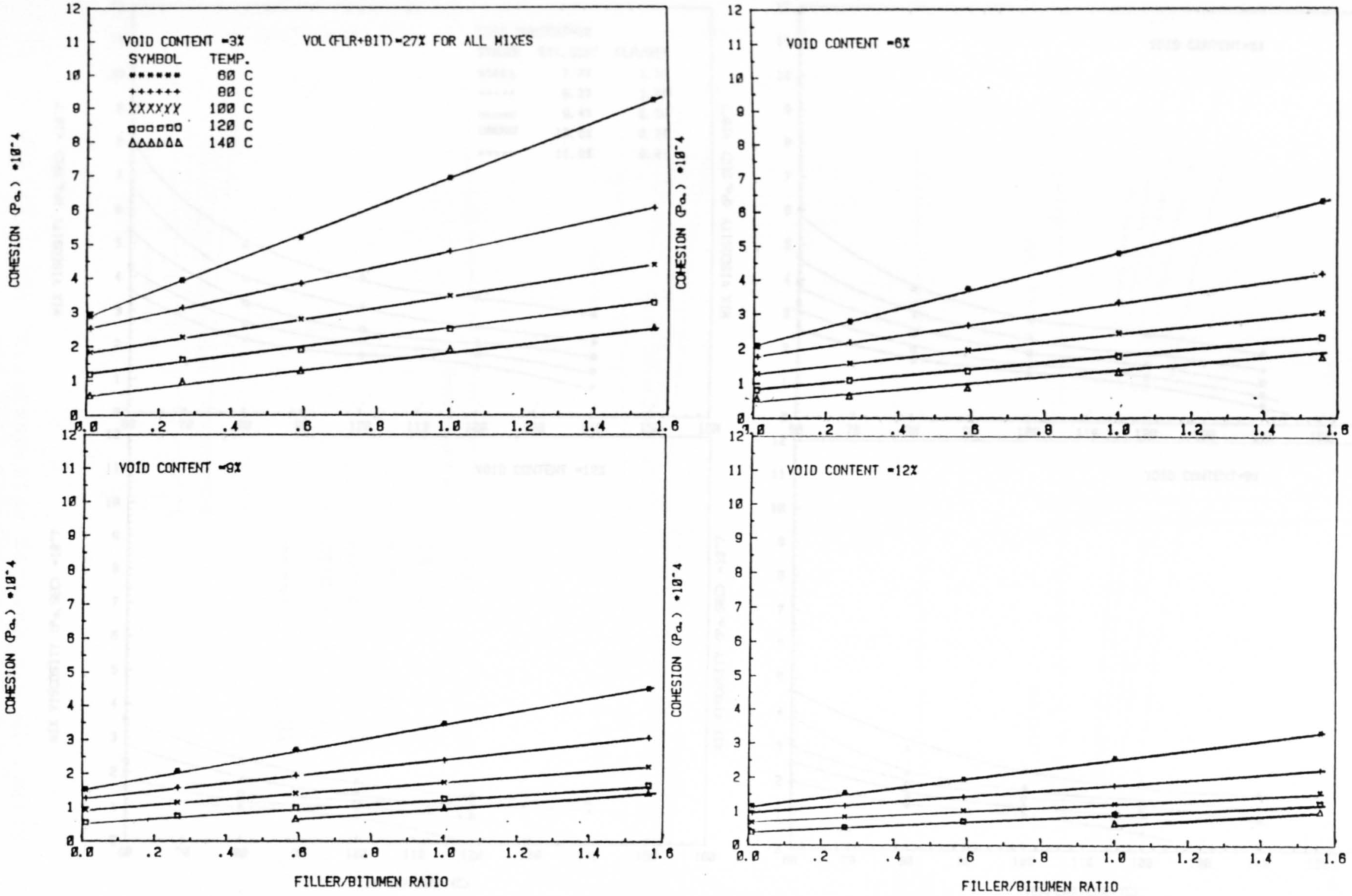


Figure 4.16: Relationships between mix cohesion and filler to bitumen ratio for series 2.

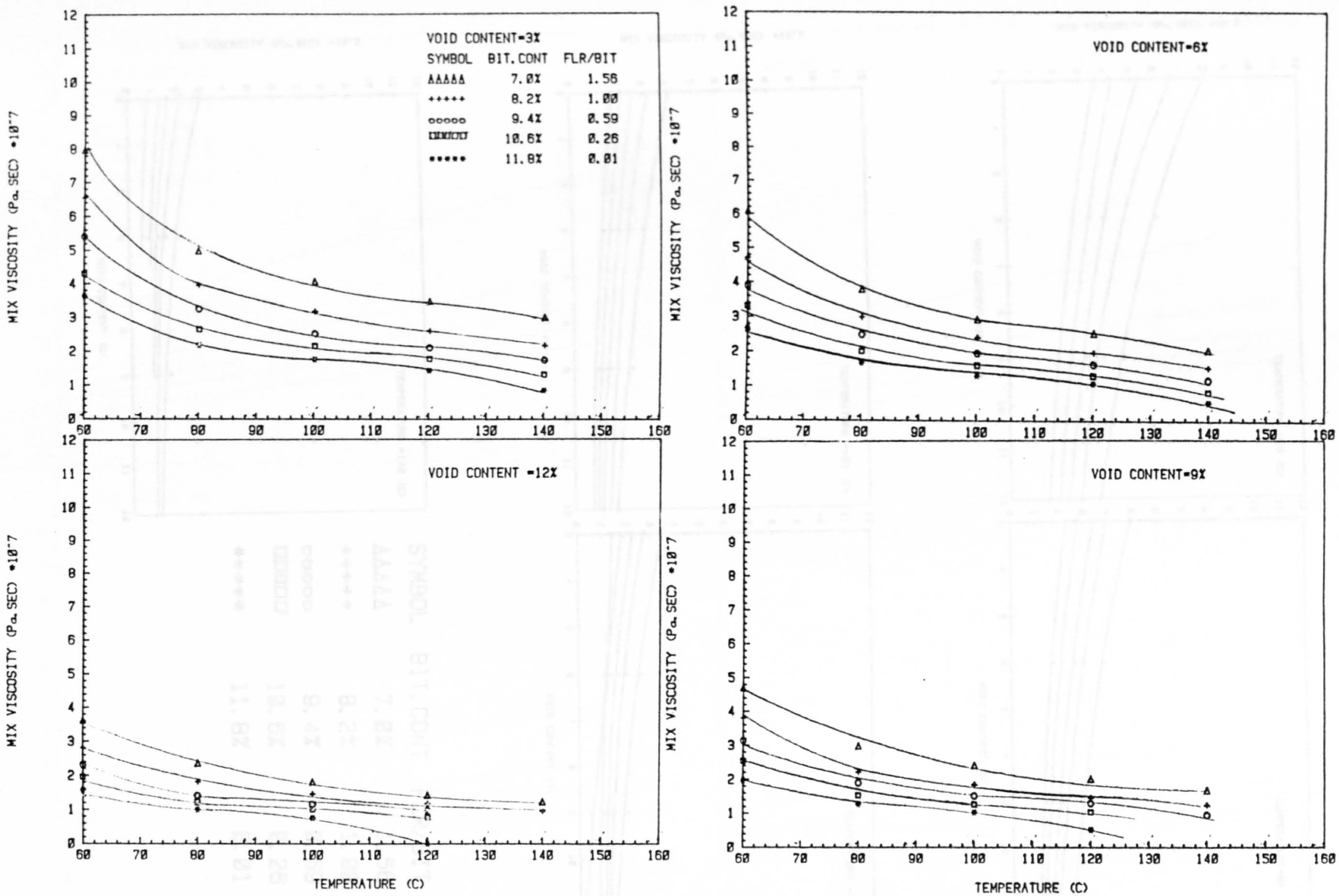


Figure 4.17: Relationships between mix viscosity and temperature for series 2.

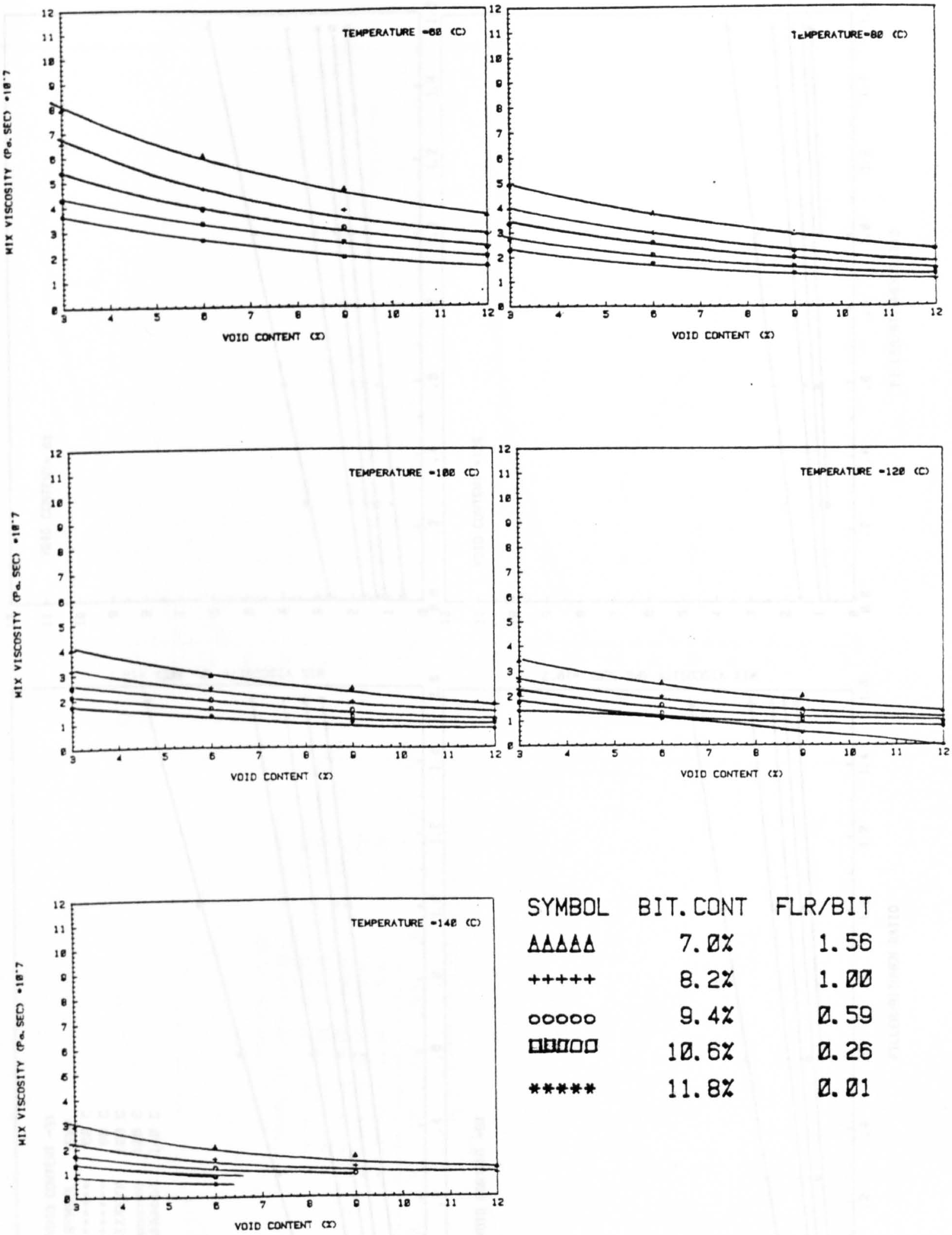


Figure 4.18: Relationships between mix viscosity and void content for series 2.

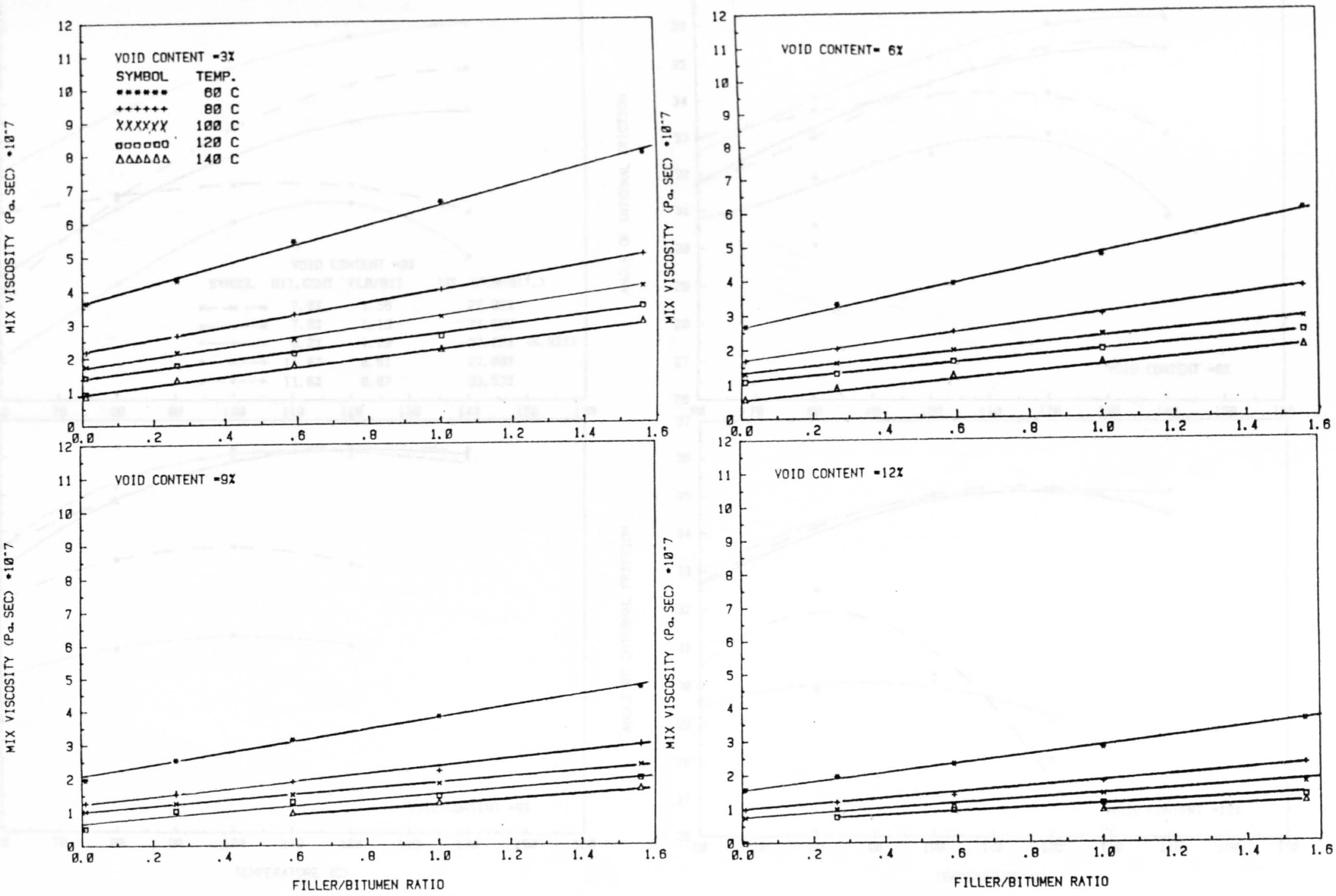


Figure 4.19: Relationships between mix viscosity and filler to bitumen ratio for series 2.

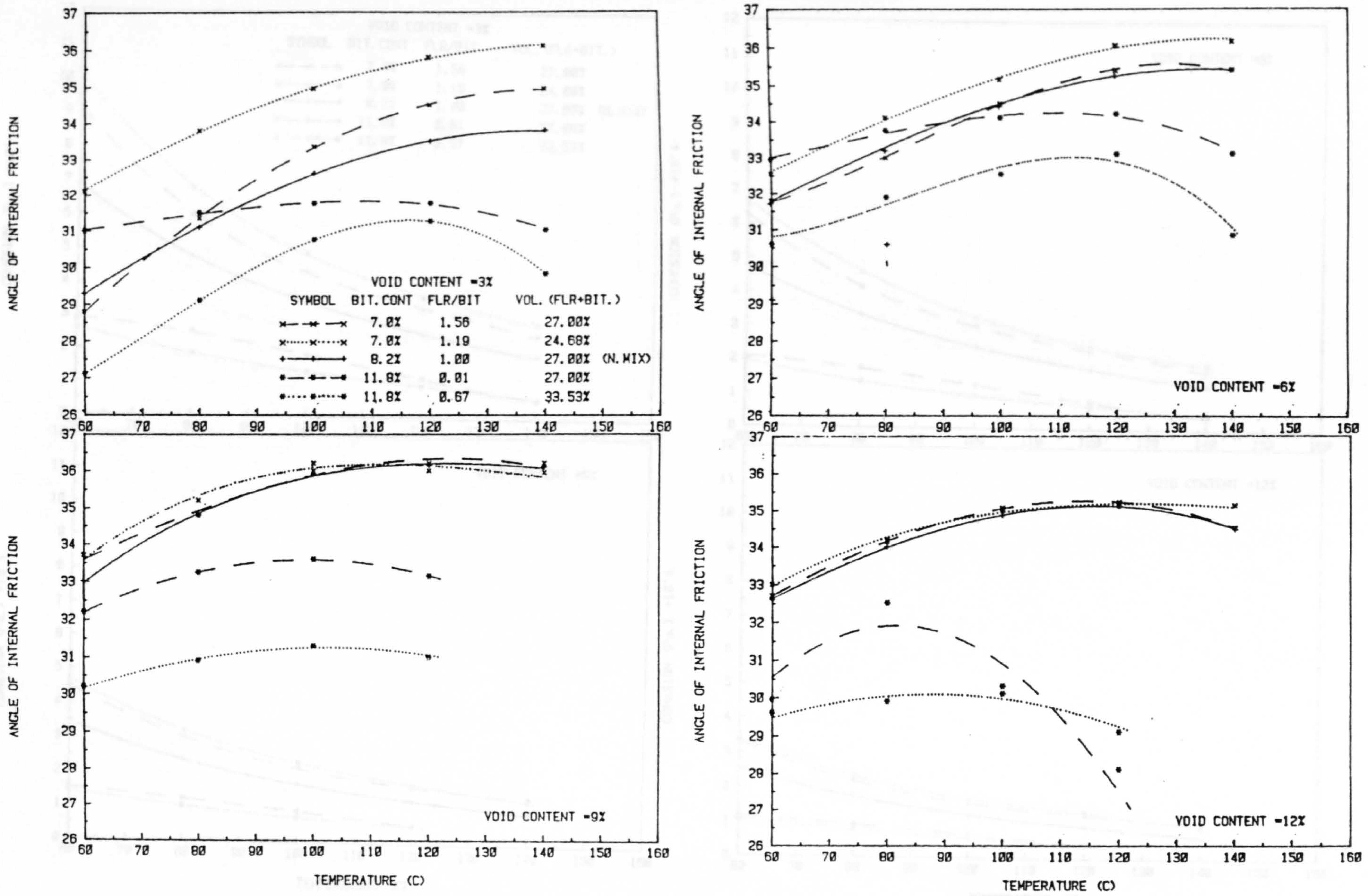


Figure 4.20: Relationships between angle of internal friction and temperature for selected mixes from series 1 and 2.

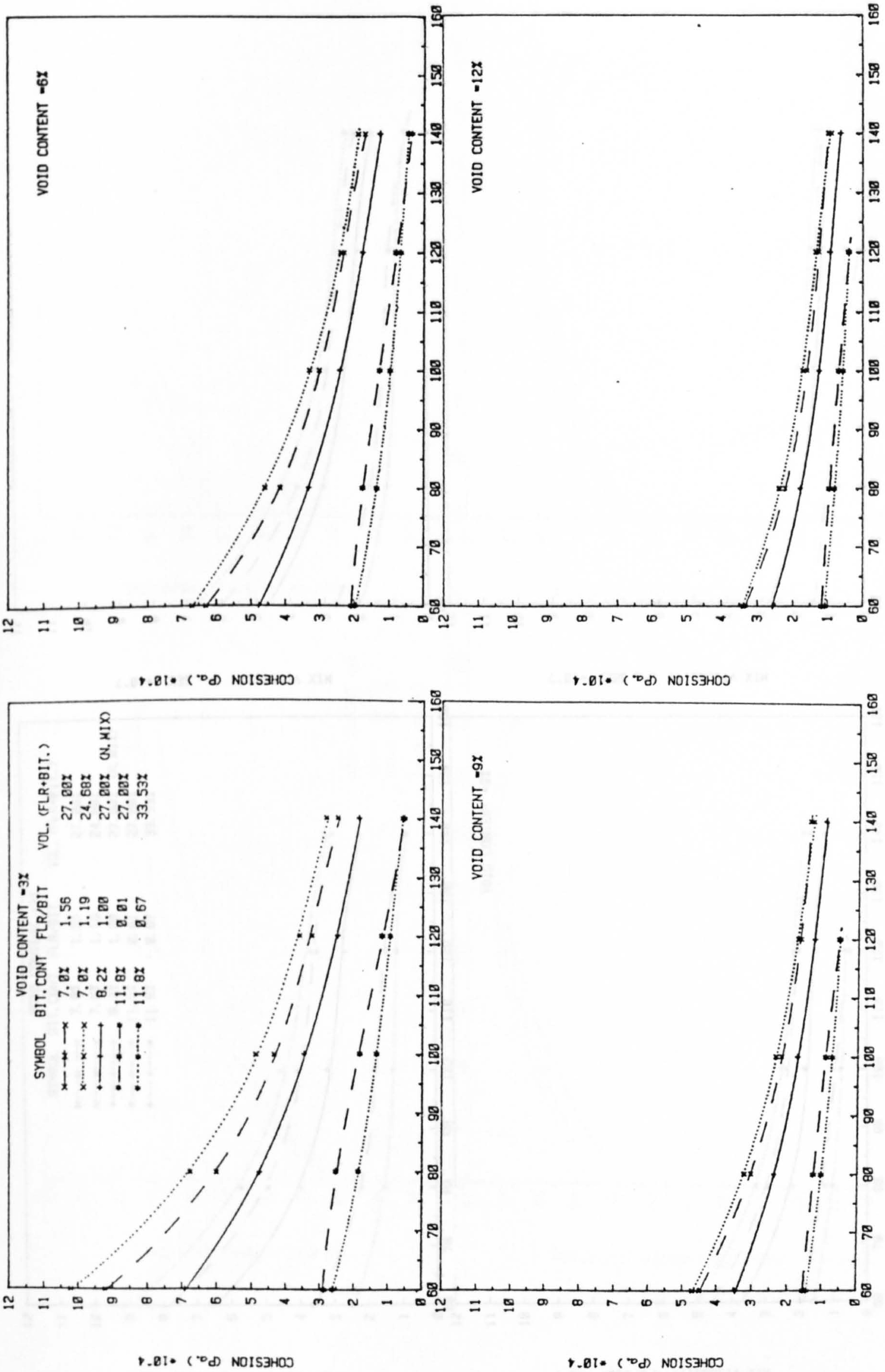


Figure 4.21: Relationships between mix cohesion and temperature for selected mixes from series 1 and 2.

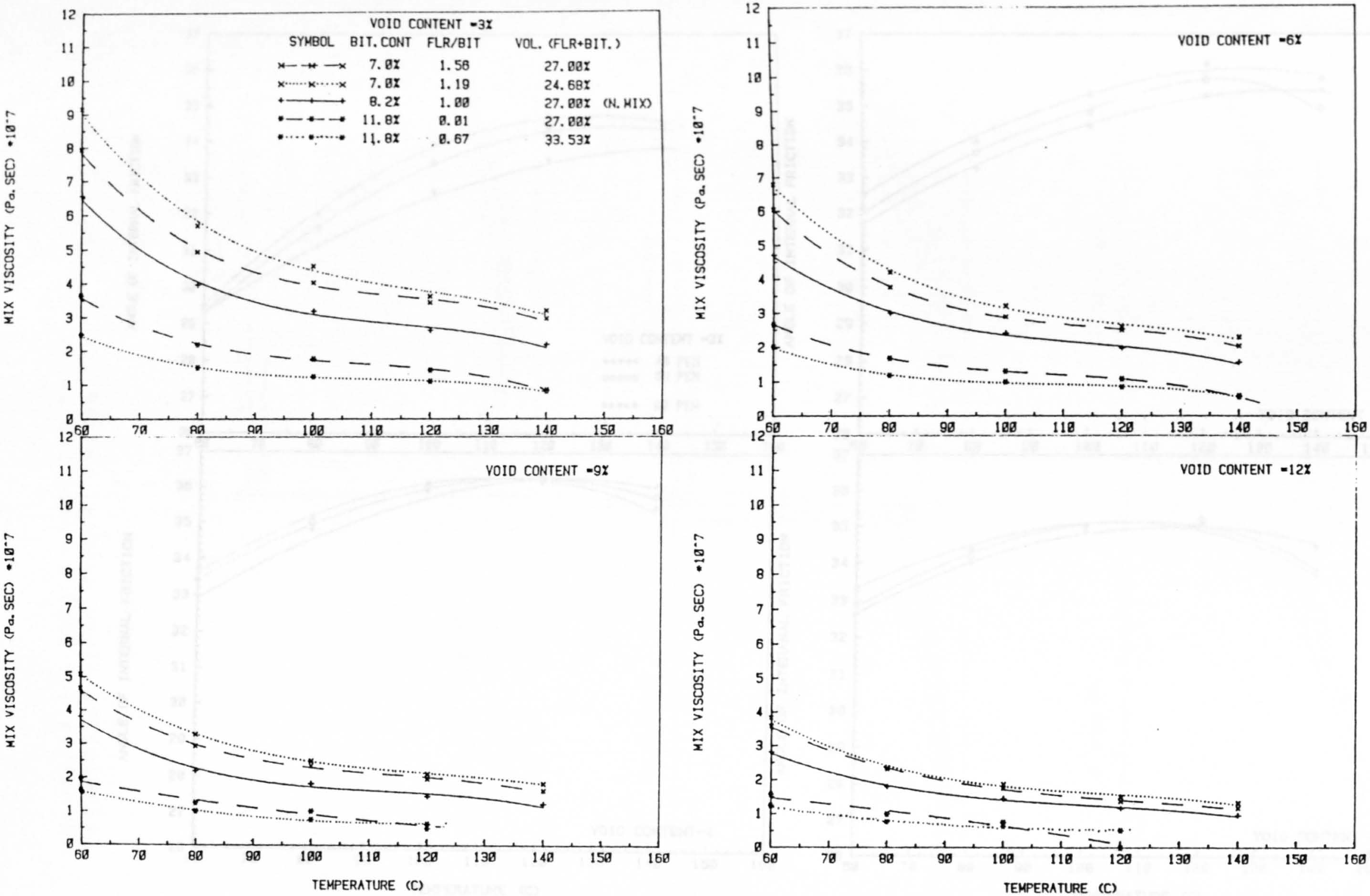


Figure 4.22: Relationships between mix viscosity and temperature for selected mixes from series 1 and 2.

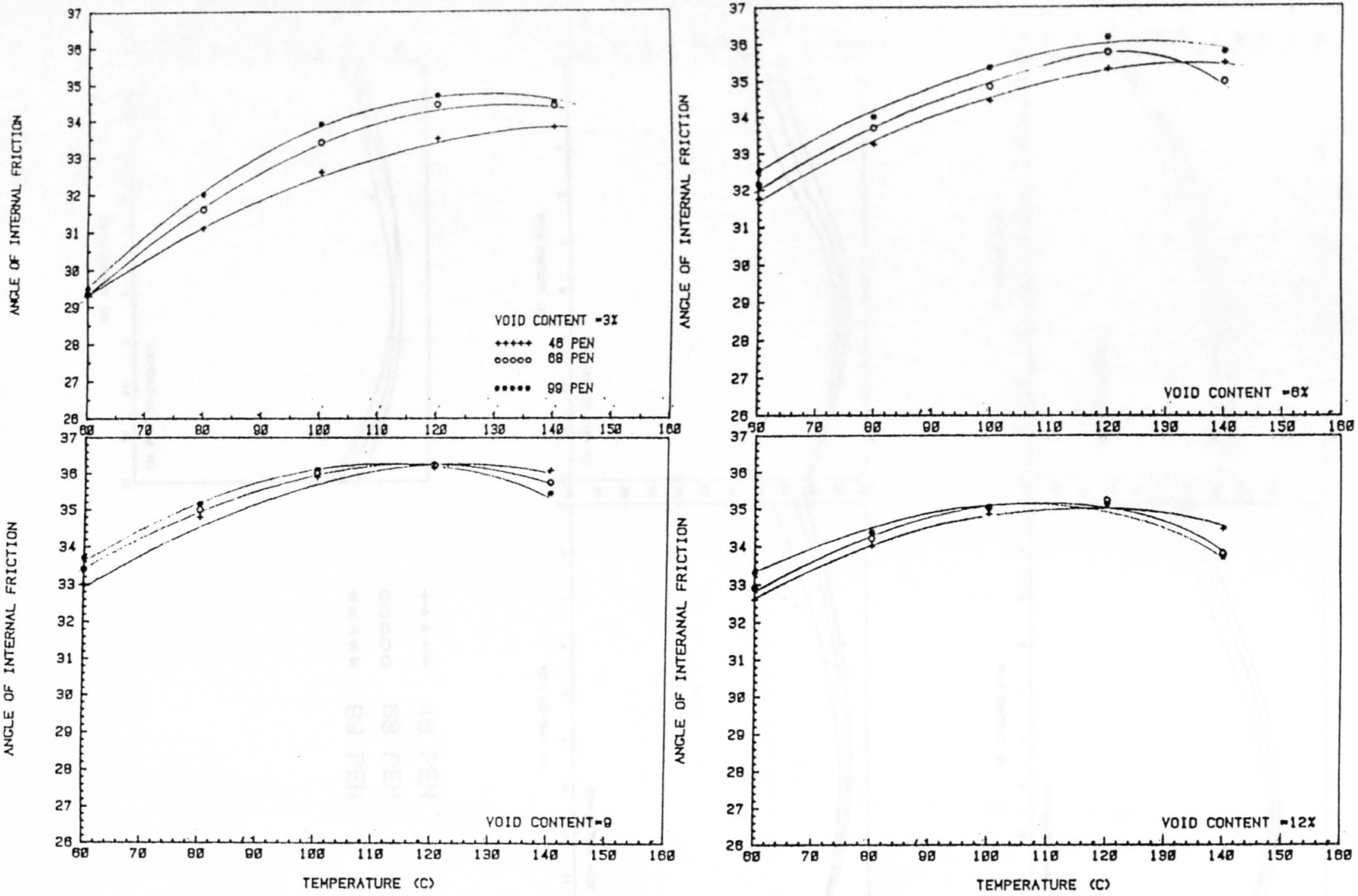


Figure 4.23: Relationships between angle of internal friction and temperature for series 3.

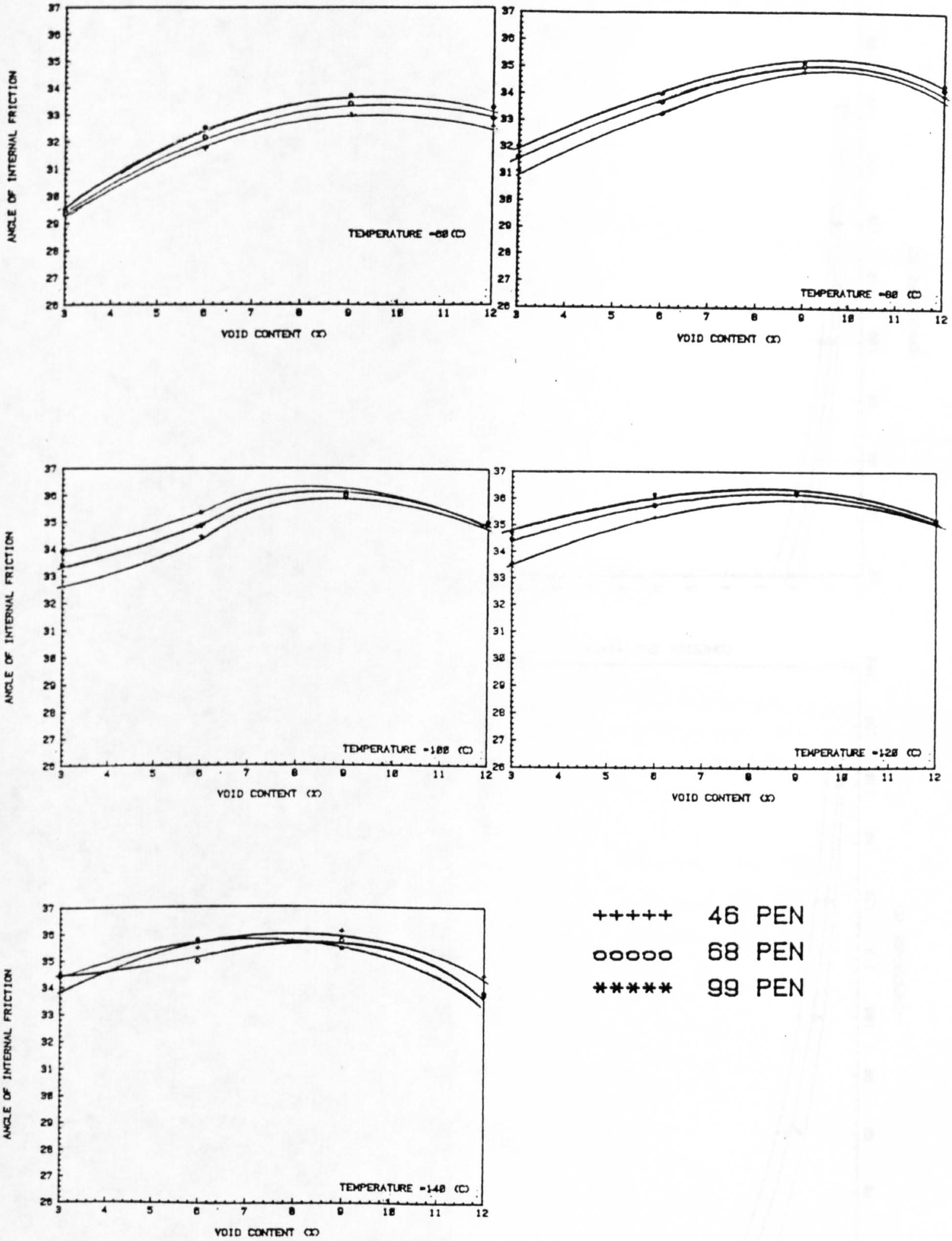


Figure 4.24: Relationships between angle of internal friction and void content for series 3.

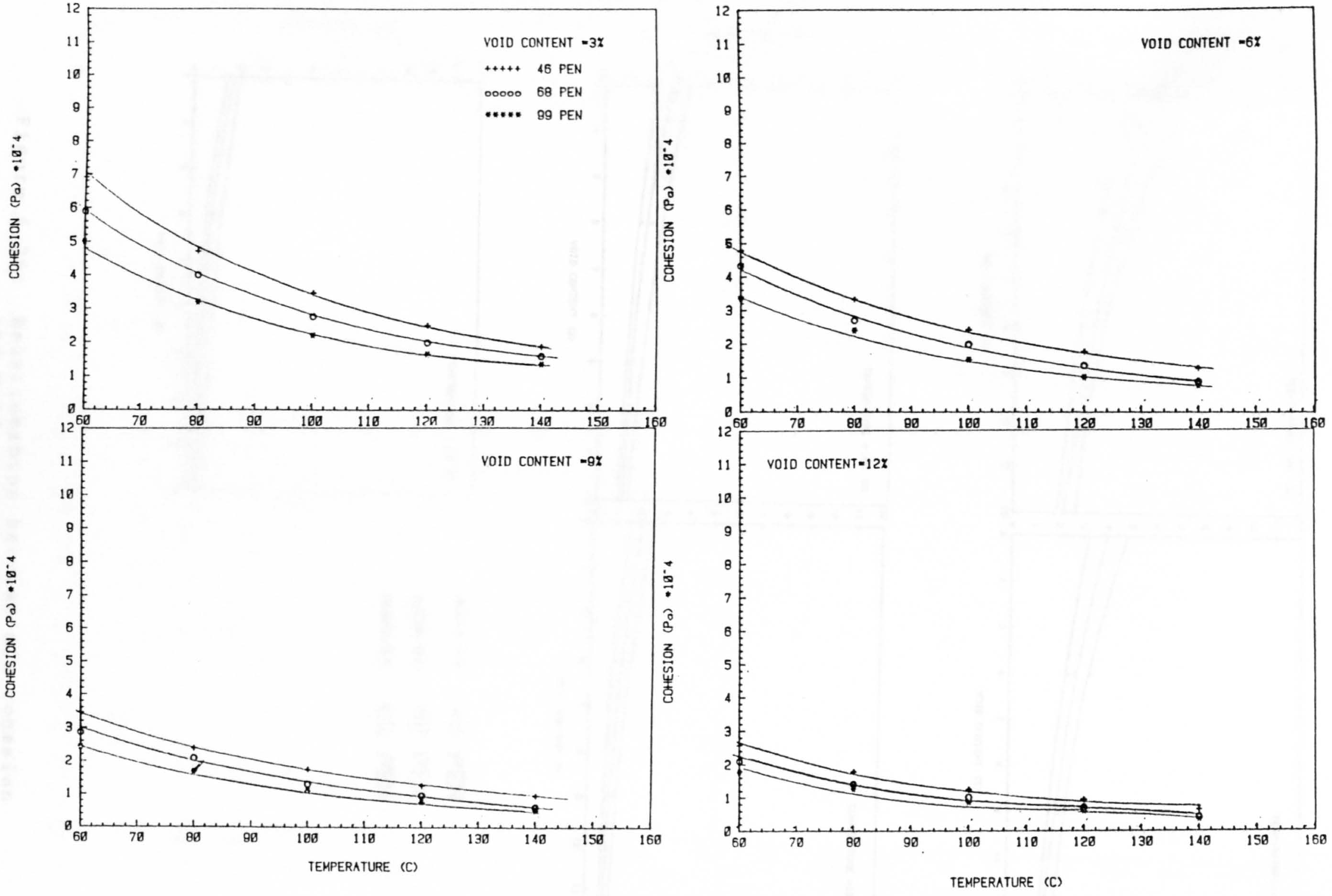


Figure 4.25: Relationships between cohesion and temperature for series 3.

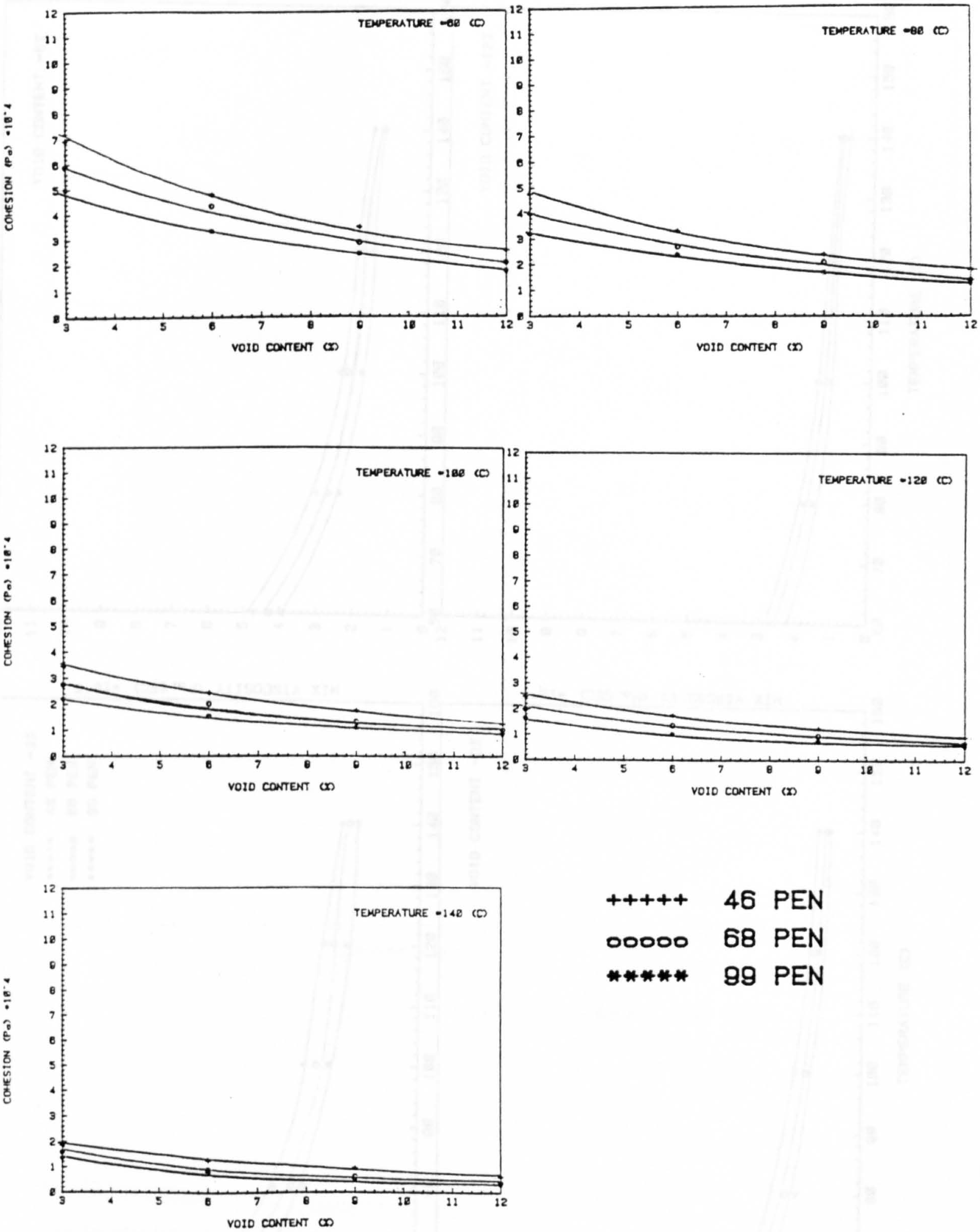


Figure 4.26: Relationships between mix cohesion and void content for series 3.

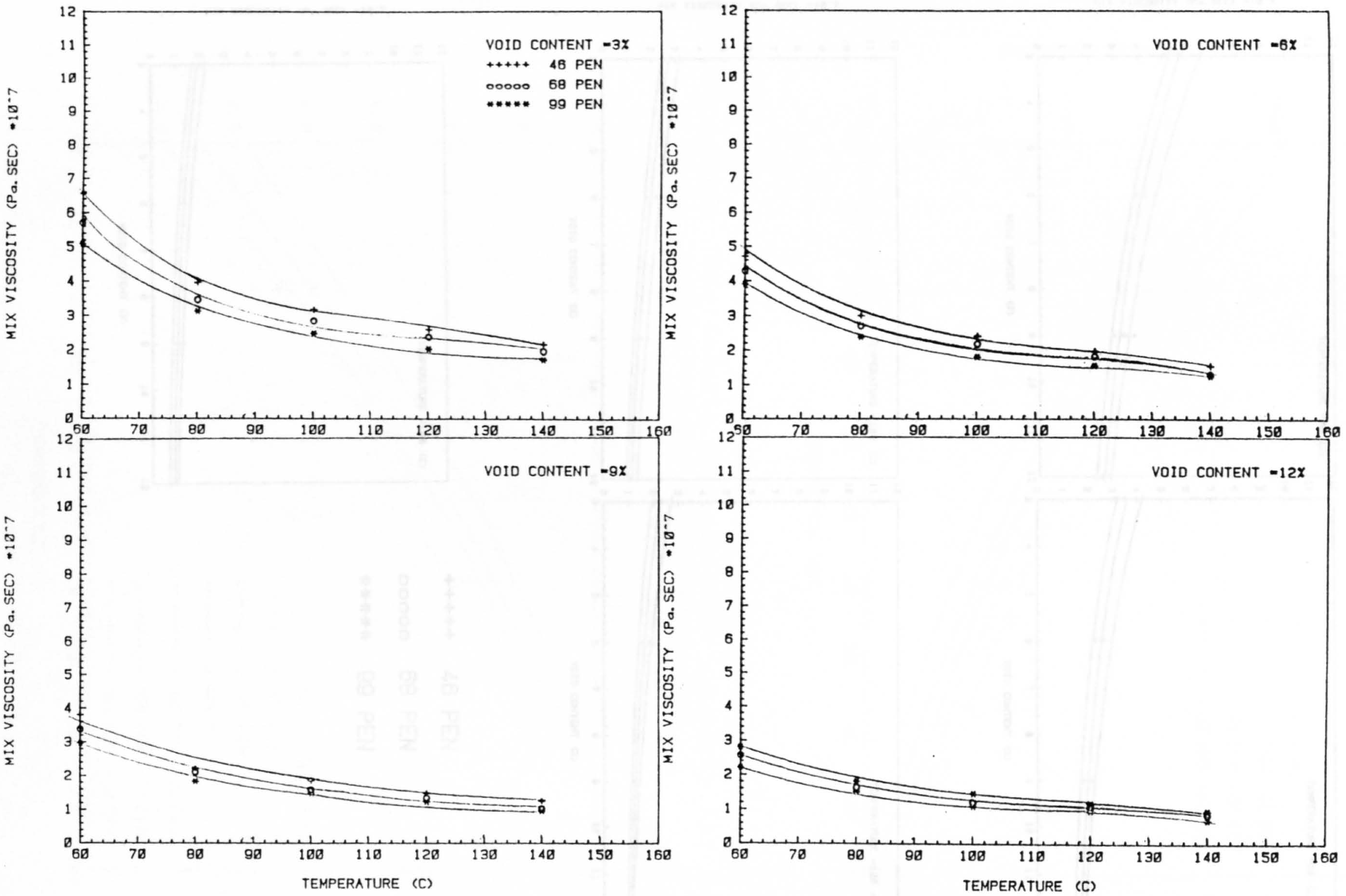


Figure 4.27: Relationships between mix viscosity and temperature for series 3.

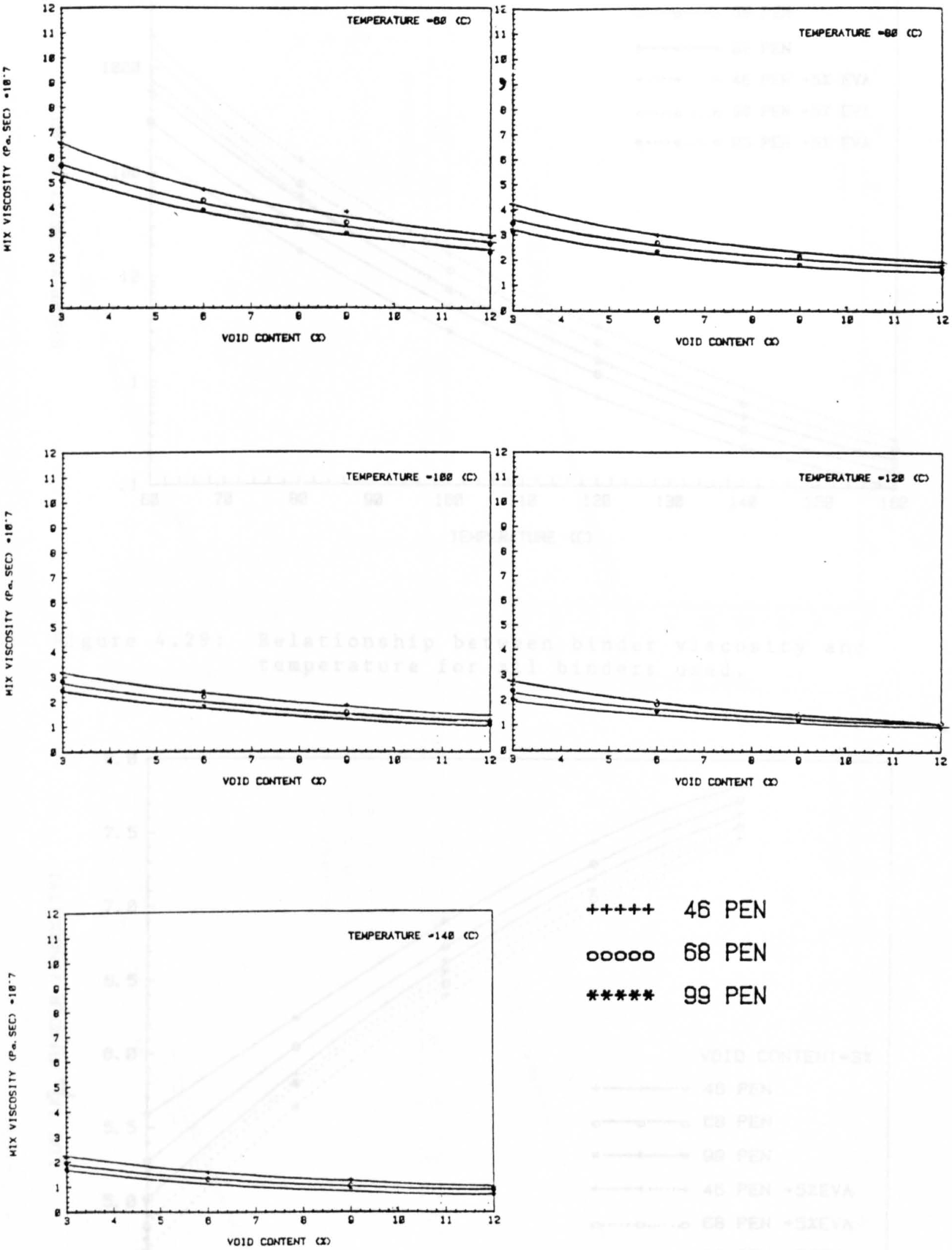


Figure 4.28: Relationships between mix viscosity and void content for series 3.

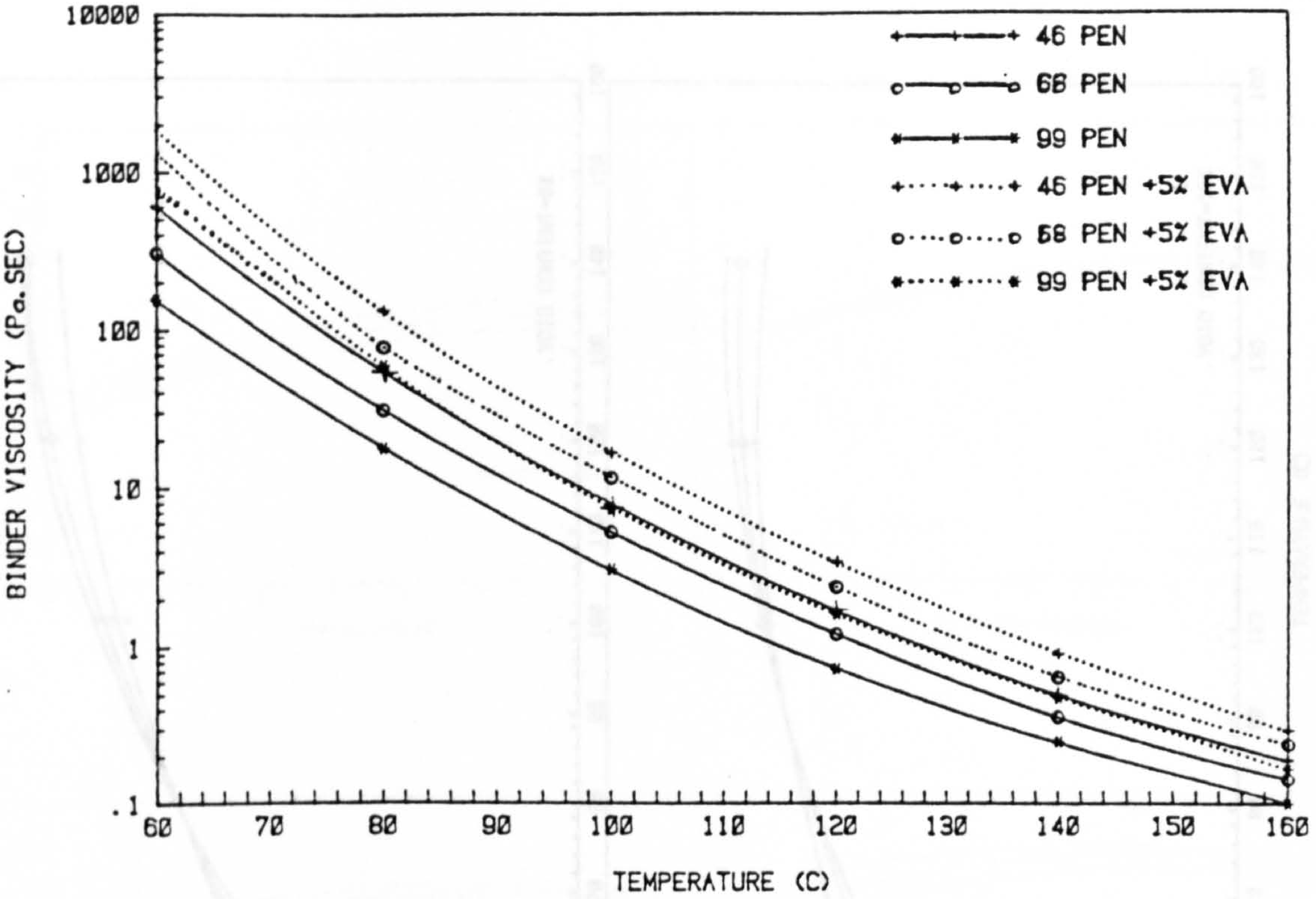


Figure 4.29: Relationship between binder viscosity and temperature for all binders used.

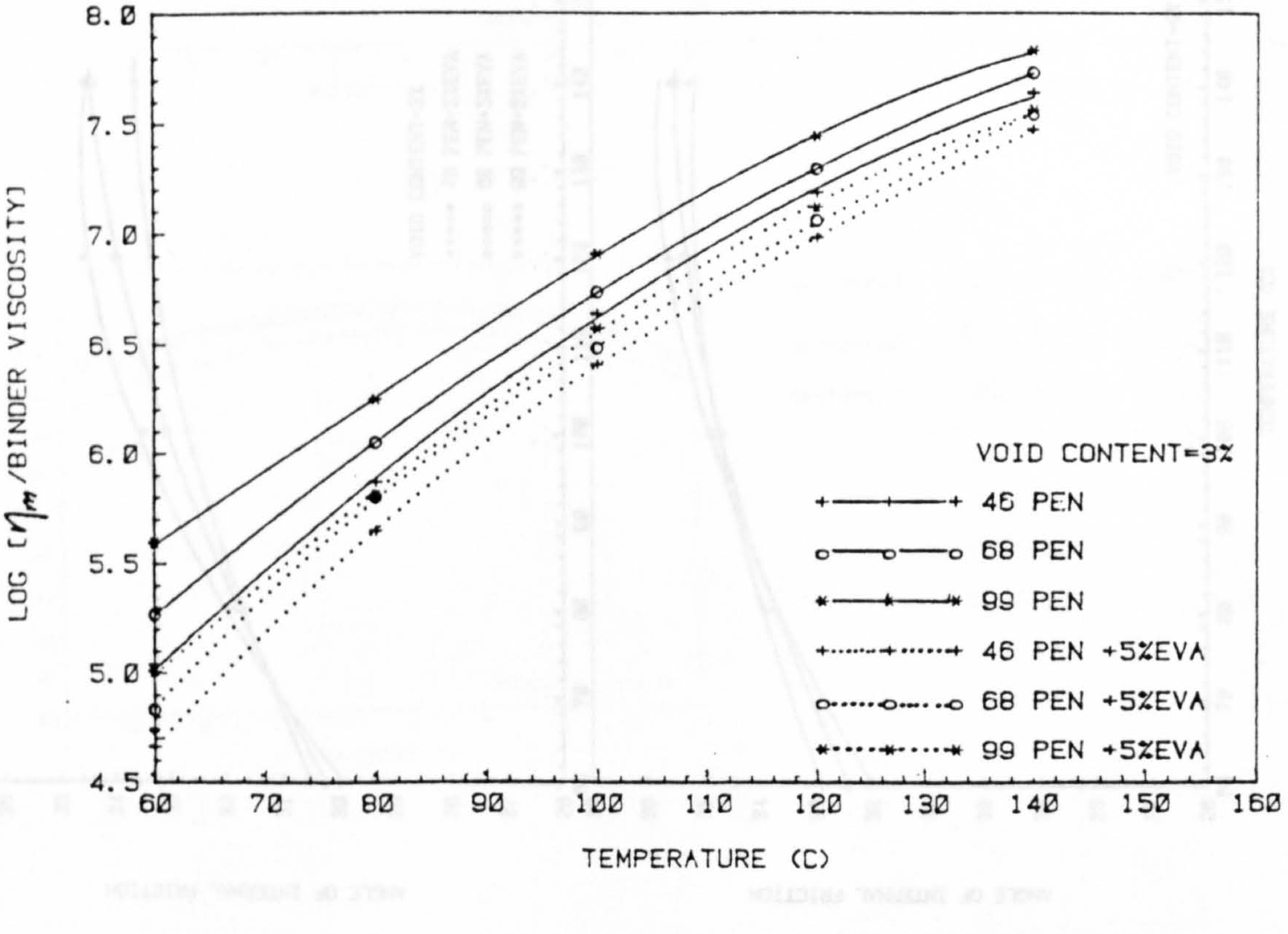


Figure 4.30: Relationship between Log $\frac{\text{mix viscosity}}{\text{binder viscosity}}$ and temperature for all binders used.

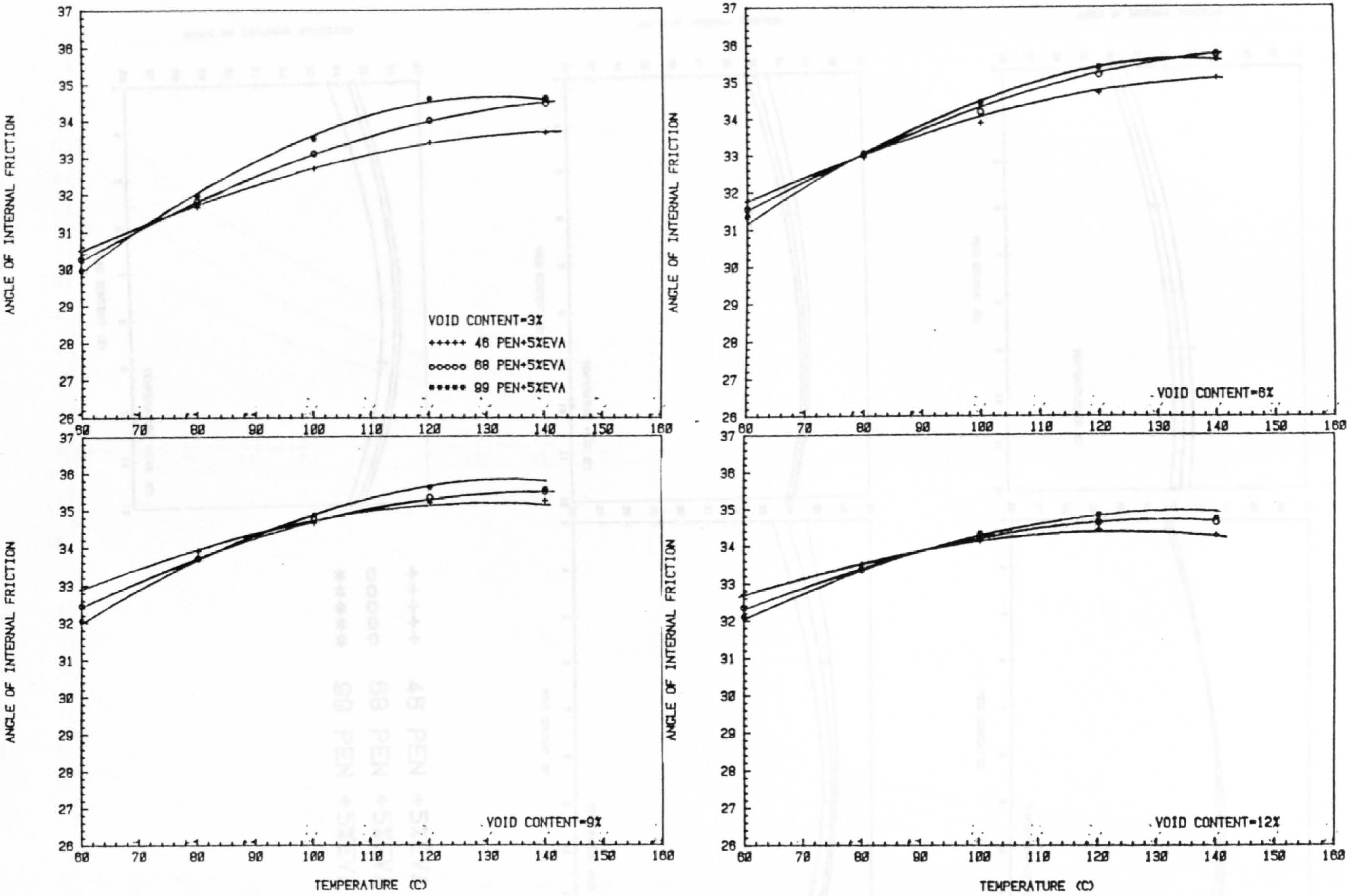


Figure 4.31: Relationships between angle of internal friction and temperature for series 4.

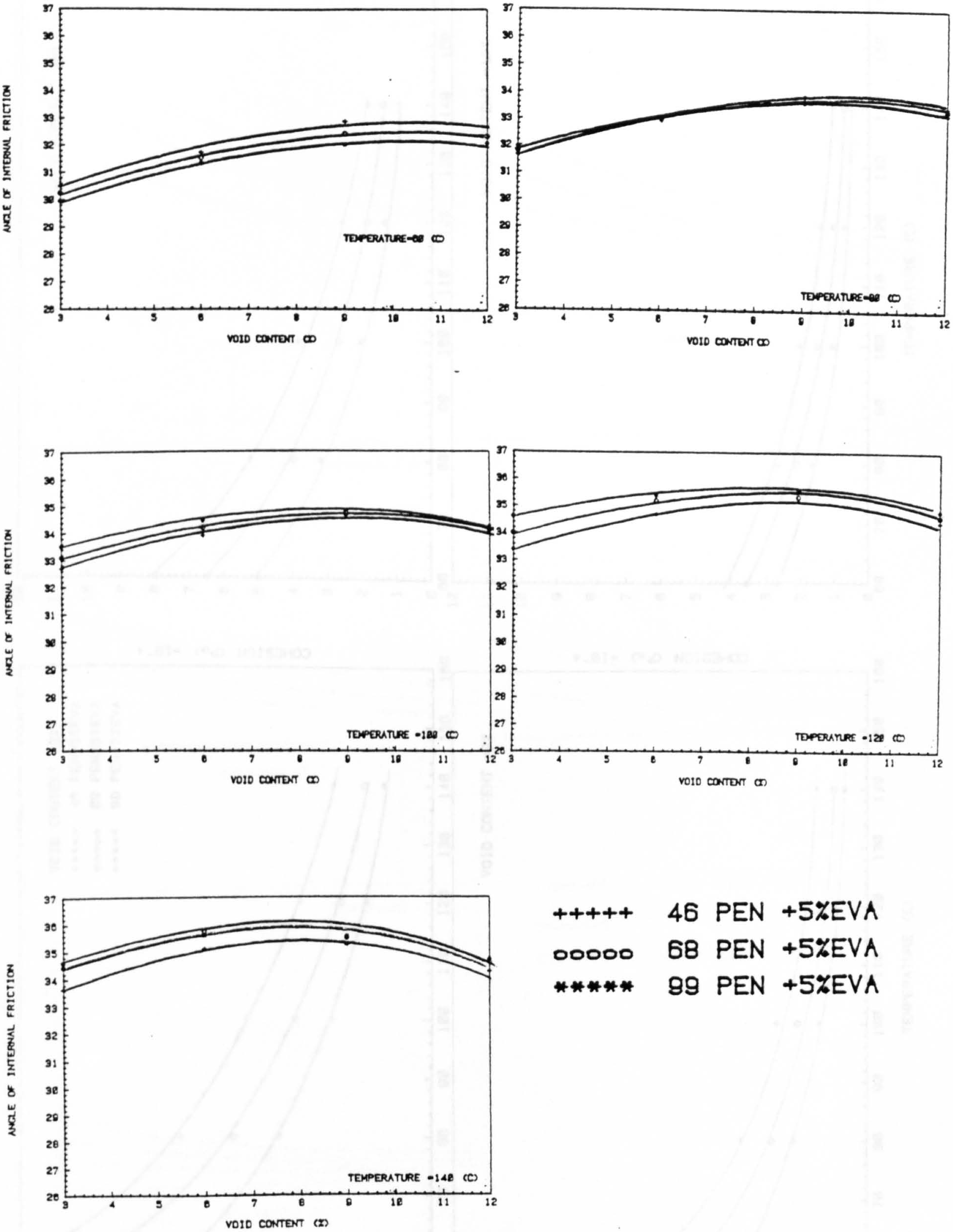


Figure 4.32: Relationships between angle of internal friction and void content for series 4.

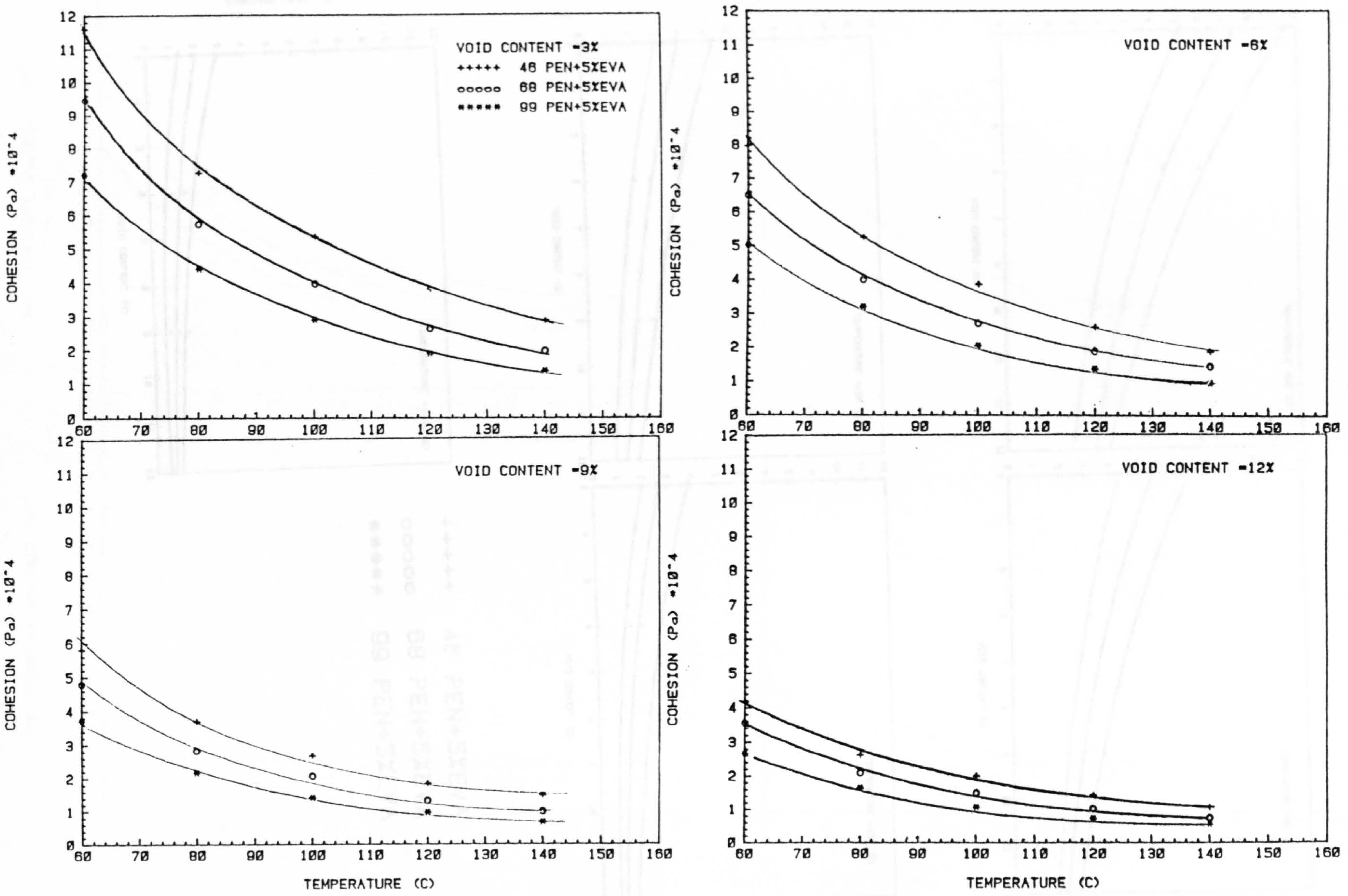


Figure 4.33: Relationships between mix cohesion and temperature for series 4.

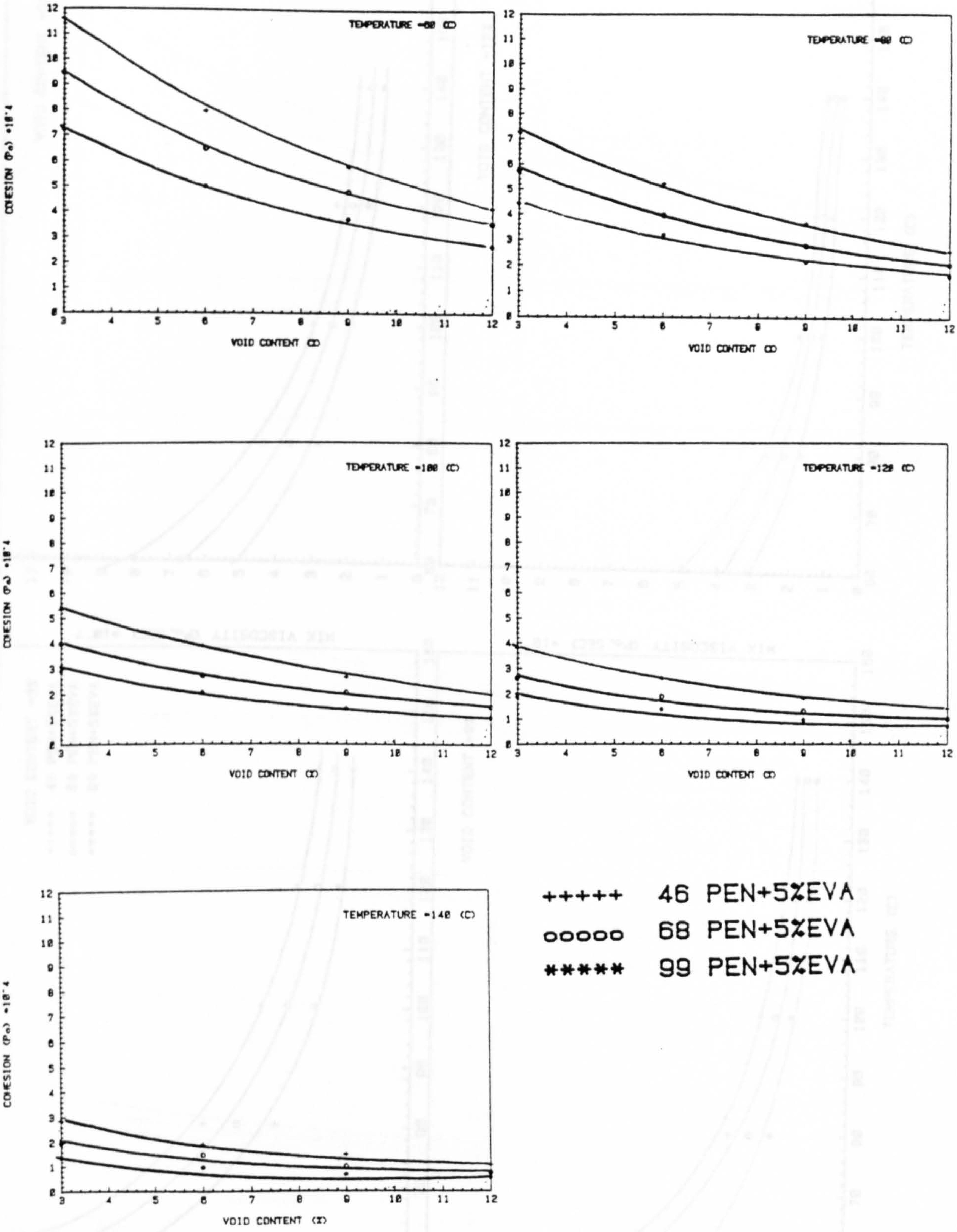


Figure 4.34: Relationships between mix cohesion and void content for series 4.

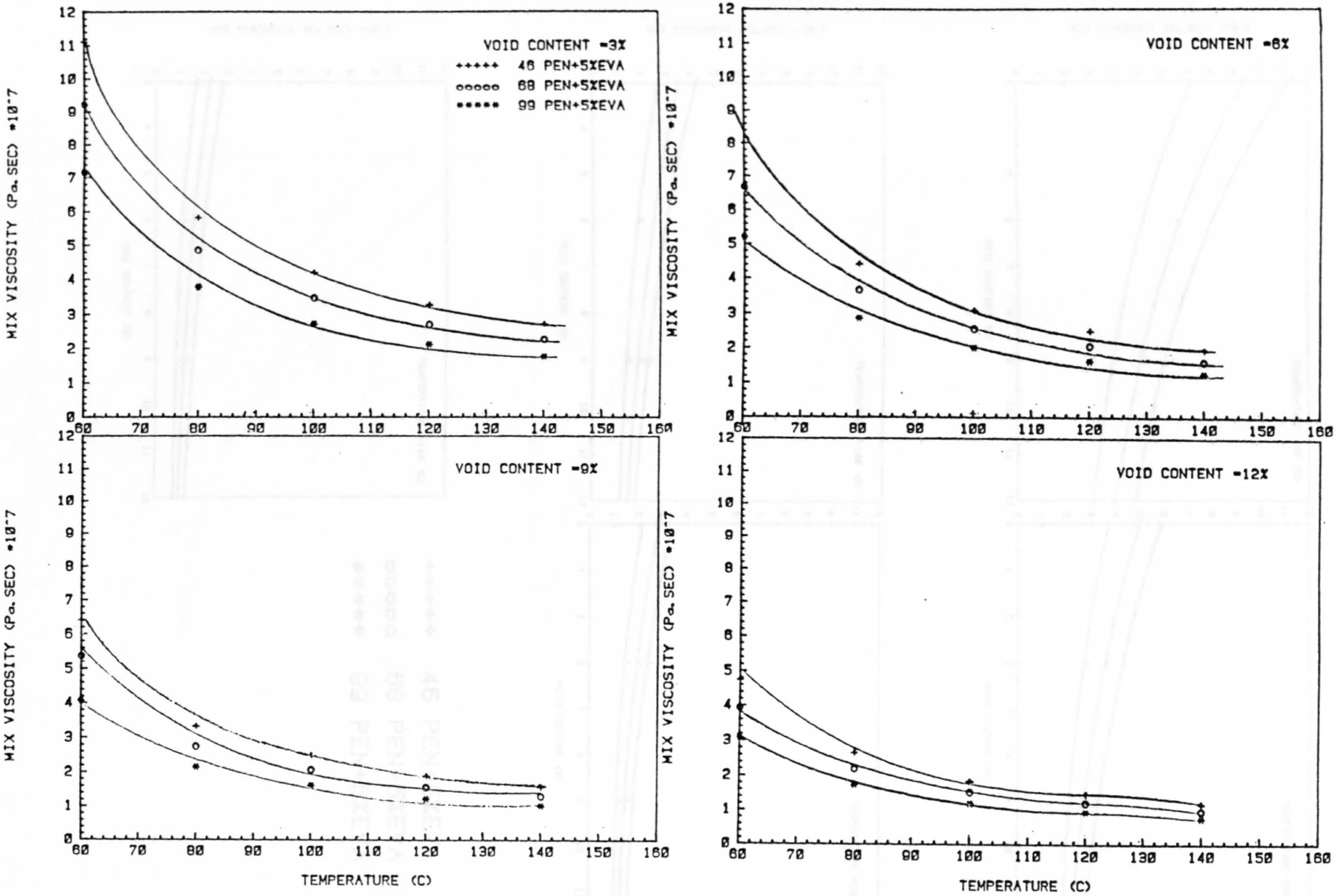


Figure 4.35: Relationships between mix viscosity and temperature for series 4.

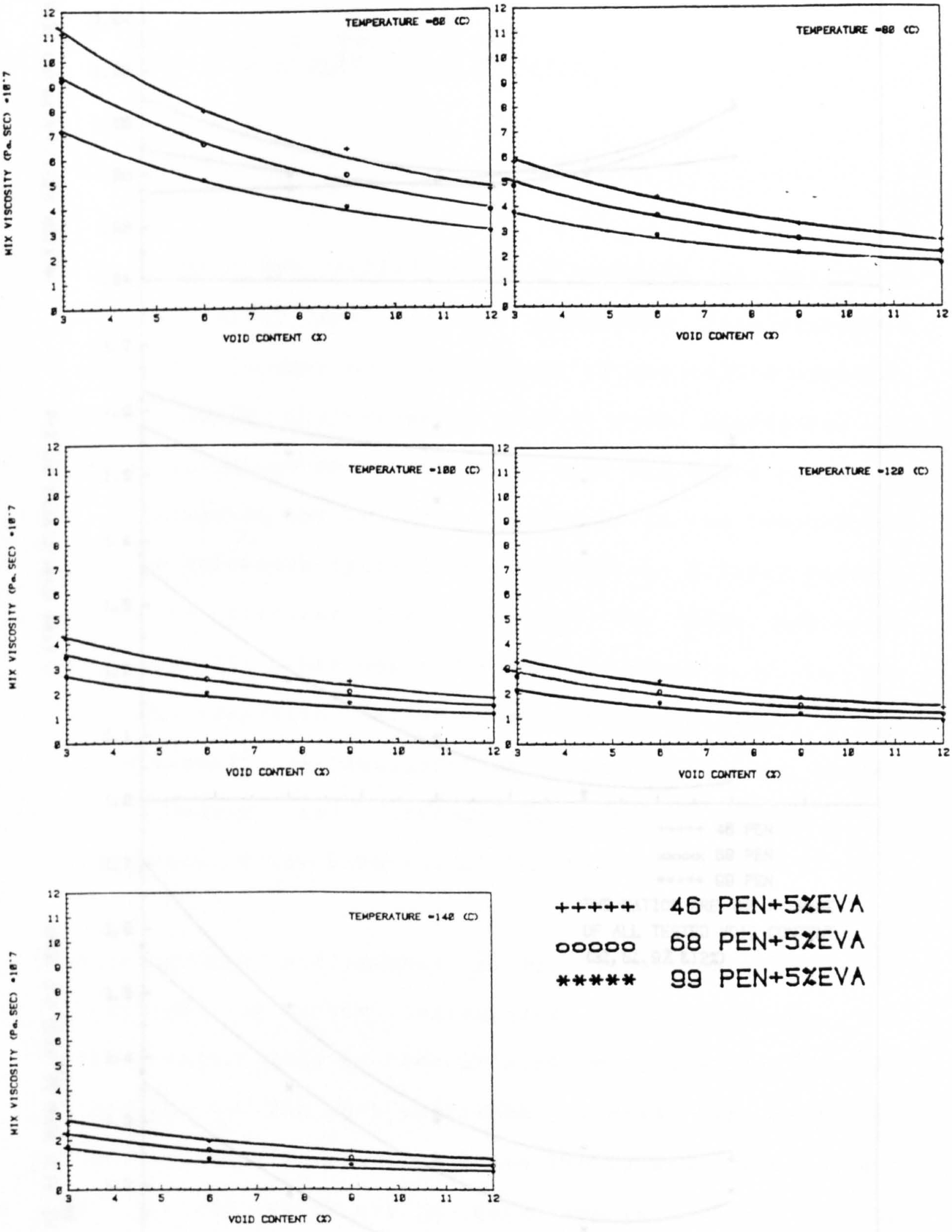


Figure 4.36: Relationships between mix viscosity and void content for series 4.

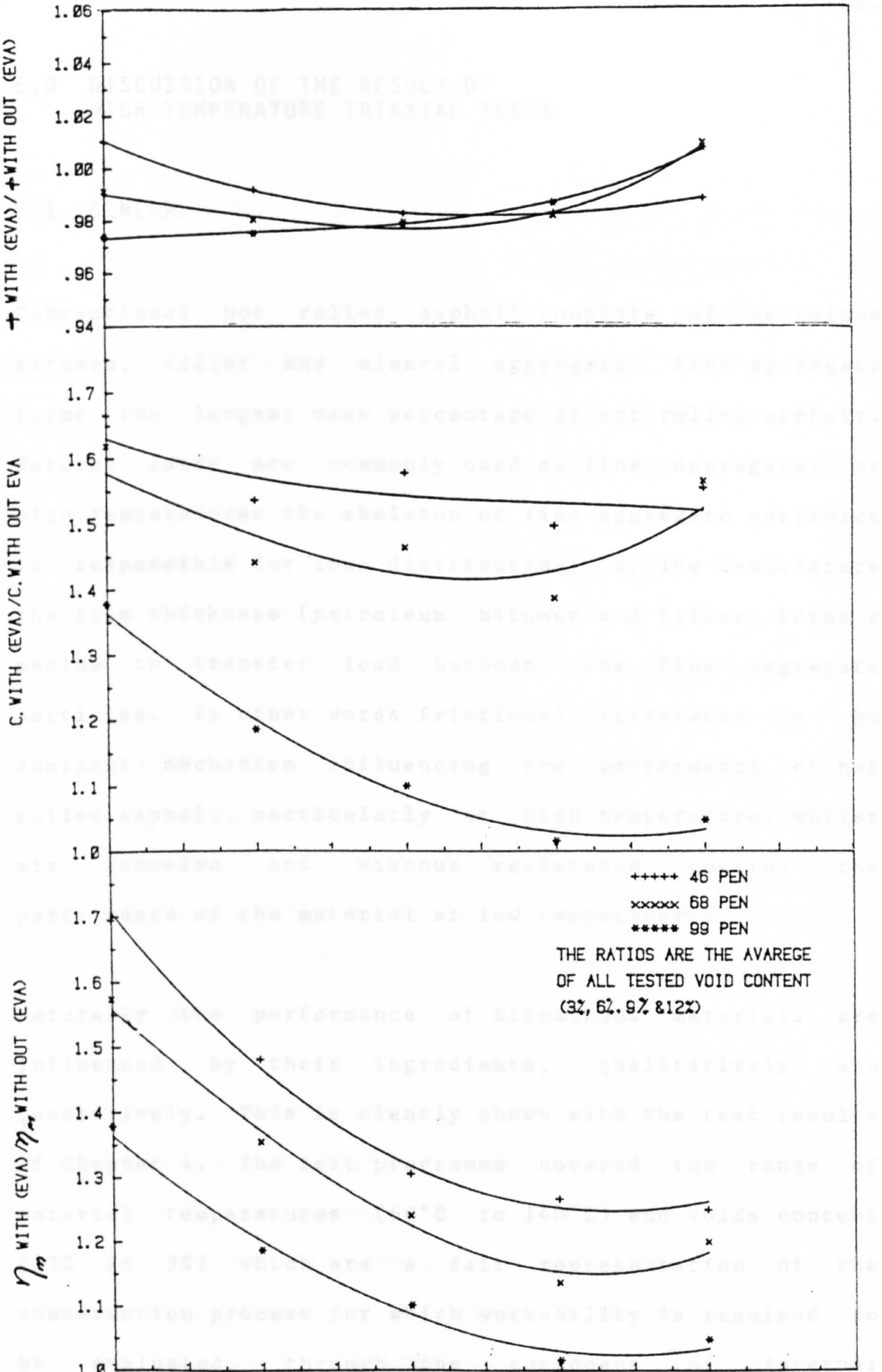


Figure 4.37: Comparison of modified and unmodified mixes through relationship between internal resistance parameters and temperature.

5.0 DISCUSSION OF THE RESULT OF HIGH TEMPERATURE TRIAXIAL TESTS

5.1 GENERAL

Conventional hot rolled asphalt consists of petroleum bitumen, filler and mineral aggregate. Fine aggregate forms the largest mass percentage of hot rolled asphalt. Natural sands are commonly used as fine aggregate. At high temperatures the skeleton of fine aggregate particles is responsible for load distribution; at low temperature the film thickness (petroleum bitumen and filler) forms a medium to transfer load between the fine aggregate particles. In other words frictional resistance is the dominant mechanism influencing the performance of hot rolled asphalt, particularly at high temperature, whilst mix cohesion and viscous resistance control the performance of the material at low temperatures.

Naturally the performance of bituminous materials are influenced by their ingredients, qualitatively and quantitively. This is clearly shown with the test results of Chapter 4. The test programme covered the range of material temperatures (60°C to 140°C) and voids content (12% to 3%) which are a fair representation of the construction process for which workability is required to be evaluated, through the component of internal resistance.

5.2 THE PHYSICAL MODEL

The physical model is an attempt to establish a mechanism for explaining the performance of hot rolled asphalt at high temperature. For hot rolled asphalt mixes at high temperature (120°C to 140°C) the influence of the bitumen is minimised whilst the influence of the mineral aggregate and the filler is maximised. The influence of the fine aggregate particles through their shape, surface texture and grading as a result has a greater chance to develop the frictional resistance as a result of the physical contact between particles. The filler particles and bitumen layer work as a lubricant helping in separating the fine aggregate particles, the thermal expansion of the bitumen plays an important role here. Any increase in the mass proportion of filler or bitumen will lead to a reduction in the value of angle of internal friction of a mix as a result of the reduction in the interlock between the fine aggregate matrix.

For hot rolled asphalt mixes at low temperature (or when the mix temperature reduces through cooling) the viscosity of the bitumen increases, the bitumen film is further stiffened through the entrapped filler. This results in high adhesive forces, which in turn increases mix cohesion and mix viscosity. An increase in mix cohesion and mix viscosity results in a reduction in frictional resistance, due to the effect of the stiff bitumen film which minimises the roughness of surface texture. The same stiff film (bitumen and filler) will play a large role in transferring the load between fine aggregate particles with smaller chance of movement between the particles.

The consequence is the effectiveness of fine aggregate particle contact is reduced resulting in lower values of angle of internal friction.

The volume of film thickness plays a major role in determining the internal resistance of a mix. Any increase in the volume leads to a reduction in the physical number of points of contact between fine mineral aggregate, which then reduces the frictional resistance and interlocking resistance. At the same time a thicker film reduces the adhesive forces and the viscous resistance. An increase in the bitumen content of a film will also increase the thickness of the bitumen layer coating the filler and fine mineral aggregate particles reducing frictional, cohesion and viscous resistance. If the filler content changes this will also change the values of angle of internal friction, mix cohesion and mix viscosity. It is found when the filler content increases the value of angle of internal resistance reduces (as will be seen in detail later), so any increase in the filler content of a mix results in a reduction in the frictional resistance and as a consequence of the decrease in number of particle contact, the mix cohesion and viscous resistance reduces. If the filler content decreases accompanied with an increase in bitumen content (i.e. the volume of film thickness is kept constant), the internal resistance components will decrease. The viscous and cohesion resistance undoubtedly will reduce due to a thicker layer of bitumen and a lower film stiffness. The frictional resistance meets two conflicting points: the filler reduction will lead to an increase in the value of angle of internal friction, but the increasing bitumen content will reduce the value of angle of internal friction. Since the bitumen is temperature dependent, so the outcome of the change in angle of internal friction is very much temperature dependent. At low temperature, where the bitumen is (relatively) stiff, mixes with lower filler content exhibit a higher value of angle of internal friction compared with those mixes which have a higher filler content and lower bitumen content, this is because in the latter case the film is stiff enough to minimise the particle contact and decrease the influence of the surface texture. When mix temperature is increased the thermal expansion of the bitumen will reduce the contact of fine aggregate particles and will result in a build-up of hydrostatic pressure, particularly with high bitumen contents.

Changes in the rheological properties of the petroleum bitumen have the same effect as changes in bitumen temperature. When the penetration value of the petroleum bitumen was increased, in the test programme, and this was accompanied by a decrease in softening point and viscosity, this resulted in the same effect on mix performance as a temperature increase; both effects resulted in a decrease in mix cohesion and viscous resistance and an increase in the frictional resistance. Void content is another important factor affecting the components of resistance to internal movement. Naturally, a reduction in void content will lead to a densification of a hot rolled asphalt, this will increase the number of points of contact between the fine mineral aggregate particles and/or fine mineral aggregate particles and film thicknss, which in turn increases the value of the components of internal resistance. The test results indicated that the value of angle of internal friction increased as the void content decreased, but only to a particular limiting value of voids content (6 percent to 9 percent). As mix compaction was increased, to reduce the voids content to 3 percent, a reduction in the value of angle of angle of internal friction occurred which may be explained as a consequence of the degradation of the edges of the fine aggregate particles in contact and/or the film thickness forms a more continuous layer around the mineral aggregate particles minimising the influence of surface texture and the angularity of the particles.

The model suggested above raises many points which need a more detailed explanation. These points are discussed in the following section.

5.2.1 Influence of filler on angle of internal friction

It is recognised that the presence of filler in bituminous materials has a considerable effect on the stiffness of the material, any increase in filler content will enhance mechanical properties. This is the case at low temperature because the filler stiffens the bitumen, but where temperature is high the bitumen loses a sizeable amount of its adhesive force, and the role of filler changes. At high temperature, when mix cohesion and viscous resistance are reduced the frictional resistance appears to dominate the performance of a material through the fact that the filler content influences the value of angle of internal friction.

In an attempt to quantify the effect of filler content on the performance of hot rolled asphalt, samples of dry fine aggregate were blended with different percentages of filler in a loose condition. The fine aggregate and filler used were the same materials used to prepare the four series forming the main test programme of this study. These samples were tested in the triaxial cell. The results indicated that the values of angle of internal friction reduced as the filler percentage increased, as shown in Figure 5.1. The results also indicated that the void content of the mix was reduced, but only up to a value of around 5 percent filler beyond this value of filler content there is no noticeable reduction in voids content, as can be seen in Figure 5.2. A reduction in value of angle of internal friction occurred despite mix density increasing. This is a consequence of the filler being trapped between the fine aggregate particles. Viewing the shape, texture and gradation of the filler through a scanning electron microscope (SEM), exemplified in Plates 5.1 and 5.2, it was found to consist of very fine particles which likely fill some the depression on the fine aggregate particle surface, particularly when the particles are angular and rough in surface texture, as shown in Plates 5.3, 5.4, 5.5 and 5.6. Such filler particles work as a lubricant by reducing the effect of the surface texture of the fine aggregate. The remaining filler facilitates the fine aggregate particles to slide, perhaps allowing the rolling of the fine aggregate particles by forming a layer between these particles which lead to a reduction in the number of contact points and therefore reducing the value of angle of internal friction.

The reduction in voids content results from the filling of the voids in the fine aggregate skeleton. But when the filler content within a mix is increased, the voids between the filler particles begin to increase and as the filler content increases the voids in the filler matrix increases; the blend connsequently transforms from one of filler in the aggregate to one of fine agregate in filler.

The relationship between value of angle of internal friction and filler content, as shown in Figure 5.1, exhibits a change in trend around the filler to fine aggregate ratio, by volume of 15 percent which is equivalent to a fine aggregate to filler ratio by mass of 6:1; this mass ratio is that used as the basis of the design of wearing course hot rolled asphalt mixes. The data suggests that any variation around this particular ratio may lead to a noticeable change in the value of angle of internal friction and subsequently the performance of a mixture.

The fine aggregate particles provide the basic frictional characteristics of a hot rolled asphalt. A mixture of coarse aggregate, fine aggregate and filler shows no difference in value of angle of internal friction to that of a fine aggregate and filler blend, as can be seen in Figure 5.1. The two data plots are drawn to different scales and both maintain the value of filler to fine aggregate ratio. The graphs emphasises the role of the fine aggregate in producing the basic frictional resistance of a mix. The coarse aggregate is 'floating' in the mixture; there is no effective contact between these particles.

Figure 5.2 shows a considerable reduction in mix voidage content when the coarse aggregate is added. The coarse aggregate replaces a volume of bulk fine aggregate which itself contains voids, the consequence is that the overall mix voidage is reduced. This finding is in line with results of other investigators, and is an accepted correction in the current design standard for hot rolled asphalt (47, 93-97).

5.2.2 The effect of temperature on angle of internal friction

The relationship between angle of internal friction and mix temperature exhibits an increase in the value of angle of internal friction when temperature is increased, within the investigated temperature range of 60°C to 140°C, as shown in Figure 4.1. Many researchers have found the same data when they investigated asphaltic concrete and sand sheet within the temperature range 5°C to 60°C (44, 52, 74). This may be related to the contact between the mineral aggregate particles and the influence of the bitumen. It is stated (98) that two important factors affect the behaviour of paving mixtures, these are: the contact (points) of the aggregate skeleton and the behaviour of the binder within this aggregate skeleton. However, the rise in temperature will reduce the viscosity of the bitumen layer between the aggregate particles. When these particles are under pressure, the bitumen layer and the filler suspension within the bitumen will be subject to movement. The resistance to movement of the mineral aggregate particles (the friction) is then governed by the flow of the binder. The binder displacement will give a greater chance for the mineral aggregate particles to develop more intimate contact and therefore increase the value of angle of internal friction. The particle contact certainly comes from the relative movement of these mineral aggregate particles, the displaced binder will push the other ingredients, including the air voids to replace any space left due to the movement of these particles. Further, it is believed (44) that the binder layer may not be totally displaced should it be limited to a certain very slight thickness. Under the influence of molecular forces exerted on this layer at the surface of the aggregate particles, its properties may deviate considerably from those of the bitumen in a thick layer (44).

5.2.3 The effect of voids content

The densification of bituminous materials will naturally produce material with a high cohesion and viscous resistance, as well as frictional resistance; this is due to the increase in mineral aggregate particle contact. However, the angle of internal friction profile exhibits a concave upward profile with voids content. This means that the value of angle of internal friction peaks at a particular voids content, around 6 percent to 9 percent voids content. When the material was compacted further to 3 percent to 6 percent voids content, a reduction in the value of angle of internal friction occurred. This point deserves attention. Under compaction pressure the materials built the best stable skeleton accommodating the film thickness at a certain voids content. When the exerted pressure increases to achieve a lower voidage a consequence will be that the mineral aggregate particles at their contact point either crush, permitting the particles to come closer together and thus decrease the volume and reduce the angularity and roughness of crushed edges (this idea of degradation is widely reported to take place during compaction and high loading application (49, 75, 99, 100)) or, once the shear forces due to compaction pressure become larger than the shear resistance at the contact points there will be a relative sliding between the aggregate particles, and this helps their re-orientation which 'fills' the voids. This latter effect will lead to movement of the film thickness to form a more continuous layer around the particles, perhaps intruding some of the fine filler to fill some depression on the particle surfaces consequently reducing the roughness of the surfaces. All these factors, degradation, sliding, coating and intrusion will lead to a reduction in frictional resistance.

The reduction in value of angle of internal friction at low voidage content may be the answer for many inconsistent results which were evident with the Tripod penetrometer and the Marshall test. The tripod penetrometer exhibited an increase in penetration value (lower resistance) when the void content of an asphalt mix reduced to 5 percent (21). Also the Marshall test data revealed that mixes varying over the voidage range 2.5 percent to 5.5 percent had very little effect on Marshall stability, and, more surprisingly, the asphalt mixture with 2.5 percent air voids was more easily compacted (33). These two phenomena might be the result of low frictional resistance, which is often not recognised.

The concept of the declared physical model will be used in the interpretation of the results of the four series of this project and shown in Chapter 4. The validity of the iterpretation will be a verification of the proposed physical model.

5.3 DISCUSSION OF ANGLE OF INTERNAL FRICTION DATA

Angle of internal friction is a measurement of frictional resistance. By definition frictional resistance to sliding and rolling of particles in contact within hot rolled asphalt comes principally from the fine aggregate.

a) Control mix data

The results from the control mix show typical profiles for most mixes studied. The values of angle of internal friction are considerably lower than that for fine aggregates with no bitumen or filler (45.6 degrees). The difference in the values of angle of internal friction between the fine aggregate and the mix is smaller at high temperatures. Further, the highest values recorded are with a mix voids content of 9 percent. This complies with the physical model proposed.

b) Data for test series 1

The relationships between angle of internal friction versus temperature, bitumen content and voidage are shown in Figures 4.2, 4.3 and 4.4 respectively. The mixes with this series behave generally as the control mix, but the variation in bitumen content highlights a number of important points. Generally the profile of angle of internal friction and temperature shows an asymptotic trend at high temperature, suggesting a maximum value of angle of internal friction. This trend is the result of two conflicting behaviours. As temperature increases the binder viscosity reduces and its movement increases; also, the contact area increases and the influence of surface texture increases. On the other hand the thermal expansion of bitumen layer increases. When the two effects cancel each other out the peak value of internal friction is observed. For mixes with high bitumen content the peak takes place at a lower temperature and a drop in the value of angle of internal friction value occurs when the temperature is increased further. It is believed that this turning point is the upper critical temperature for an asphalt mix. Above this temperature the frictional resistance reduces and no longer is the material capable of building a 'better' skeleton. This change in profile, accompanied with low mix cohesion and viscous resistance, indicates that such a material is likely to deform under the action of a roller rather than consolidate. For mixes with 3 percent voids content, the thermal expansion with high bitumen content mixes will reduce the voids content and pressurise the air within the disconnected voids, this will push the aggregate particles apart reducing the points of contact, the mix getting closer to the influence of hydrostatic pressure and leading to a reduction in frictional resistance. For mixes with high voids content and high temperature the mineral aggregate particles will be surrounded by a medium of bitumen in a fluid state, along with air voids. When the material is subject to shear stress the free movement of the binder will create an unstable condition and help in sliding the mineral particles; this will be accompanied by a reduction in the value of angle of internal friction. A further point concerning angle of internal friction with temperature relationships is the apparent reduction in the variation in values of angle of internal friction when the voids content of the mix increased. The variation in value of angle of internal friction depends on the contact points between the mineral aggregate particles which increase when mix temperature increases. When the void content is high, the number of conglomerates inside the mix is low and consequently the number of contact points will be low; the gain in value of angle of internal friction will conseqently be low.

When angle of internal friction is plotted against voids content, Figure 4.4, it is found that mixes with low bitumen content change less than mixes with high bitumen content; this is because a thicker film has a greater response to densification pressure than a thinner film. The same reasoning explains the movement in the peak value of angle of internal friction at 9 percent voids content with mixes of low bitumen content to 6 percent voids content with high bitumen content mixes. It is reasonable that when the volume of bitumen is less than the voids in the mineral aggregate, the mix will form its structure with high voids content and any attempt to reduce the voids content will lead to a degradation of the aggregate particles, but, for mixes with a high bitumen content there is more material to fill the voids and a skeleton will be formed with a lower voids content.

Figure 4.3 shows how the value of angle of internal friction changes with bitumen content. The decrease in value of angle of internal friction when the bitumen content increases is due to the lubrication created by the bitumen; this is seen in many studies using the triaxial technique at lower temperature ranges (45, 53, 69, 70, 71, 74, 101).

c) Data for test series 2

Mixes of this series showed points of agreement and difference with series 1: points of agreement have been explained before. One of the new points raised in this test series is the relationship between angle of internal friction and temperature; individual relationship 'pivot' around a point which corresponds to a temperature of 80°C for mixes with 3 percent voids content, and around 100°C for mixes with 6 percent voids content. Below these temperatures, values of angle of internal friction increase when the filler to bitumen ratio decreases and vice versa above those temperatures, as shown in Figure 4.11. The controversial point is the values of internal friction below the 'pivot point'. At a temperature of 60°C and with mix voids content of 3 percent and 6 percent the presence of filler in quantity and with mixes with low bitumen content the film thickness forms a stiff coating layer around the fine aggregate particles, this is in additon to the intrusion of the fine fraction of the filler adhering to the surface of the fine aggregate producing effectively sub-rounded particles with a 'smooth' surface texture. This factor aids the process of sliding when the mix is subject to compaction pressure. As the bitumen content increases and the filler content decreases (low filler to bitumen ratio) this effect becomes less when the filler content reduces to as little as 0.12 percent of the total ingredients, the effect of the shape and the surface area of the fine aggregate is high enough to give the marginal increase in value of angle of internal friction. This phenomena disappeared when the void content increased. At higher voids content there is not enough internal pressure to develop the coating or boundary conditions around the fine aggregate particles with mixes of high filler content.

Another noticeable point can be seen from the angle of internal friction - temperature relationships. The profile of angle of internal friction for mixes of low void content becomes flatter as the filler to bitumen ratio decreases, or in other words, as the volume of bitumen increases significantly around the fine aggregate particles - which in turn is a result of the increase in the bitumen content and reduction in the filler content. Here the surface area of the mineral aggregate is reduced and consequently the binder film is greatly increased. Such a thick film of bitumen wll be greatly influenced by thermal expansion which works to prevent the physical contact of the aggregate particles when the temperature is raised, or it will help in creating hydrostatic pressure within the system. This effect will prevent the rise in value of angle of internal friction, and more probably decrease it. At high voids content (9 percent and 12 percent) the relationships are similar to those of series 1.

d) Comparison of test data from test series 1 and 2

Figure 4.20 shows that for mixes with the same bitumen content the value of angle of internal friction increases when the filler content of the mix decreases. Also, due to the increase in filler to sand ratio, which was discussed earlier in section 5.2.1, an increase in filler content reduces the value of angle of internal friction. Another point noted from Figure 4.20 is that the angle of internal friction profile for mixes with high filler content are more susceptible to change with temperature than for mixes with a low filler content. This can be explained by the fact that a high filler content means a high surface area and a thinner film of bitumen, this consequently results in a mix exhibiting a greater response to temperature than one with a thicker film.

e) Data for test series 3

In this series three different bitumen penetration grades were used (46 pen, 68 pen and 99 pen), whilst the proportions of all the ingredients were kept constant. Increasing the penetration grade of the bitumen increases the value of angle of internal friction. This is not inconsistent in that a binder with reduced viscosity will displace more readily and allow more intimate fine aggregate particle contact. This is consistent with the effect of temperature.

The relationship shown in Figure 4.23 indicates that the change in value of angle of internal friction is marginal and the profiles are not parallel, in spite of the same mix properties, this may be ascribed to the temperature sensivity of the bitumen. Results of penetration and softening point tests show that penetration indices of the 46 pen, 68 pen and 99 pen bitumens are -0.11, -0.06 and +0.66 respectively. The relationships between angle of internal friction and voids content (Figure 4.24) for this series are consistent with previous ones. However the angle of internal friction profile peaks at around 9 percent voids content at low temperature (60°C) and between 6 percent and 9 percent at high temperature. This phenomena can be explained in terms of two conflicting behaviour patterns. When mix temperature is increased the bitumen viscosity reduces and the lubrication effect reduces, this allows more displacement of the binder which results in more intimate fine aggregate particle contact leading consequently to an increase in value of angle of internal friction. This behaviour conflicts with the reduction in value of angle of internal friction resulting from a degradation of the edges and surface texture of the fine aggregate particles when the mix is subjected to high pressure during the densification process.

Although the effect of bitumen penetration grade on value of angle of internal friction is marginal at a particular temperature, which complies with other work (44, 45, 69, 70), the importance is the profile of angle of internal friction through the change of temperature and voidage. The important feature of this is that the upper critical temperature which decreases when the penetration value of the bitumen increases.

f) Data for test series 4

The use of EVA with penetration grade bitumen increases the viscosity of the binder and makes it less sensitive to temperature change. As the influence of the EVA increases at low mix temperature and decreases at high mix temperature, the value of angle of internal friction shows marginally higher values at 60°C when compared with unmodified mixes. But, as mix temperature increases the value of angle of internal friction between modified and unmodified mixes becomes much closer. The general behaviour of frictional resistance with these mixes is as follows.

i) There is no drop in value of angle of internal friction at high mix temperature, due to the control that the EVA has on the binder flow. However, the profiles suggest the possibility of such a drop at higher temperatures.

ii) At low mix temperature (60°C) a reverse order of the grade profile to that at high mix temperature occurs. The possible reason for this is the effect of crystalization of the EVA. This effect will help the fine aggregate particles enhance the micro-structure of the mixture and enable it to stand firm in resisting sliding.

iii) The use of EVA with penetration grade bitumen generally reduces the temperature sensitivity of the mix, which can be related to the binder itself. The penetration indices of these binders are found to be in the range -2.47 to -1.94 corresponding to the range of unmodified bitumen -0.11 to +0.66.

5.4 DISCUSSION OF THE COHESION RESULTS

Cohesion in bituminous materials can be defined as the property of a material which produces resistance to displacement due to the presence of bitumen and as a result of the packing of the mineral aggregate.

It involves the adhesion between the aggregate and the binder which is caused by the binder effect of cementing together the faces and points of the aggregate, in addition to the interlocking cohesion caused by aggregate packing and densification during a compaction process which is quite different from the performance of an aggregate in a loose condition.

Although the mineral aggregate used in asphaltic mixes is cohesionless in its loose condition, it does produce some cohesion when packed to low voids content. Many researchers report some value ascribed to interlocking cohesion concerning sand sheet asphalt or asphaltic concrete, or granular materials used in the production of bituminous materials (41, 44, 52, 53, 102, 103).

In this study the effect of temperature on the cohesion value of mixes is made explicit. At low mix temperatures the cohesion value of mixes is dominant and results from the influence of the bitumen; at high mix temperatures interlocking cohesion is the dominant characteristic.

a) Test data for the control mix

Generally cohesion values decrease markedly when mix temperature is increased and, or the voids content of the mix is increased.

When mix temperature increases two conflicting behaviour patterns result. First, the cohesion value decreases due to a decrease in the true and apparent cohesion of the mix. The true cohesion reduces as a result of a decrease in the adhesive forces (with decreasing bitumen viscosity), whilst the apparent cohesion results from the thermal expansion of the bitumen layer in contact with the mineral aggregate. Second, the interlocking cohesion is allowed to develop through the increasing role of surface texture. However, the influence of true and apparent cohesion is greater than interlocking cohesion.

Void content is another variable affecting cohesion values. For mixes with low voids content, the binder is a continuous cementing layer and the mineral aggregate particles are in intimate contact with each other; this enhances true and interlocking cohesion. At high voids content the mineral aggregate particles have a discontinuous skeleton, the binder is less effective resulting in low interlocking and true cohesion. But, the apparent cohesion may be higher in mixes with high voids content although this component is small.

b) Data for test series 1

This series was based on different bitumen contents, the range of bitumen content being 7 percent to 11.8 percent. Within this range of bitumen content, and at temperatures below 60°C, it is reported in the literature that cohesion values decrease when the bitumen content increases with asphalt concrete and sand sheet mixes (74, 45, 53, 69, 70, 71, 101).

Figures 4.5 and 4.6 show that cohesion decreases when mix temperature increases, but the rate of decrease is reduced when the bitumen content or void content increases. The cohesion between the bituminous ingredients varies inversely with the thickness of the binder layer between the mineral aggregate. The proportion of filler to aggregate is constant in this series. When the bitumen content increases the cementing effect, and the interlocking effect of the aggregate, is reduced due to the increase in bitumen layer thickness.

The gain in cohesion value when mix temperature drops is also a function of the thickness of the bitumen layer. A thin layer will be more effective in combining the aggregate particles than a thick layer which has a low sliding resistance. Mixes with low bitumen content - thin bitumen layer - show considerable cohesion at high temperature. Two factors work together to produce this interlocking and apparent cohesion. Apparent cohesion is as a result, most likely, of surface tension around contained discrete air voids.

The effect of void content is shown in Figure 4.7. The relationships indicate that interlocking cohesion is more influential with mixes of low bitumen content than with mixes with high bitumen content, due to the effect of the packing of the mineral aggregate. It was noticed that mixes with high bitumen content exhibited a small gain in cohesion value when the voids content of the mix reduced because of a weak aggregate skeleton and bitumen binding effect.

c) Data for test series 2

This series is based on different filler to bitumen ratios. On the whole, mixes with this test series exhibited the same behaviour as test series 1, when looked at from a datum of temperature, bitumen content and voids content, as shown in Figures 4.14 and 4.15.

It was found that the relationship between mix cohesion and mix temperature changed from concave downward, for mixes with a low bitumen content and high filler to bitumen ratio (the normal profile for all mixes), to concave upward for mixes of high bitumen content and almost no filler. The absence of the filler and high bitumen content keeps the cohesion value developing slowly when mix temperature drops due to a weak aggregate skeleton, particularly at low mix temperature when the interlocking cohesion diminishes. The cohesion value of such mixes might be reduced to zero at some elevated temperature or high voidage, because of the lack of effect of packing and the lack of cohesion of the bitumen. Figure 4.16 shows a direct and linear relationship between mix cohesion and filler to bitumen ratio, which emphasises the point that when the bitumen content decreases and filler content increases the film thickness is more able to cement the mineral aggregate particles and provide the lateral confinement to enable the material to resist loading during layer compaction. This effect is greatest when the temperature and void content is low, due to the effectiveness of the bitumen in the narrow channels and pores between the filler and mineral aggregate.

d) Comparison of the data in test series 1 and 2

A selection of mixes from both series are shown in Figure 4.21. It is evident that when the bitumen content remains constant, mixes with a higher filler content have less cohesion than mixes with a lower filler content. This is because the volume of film thickness increases when the filler content increases and the stability of the skeleton of the mineral aggregate is reduced due to the lack of contact between the mineral aggregate particles. This behaviour might be surprising for many researchers who believed that when the filler to bitumen ratio is increased a stiffer mix is obtained. The factor that falsifies this rule is the volume of film thickness which is more effective than the proportion of its ingredients over the range of temperatures of the test. Although the range of bitumen content is the same for both series, the change in the volume of film thickness for test series 1 has a wider range in cohesion values than test series 2.

Another point raised between the two series is that when the bitumen content is equal to 11.8 percent, mixes with 8 percent filler showed a steadier gain in cohesion value than mixes with no filler. Such behaviour might reflect that at a lower temperature than 60°C the effect of the filler to bitumen ratio will reverse. This is another example of the 'exception to the rule', which is that the trend of behaviour of bituminous mixtures at low temperature can be extended to high temperature.

e) Data from test series 3

The behaviour shown in Figure 4.25 and Figure 4.26, which exhibits the effect of the use of a softer grade of bitumen, is that the measured cohesion reduces with grade of bitumen. This arises from the fact that less binder viscosity can be interpreted as less cohesion in exactly the same manner as when bitumen temperature increases. The effect of temperature on the grade is more influential at high temperature. All grades exhibit small differences between each other which reflects the difference in binder viscosity more distinctly; the difference is small, but when the mix temperature drops the difference becomes more distinct. This is in line with reported work at low temperature (25°C) which shows that a 25 percent increase in measured mix cohesion occurs when the penetration value of the bitumen drops from 100 pen to 50 pen (45, 69, 70).

f) Data from test series 4

The modified binder caused a marked increase in mix cohesion, the profile becoming steeper compared with unmodified mixes. The profile of the temperature - cohesion relationship, Figure 4.33, shows a continuous drop in mix cohesion value when the mix temperature was increased, particularly at low void content. The reason is likely to be the change in rheological properties of the binder, such as viscosity reflected in softening point and penetration. The modified mixes with 8.2 percent bitumen content including a 5 percent EVA replacement have a cohesion value higher than with a drop of 1.2 percent in bitumen content when compared with mixes of 7 percent bitumen content of series 2.

The presence of EVA made the material sensitive to temperature change under 100°C, this is móst probably due to the crystalization of the EVA. The relationships between cohesion and void content, Figure 4.34, also show the effect of EVA. At low temperature the adhesive force of the binder is (quite) effective due to the high value of binder viscosity. As a consequence, any increase in the density of a mix generates more cohesion, whilst at high temperatures the adhesive force is weak enough to give small changes in the cohesion when the void content decreases.

g) Comparison between the data for mixes with and without EVA

The effect of the rheological properties of the binder is the important factor in the changes evident in measured cohesion for both series. Mix temperature is a second factor. The effect of EVA is to increase the cohesion, the effect is greater when the temperature is lower. Figure 4.37 shows the effect of modified mixes using 100 pen bitumen . This mix is more sensitive to temperature change than mixes using 68 pen grade, the latter being slightly more sensitive than mixes with 46 pen grade bitumen. This sensitivity is similar to that shown with the angle of internal friction profiles. The effect of the EVA modifier is limited at high temperature but marked at low temperature.

5.5 DISCUSSION OF MIX VISCOSITY RESULTS

The third component of internal resistance is viscous resistance. This component represents the potential ability of a bituminous material to compact. The presence of the bitumen imparts the mix viscosity to a bituminous material. When paving mixtures are deformed highly viscous binders provide the mixture with a viscous resistance, but when this material is subjected to temperature change, the binder will greatly reduce in viscosity and the mix viscosity will subsequently reduce in a high mix temperature. Low bitumen viscosity will give a more important role to the filler and mineral aggregate in determining mix viscosity.

a) The control mix

The mix viscosity shows a concave downward profile with increasing temperature, which is similar to the profile for variation in bitumen viscosity. The rate of decrease in the viscosity of the bitumen is modified by the presence of aggregate, but the magnitude of the mix viscosity change with temperature increases sharply when compared with that of the bitumen as mix temperature drops. The profile of mix viscosity becomes flatter above 80°C, as shown in Figure 4.1. The data indicates that the effect of the viscosity of the bitumen binder reduces as mix temperature increases; the properties of the mineral aggregate regulating the viscous resistance of the mix as the temperature increases further, the effect of the mineral aggregate and filler becomes greater through increasing contact caused by decreasing binder viscosity. Below 80°C the effect of the bitumen increases sharply due to the increase in its viscosity.

An increase in mix voidage reduces mix viscosity as a result of discontinuous planes of sliding and widening of the gap between these planes. This helps in increasing the rate of deformation of a sample, consequently the viscous resistance is reduced.

b) Data from test series 1

The profile of mix viscosity shows three stages as shown in Figure 4.8. The first stage, from 60°C to 80°C, or just below 80°C, for mixes with high bitumen content and above 80°C for mixes with low bitumen content, exhibits a large increase in mix viscosity when the mix temperature drops to 60°C. This comes from the effect of the bitumen in a similar manner to that with mix cohesion and angle of internal friction. The second stage comes after the first one, up to 120°C in case of soft mixes (high bitumen content) or up to 140°C in case of stiff mixes (low bitumen content). The profile of this stage is flat, which results from the decreasing effect of the bitumen through a decrease in bitumen viscosity and an increase in the effect of the aggregate. The loss of the effect of the bitumen is regulated by an increase in the contribution from the mineral aggregate in terms of generating internal shear resistance.

The third stage comes after the second stage. When the mix temperature is raised the soft mixes exhibit a tendency for a noticeable drop in viscosity. This critical temperature for an asphalt mix is in agreement with drop in angle of internal friction which is caused, it is believed, by the effect of the thermal expansion of the bitumen layer, and the potential of the bitumen to displace in aggregate. This increases the rate of deformation and decreases mix viscosity.

The effect of bitumen content on mix viscosity is a reflection of the thickness of the bitumen layer, as shown in Figure 4.9. When the bitumen content is increased the thickness of the bitumen film is increased and the amount of sliding across internal planes is increased, consequently the viscosity of the mix is reduced.

The void content of a mix has less effect on mix viscosity as shown in Figure 4.10, particularly at high mix temperature or high bitumen content. The reason for this is that as the bitumen layer becomes thicker the mineral aggregate is kept apart reducing the sliding resistance, regardless of the volume of the voids. Mix densification has a marginal effect on mix viscosity as long as the contact between the particles is low.

c) Data from test series 2

The three stages of the profile of mix viscosity versus temperature is quite clear in this test series as shown in Figure 4.17. Stage three of this profile is more recognisable and a precursor of an unstable mix, marked by an upper critical temperature. This behaviour again endorses the behaviour of the angle of internal friction. This undoubtedly forms a bench mark for the internal resistance of a mix. It was found that the turning point in the profile of mix viscosity took place at a lower temperature when filler to bitumen ratio decreased. For mixes with a filler to bitumen ratio of 0.01 the turning point started around 100°C to 110°C. As the ratio of the filler to bitumen increases the turning point temperature increases.

It is quite important to take this upper critical temperature into account when such mixes are subject to loading as occurs during the compaction process, the second stage possibly shows the range of temperature for which the material maintains its viscous resistance with little change. This is possibly a sign of a workability range, before and after this stage either the material is unstable and will deform readily ahead of the roller, as in stage three, or the viscous resistance increases significantly which limits the chances of compaction, as in stage one. This series highlights the effect of the filler. When the filler content decreases the surface area of the mineral aggregate reduces and subsequently the thickness of the bitumen layer increases, this reduces the sliding resistance of a mix.

Relationships between void content and mix viscosity for this test series, shown in Figure 4.18, are not much different from the case with test series 1. The profiles of test series 2 are flatter than those in test series 1 - which are as a result of a constant volume of film thickness. It is natural for an increase in filler to bitumen ratio to increase the values of mix viscosity where the presence of the filler stiffens the film thickness and increases the resistance to sliding across internal planes of movement within a mix.

d) Comparison of data with test series 1 and 2

When selected mixes from test series 1 and 2 are compared as in Figure 4.22, it is seen that mixes with higher filler content exhibit a lower mix viscosity compared with mixes with lower filler content. It is believed that when the bitumen content is constant any increase in the filler content will reduce the viscous resistance by increasing the volume of the mastic between the mineral aggregate; this has a significant influence on sliding resistance. The filler particles will facilitate the turning over of the larger mineral aggregate particles, by acting as an intermediate 'wheel' between the larger particles, at the same time reducing the interlocking between the fine aggregate (larger mineral aggregate) particles. Here again, as with mix cohesion and angle of internal friction, the effect of the geometry of the micro structure of an asphalt mix at high temperature is more effective than the quality of the mastic between the aggregate structure or skeleton.

e) Data with test series 3

The decrease in mix viscosity with increasing penetration grade of bitumen is in agreement with the fact that the bitumen provides the basic viscous resistance to a mix, as shown in Fiure 4.27 and Figure 4.29. Although the differences in mix viscosity are small between different basic penetration grades of bitumen it is enough to provide a 10°C to 20°C difference between profiles for the same mix viscosity with any two consecutive grades of bitumen at high temperature. This is important when an upper critical, or compaction temperature is required to be defined.

Mixes in this test series have an equal percentage of all ingredients, even bitumen; the only difference between mixes is in the type of binder. It was quite useful to use these mixes to show the effect that the mineral aggregate and filler have on mix viscosity. Figure 4.30 shows that the ratio of mix viscosity to binder viscosity increases when mix temperature and/or the softness of the binder increased. This emphasises the role material ingredients have on the behaviour of an asphalt mix during layer compaction and which cannot be determined though low temperature testing, even using a fundamenntal procedure.

f) Data with test series 4 (effect of EVA)

The use of EVA increases mix viscosity sharply; mixes with 8.2 percent modified binder content had more viscous resistance than mixes with 7 percent unmodified bitumen content using the same penetration grade bitumen (46 pen).

Mixes with 68 pen modified bitumen show greater mix viscosity than those with 46 pen unmodified bitumen. However, mixes with 100 pen modified bitumen may be considered equivalent to those made with conventional 46 pen bitumen.

The modified mixes show high sensitivity with temperature, particularly when mix temperature drops below 100°C as shown in Figure 4.35. This is likely to be due to the crystalization of EVA; it is reported (104, 105) that additive stiffness develops rapidly as the EVA crystalises. This process occurs below 100°C with the type of EVA used (UL 15019); this type of EVA is widely used in the U.K. Furthermore it is stated that a rapid drop in workability was observed through field experiments and experience (105); such behaviour might provide a lower limit for compaction temperature.

It is very important to report two atypical behaviour patterns noted whilst measuring mix viscosity with this test series. First, the relationship between viscous resistance (dynamic cohesion) and the rate of deformation is not a straight line as for other test series. This shows a tendency toward a concave upward profile when the rate of deformation increases, particularly at 10mm/min. This may be attributed to the shear susceptibility of the mixes due to the presence of EVA, which means that at any stage of compaction with high rates of strain, such mixes would not necessarily develop a high viscous resistance, as with the other series.

Secondly, some time delay was noticed between the time of opening the bleed valve to reduce the confining pressure and the time at which the mix responded to the drop in confining pressure by deforming. This means that some time is required by the roller at any point to cause material movement at the point. Too fast a rolling speed may result in little internal movement.

g) Comparison of the data with series 3 and 4

The difference between these series is only the presence of 5 percent EVA. It can be seen from Figure 4.37 that the effect of EVA is greater with the lower pen grade bitumen and more effective when mix temperature drops. It seems that with 99 pen bitumen the effect of EVA is almost negligible at high mix temperature, which is quite important when workability is required. As mix temperature drops a considerable rise in viscous resistance occurs. It is reported that EVA improves workability when used with soft penetration grade bitumens but at the same time maintaning higher stability at service temperature (106). This is consistent with the data reported here.

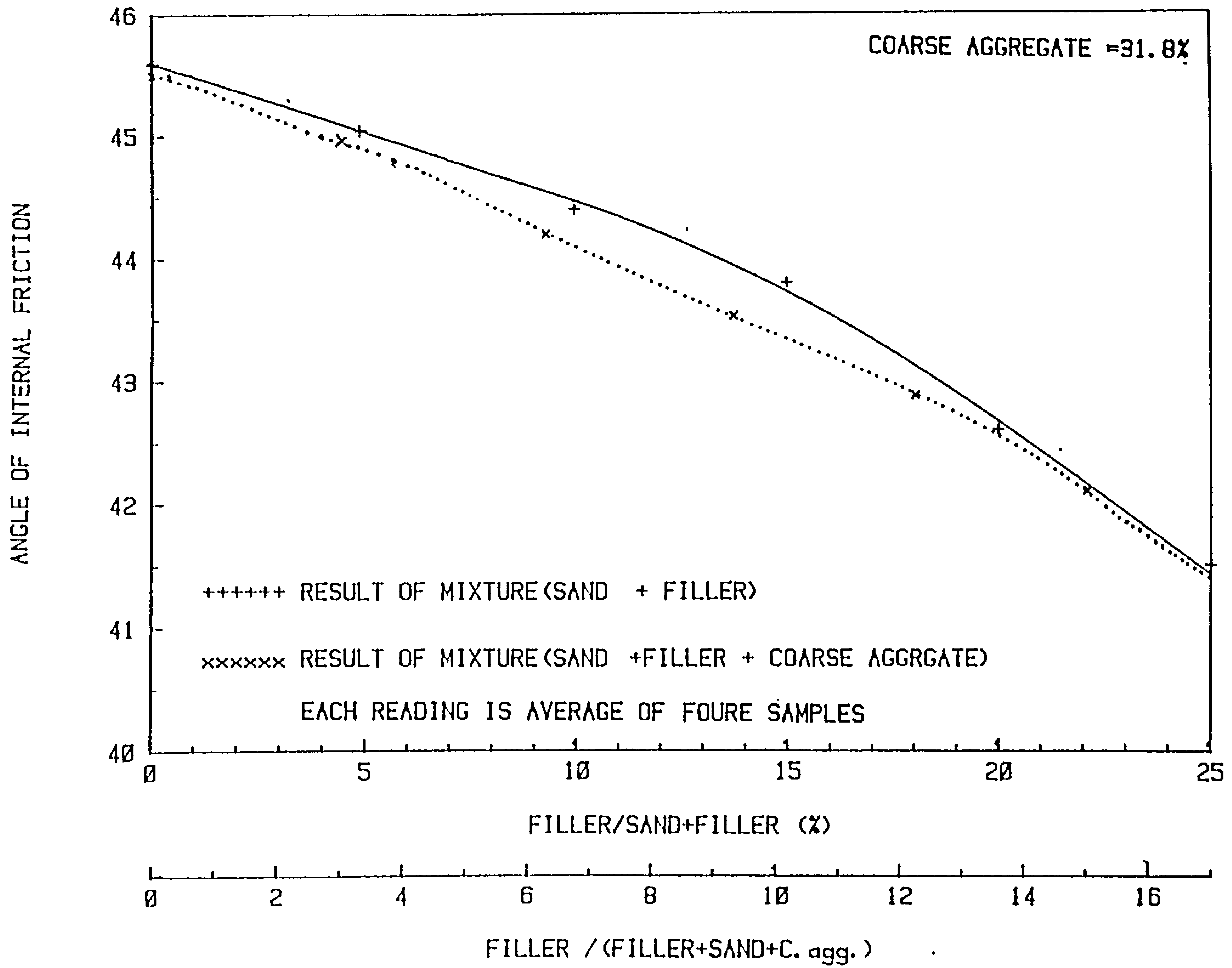


FIGURE (5-1) ANGLE OF INTERNAL FRICTION VERSUS FILLER PERCENTAGE

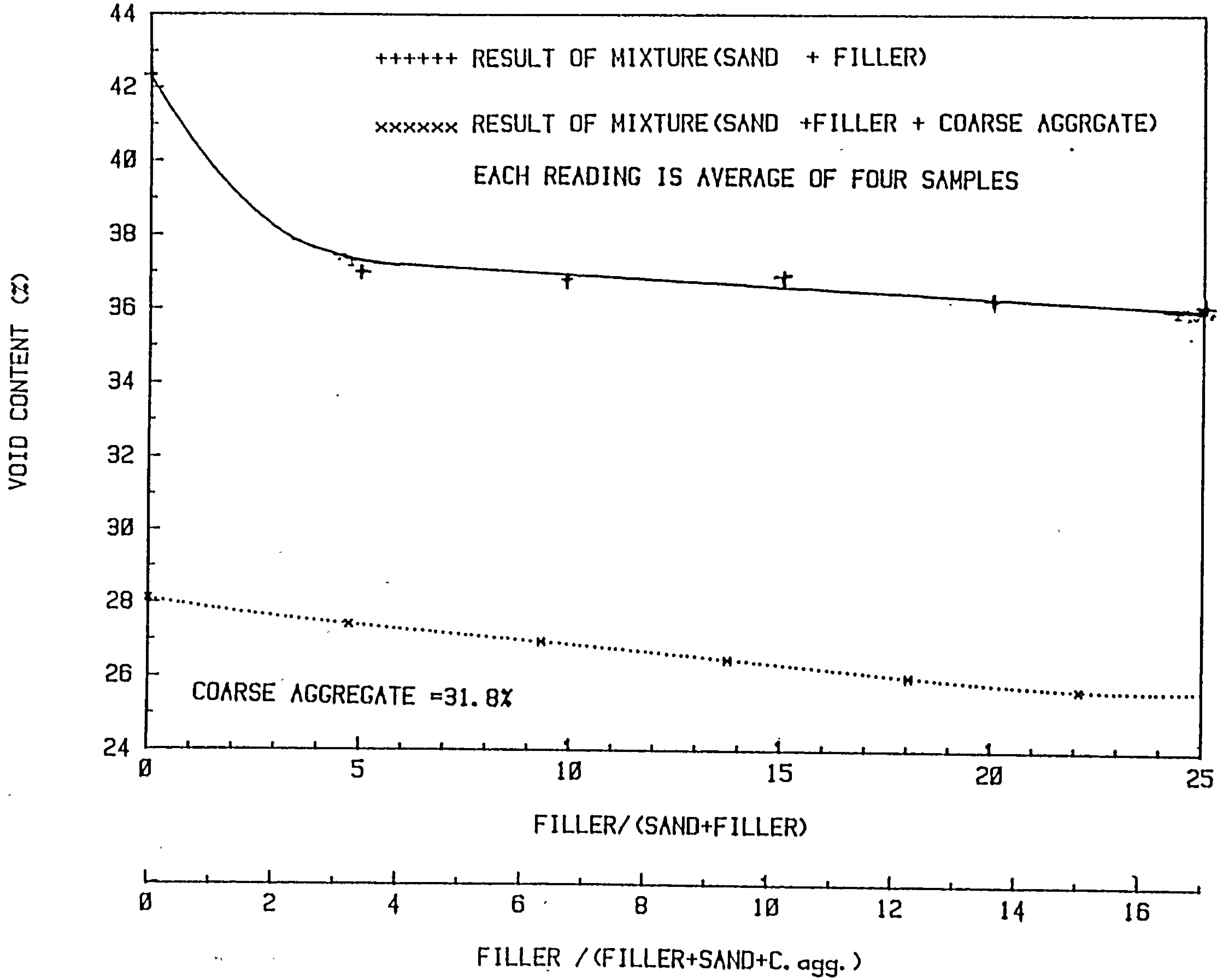


FIGURE (5-2) VOID CONTENT VERSUS FILLER PERCENTAGE

PLATE [5-1] CRUSHED LIMESTONE FILLER 93.5% PASS 0.075 MM SIEVE

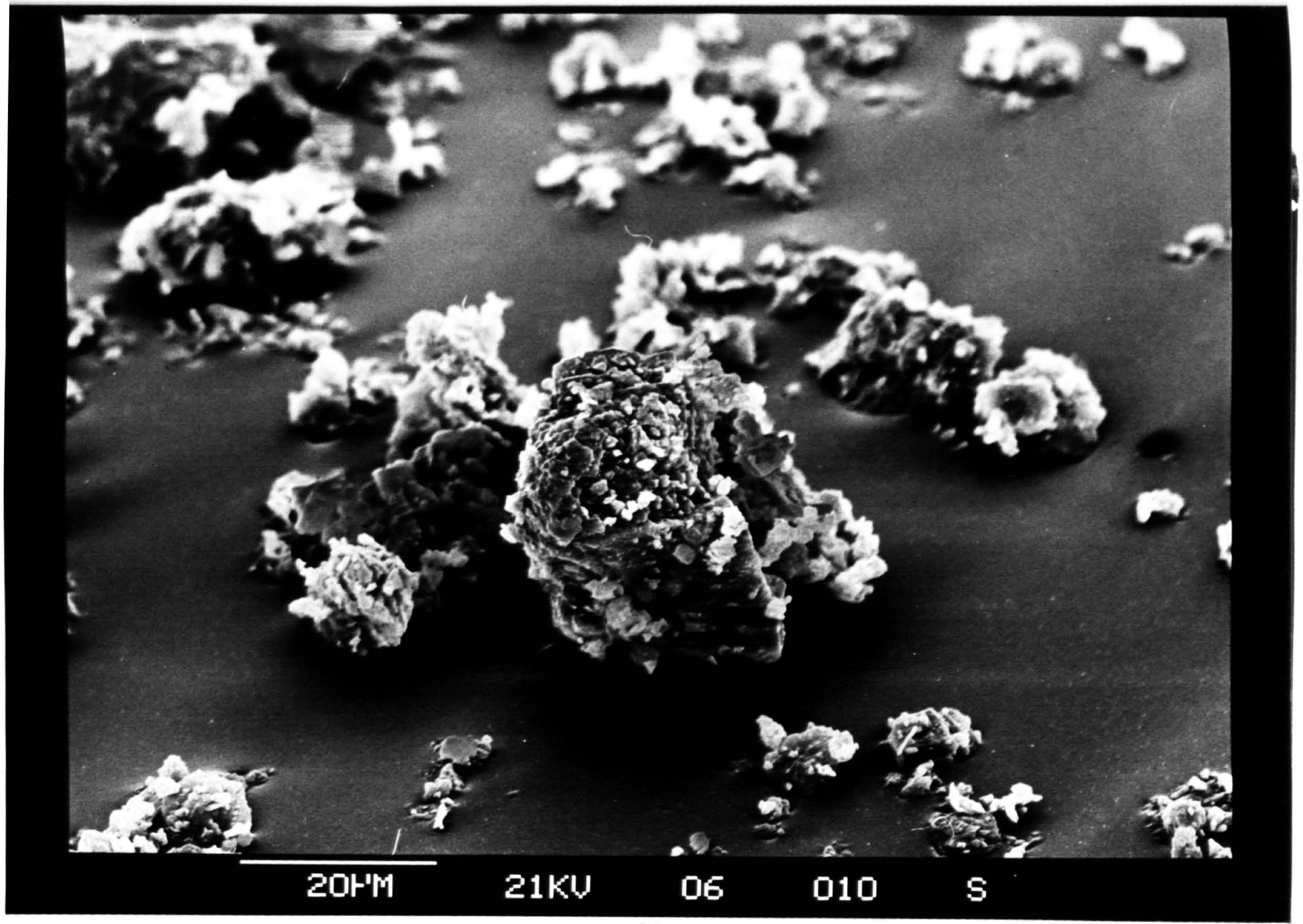


PLATE [5-2] CRUSHED LIMESTONE FILLER 93.5% PASS 0.075 MM SIEVE

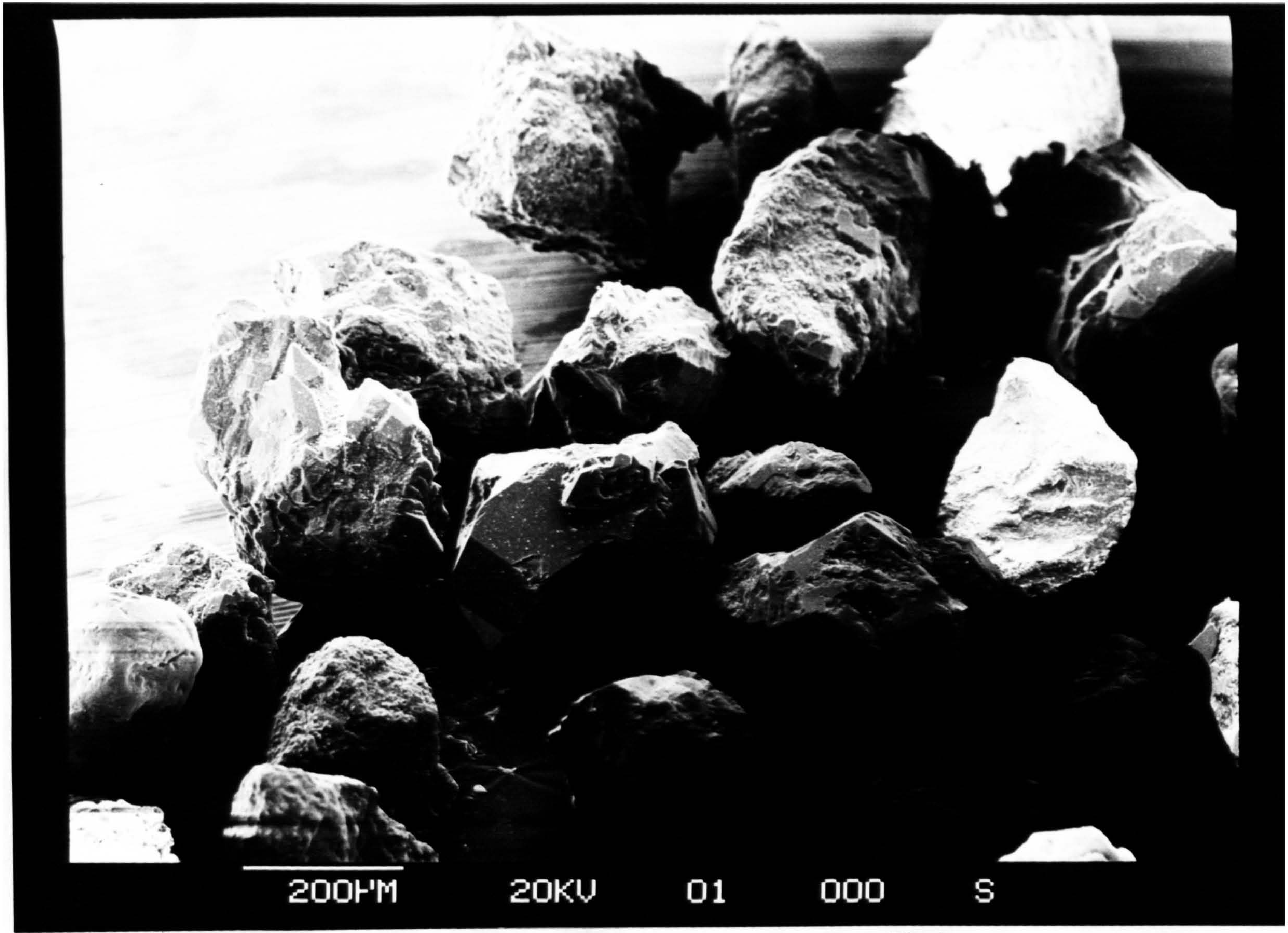


PLATE [5-3] SAND PARTICLES USED WITH MIXES OF SERIES 1 TO 4
PARTICLES SIZE (0.15 TO 0.3 MM)

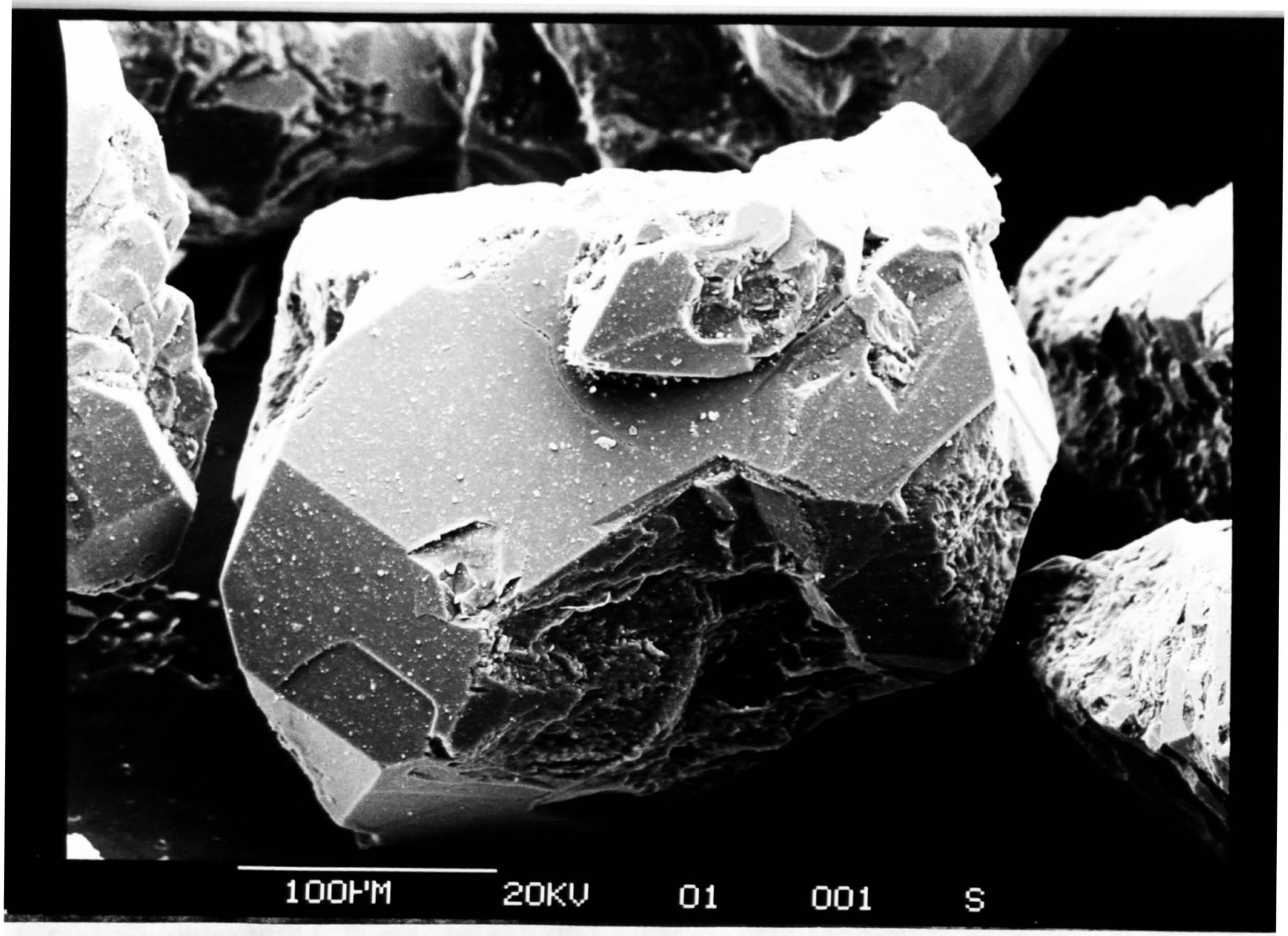


PLATE [5-4] SAND PARTICLES USED WITH MIXES OF SERIES 1 TO 4

PARTICLES SIZE (0.15 TO 0.3 MM)

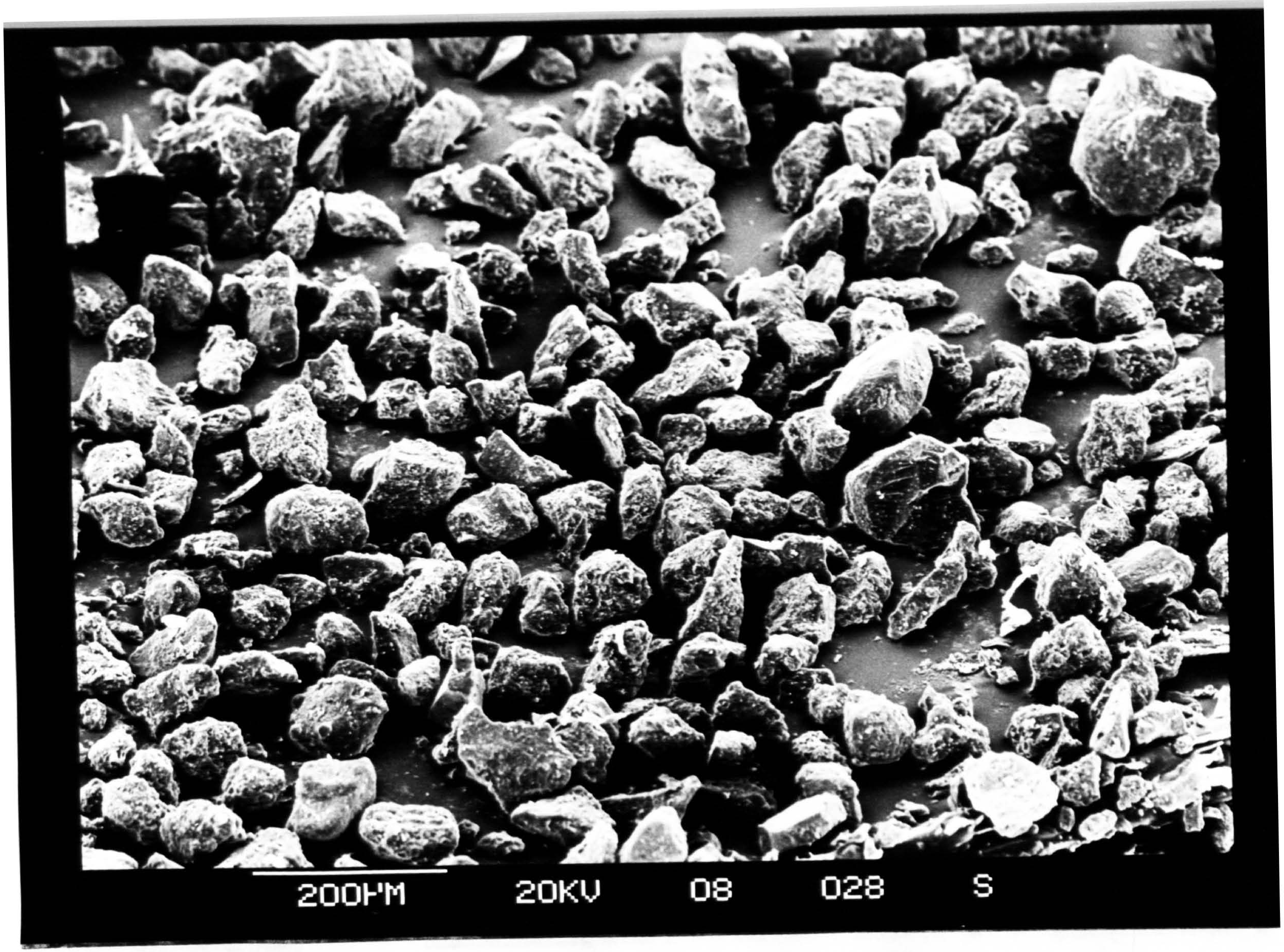


PLATE [5-5] SAND PARTICLES USED WITH MIXES OF SERIES 1 TO 4

PARTICLES SIZE < 0.075 MM

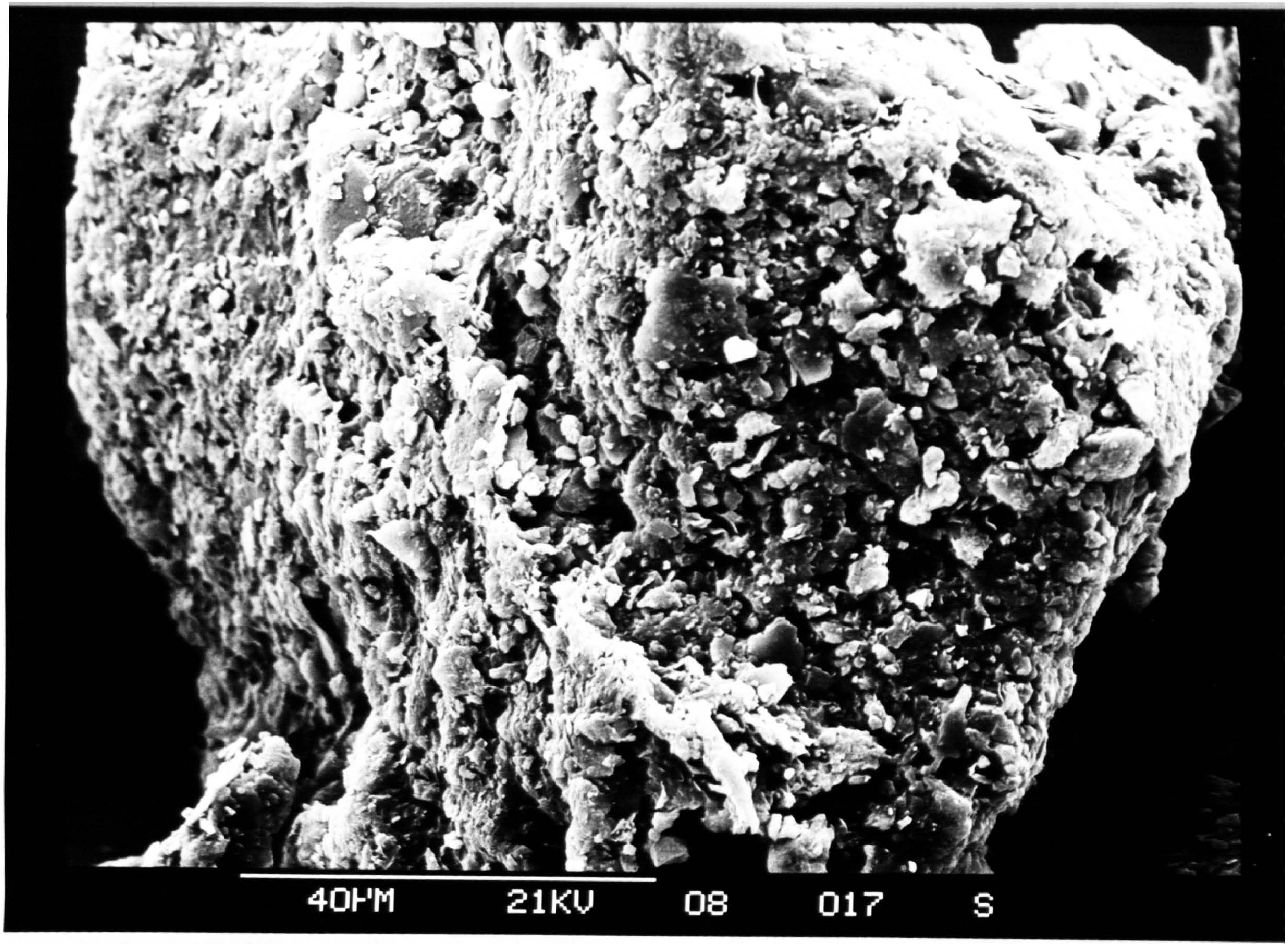


PLATE [5-6] SAND PARTICLES USED WITH MIXES OF SERIES 1 TO 4
PARTICLES SIZE < 0.075 MM

6.0 COMPACTION DATA AND DISCUSSION

6.1 INRODUCTION

The significance of the laboratory rolling programme comes from the fact that the rolling stage is the ultimate process of the compaction with an asphaltic layer. Many factors influence the behaviour of bituminous materials when they are subject to the action of a steel roll. Material ingredients are the key factor which will influence the performance of a mixture under the action of a steel roll. For a material, temperature and number of the roll passages are critical to layer densification.

There is a form of 'equilibrium' between the internal resistance of a material and the pressure exerted by a roll. The nature of this 'equilibrium' will lead to deformation which will result in the consolidation of a material layer. The triaxial test offers a fundamental evaluation of the components of resistance to internal movement (angle of internal friction, mix cohesion and viscous resistance) with an asphalt mix; the components can be related to the rolling process. However theoretically, the rolling process may result in three different types of deformation. The first and most important of these deformations is the method by which the material is compacted through rolling. This deformation is of a plastic character so that the form of the material changes permanently. This is attended with a decrease in the voidage of the material. The second type of deformation may not result in a decrease in the voidage of the material layer; here the material flows at constant volume. This means that the voidage remains constant but the form of the material changes, so that in this case unevenness of the surface of the layer may occur. Finally, there is a possibility that owing to the rolling forces acting on a material it is deformed but this deformation is of an elastic character. In this case the voidage and the form of the material layer will be unchanged after the surface contact pressure is removed (59).

The individuality of any of the three types of deformation may not be the case during a particular rolling process. The possibility of a combinaton of type of deformation is very high.

Mixes exhibit a plastic deformation when the exerted pressure from a roller is higher than the components of internal resistance, and the deformation tends to consolidate the material and decrease the voids content of a layer.

Mixes with low resistance to internal movement , possess a combination of plastic and flow deformation which will turn the potential of the rolling action into a limited reduction in voidage accompanied by surface unevenness.

Elastic deformation may be included in all rolling of asphaltic materials. However, it is likely to dominate the case when the pavement has low workability or the voidage of the material is very low as a consequence of a large number of roller passages.

6.2 LABORATORY ROLLING DATA

In this study a laboratory rolling programme was followed in an attempt to simulate the compaction process through different number of roller passages and material temperature combinations. A full scale roller in terms of weight per unit width, diameter and speed of roll was used to compact slabs of material 300mm by 300mm by 40mm; the slab represents an area of wearing course. The rolling programme was carried out on all four material variations used in the triaxial programme and discussed in chapter three. For each mix samples were rolled with six different number of roller passages: the roller passages were 1, 3, 6, 9, 12 and 18. Samples were rolled, for each number of roller passages, at six different temperatures: 60°C, 80°C, 100°C, 120°C, 140°C and 160°C. A total of 36 determinations of compaction were made for each mix variation used.

Each compaction assessment made for one temperature and roller passage combination was done so using only one slab, but at the beginning of the testing programme the control mix was used to assess repeatability and establish a level of confidence and consistency in slab production and testing. Although only data from single slabs were used in the main programme, multiple slabs were prepared to allow for data rechecking. Each roller passage was represented as a forward and reverse action on the slab. The slabs in the main programme were compacted without applying chippings. This was done for the principal reason that in an earlier study (6) it was found that the material layer below chippings controlled the slab response to the action of a roller and chipping embedment; below the chippings slab performance can be represented by an unchipped slab. Other factors behind that decision to use unchipped slabs can be found in section 3.4.2.

All samples were prepared with an initial voids content of 12 percent (∓0.5 percent) and the results after rolling were expressed as a percentage of maximum theoretical density described as Percentage Compacting Factor (PCF) and defined as follows,

$$\text{PCF} = \frac{\text{compacted slab density}}{\text{max. theoretical density}}$$

by definition PCF = 1- voids content

The results highlighted many important points concerning material ingredients. For example, it appears that there is an upper critical temperature for an asphaltic mix, and therefore (potentially) an optimum compaction temperature for a mix. This temperature is influenced by three specific parameters: bitumen content, filler to bitumen ratio and penetration grade of the petroleum bitumen. The upper critical temperatures defined were found to be in close agreement with these defined from the triaxial programme.

The results of the rolling programme were plotted as relationships between Percentage Compacting Factor, and temperature, as shown in Figures 6.3 to 6.8, and Percentage Compacting Factor and number of roller passages, as shown in Figures 6.9 to 6.14. Also, relationships established between Percentage Compacting Factor and bitumen content and Percentage Compacting Factor and filler to bitumen ratio are plotted in Figures 6.15 and 6.16 respectively. All of the relationships were obtained by testing unchipped slabs. However, a secondary rolling programme was carried out on chipped slabs relating to all mixes of triaxial test series 1 and 2. The results of chipped samples are plotted in Figures 6.17 to 6.19. These results are for 18 roll passages. The Figures show the relationships between Percentage Compacting Factor values and temperature for the whole layer and Percentage Compacting Factor for the top sub-layer (between the chipping) and the bottom sub-layer (under chipping).

6.3 EFFECT OF TEMPERATURE ON LAYER COMPACTION

Temperature is an important factor influencing layer compaction. It influences the values of the components of internal resistance as shown with results of angle of internal friction, mix cohesion and mix viscosity from the triaxial programme. Many researchers define the rolling of an asphaltic mix as a means of an applying pressure and kneading action so that internal shear and subsequently compaction will occur. The roller deforms the hot asphalt layer until the contact area is large enough to reduce the contact pressure of the roller wheel to approximately that sustainable by the internal resistance of the mix. As the roller moves forward horizontal shear forces develop and decompaction occurs in front of the roll, accompanied by a minor decompaction of material at the rear of the roll, as shown in Figure 6.1. Compaction and a reduction in voidage occurs as a roll passes directly over the mix (107, 108).

Compaction takes place when the exerted surface pressure is greater than the initial internal resistance (mix cohesion and friction resistance) of the asphaltic layer, then, subsequently the viscous resistance comes into effect. As long as the viscous resistance is low more deformation takes place leading to more densification (44, 52, 53, 109. 110, 111). This appears to be an optimum case in which the internal resistance permits maximum compaction to occur.

Depending to the mix ingredients (bitumen and filler content, type of binder and the properties of the mineral aggregate), two extreme conditions may occur: a mix may have so high an internal resistance that negligible compaction takes place with a given roller, the roller rides on such a mix so that no reduction in layer voidage occurs (as shown in Figure 6.2); at the other extreme the mix can have such a low internal resistance that it cannot support the weight of the roller, the material layer deforms excessively resulting in surface cracking, again there is no reduction in layer voidage (107).

Mixes used in this study covered the range between the above two extreme cases. However, in the light of triaxial cell data an explanation can be made for those cases. When the exerted surface pressure by a roll exceeds the frictional and cohesion resistance, and layer compaction takes place controlled by the viscous resistance, the contact area under the roller will develop a lateral stress within the material layer, particularly in the direction of movement of the roll, but also in the reverse direction. The magnitude of the lateral stress will be a fraction of that exerted vertically. This will lead to one of two situations. Either the material ahead and behind the roll which confines the material directly below the roll has enough reaction (cohesion and frictional resistance) to provide a state of equilibrium which will lead to consolidation of the material below the contact area, by inducing some shear strain that will reduce the voids content. Or, the surrounding material has low initial resistance, unable to resist the material stress, coming from material below the contact area, and this will lead to a deformation of the material principally ahead of the roll causing the material deformation (a bow wave) and resulting in less consolidation of material under the roll (2, 4, 21, 109, 111, 112, 113). As the lateral stress increases deformation increases, the disturbance causes waviness, shoving the material under the wheel achieves no densification.

If the initial resistance of any mix at any temperature is greater than the applied surface pressure caused by the roll, no strain will take place and no lateral deformation will occur. This case is described as 'under stress'.

6.3.1 Data and discussion for material relating to test series 1

Mixes with 7 percent bitumen content in this series show that at low temperature and one roller passage mixes a small response to the action of the roll was exhibited, as shown in Figure 6.3. This was the consequence of too high a resistance to internal movement. Even when the temperature of the layer was increased only a marginal improvement in the Percentage Compating Factor was obtained. This case represents the situation of high internal resistance to movement; the applied load requires more time to introduce noticeable internal shear strain within a material layer. When the number of roller passages is increased a noticeable reduction in layer voidage was noted, due to more shear strain taking place and that strain transferring from elastic to plastic in character. However, these mixes (7 percent bitumen content) have a higher voids content than other mixes. This is due to low workability which is represented by high frictional cohesion and viscous resistance.

When the bitumen content of a mix is increased (increasing the volume of film thickness), the internal resistance components (cohesion, frictional and viscous resistance) decreases, this induces more consolidation and a significant decrease in the voids content of a layer represented by an increase in the Percentage Compacting Factor value. As the bitumen content and/or mix temperature is increased further, more densification takes place. But, when the mix temperature is increased to 160°C, or 140°C for mixes with high bitumen content, a reduction in layer densification occurs, or there is a decrease in the value of Percentage Compacting Factor. This behaviour is the result of low resistance to internal movement which leads to high lateral deformation of the material layer under the action of the roll rather than layer compaction. This happens because of a lack of confinement (reaction) provided by the material around and below the roll.

It was noted that there was a drop in the value of Percentage Compacting Factor which occurred at 120°C for mixes with 11.8 percent bitumen content, and even below this temperature for a lower number of roller passages.

These temperatures confirm the suggestion of an upper critical compaction temperature, a temperature beyond which no improvement in layer density can be achieved. On the contrary a drop in layer density may take place due to decompaction. The upper critical temperature increases the bitumen content of a material decreases. Mixes with a bitumen content as low as 7 percent exhibited an upper compaction temperature as high as 150°C to 160°C.

For the same reasons which lead to an upper compaction temperature for a material, compaction data reveals an upper bitumen content (for this particular aggregate) of around 10.6 percent, as shown in Figure 6.15. When the bitumen content increases beyond this value no improvement in Percentage Compacting Factor value occurs, in fact a fall in the value was recorded. This is more evident at high temperatures.

6.3.2 Data for material relating to test series 2

Mixes with this series showed some similarity in behaviour to the mixes of test series 1, as shown in Figure 6.4. The values of Percentage Compacting Factor exhibit an increase when the filler to bitumen ratio decreases, which is in line with the evidence of the variations in components of internal resistance. This series showed that the bitumen content had less influence compared with the mixes of test series 1. This is the result of a constant volume of film thickness for all mixes with this test series.

The data shows the effect of temperature increase when the filler to bitumen ratio increases, or in other words, the bitumen content decreases. This means a thin layer will be more sensitive to the temperature than a thick one. Again this is in line with patterns of angle of internal friction, mix cohesion and mix viscosity with temperature.

The upper limit of compaction temperature is reduced significantly when the filler to bitumen ratio is reduced. For mixes with a filler to bitumen ratio of 1.56 the upper temperature limit for temperature is around 160°C; this critical temperature is reduced to about 100°C when the filler to bitumen ratio has a very low value, around 0.01. The value of Percentage Compacting Factor peaked at a filler to bitumen ratio of 0.26. However, there is no significant improvement in Percentage Compacting Factor value when the filler to bitumen ratio drops below a value of 0.6, particularly at high mix temperatures, as shown in Figure 6.16.

6.3.3 Comparison of data between the mixes relating to test series 1 and 2

Comparison was made between Test Series 1 and Test Series 2 by superimposng profiles of selected mixes (extremes) from both Series, along with the profile for the control mix, as shown in Figure 6.5. It is found that mixes with the same bitumen but different filler content exhibit clear differences in Percentage Compacting Factor, or compacted density. Mixes with higher filler content exhibit higher Percentage Compacting Factor values compared with those with less filler. This is in agreement with the results of internal resistance component data which show that mixes with higher filler content, but the same bitumen content, exhibit a lower angle of internal friction value, lower cohesion value and lower mix viscosity value, as shown in Figures 4.20, 4.21 and 4.22, compared with those mixes with lower filler content. This lower resistance to internal movement results in greater internal shear strain required to be induced, and therefore a greater reduction in voids content, so that the Percentage Compacting Factor value is increased.

Both Test Series show an upper limit for compaction temperature which is dependent on the properties of material ingredients; the upper limiting temperature increases as the resistance of the mix increases.

Both Test Series show a decrease in the internal resistance components, but this does not infer an increase in Percentage Compacting Factor value. It appears there are limits for bitumen content or filler to bitumen ratio, and there is no improvement, or drop in Percentage Compacting Factor value when these limits are exceeded with that particular mineral aggregate. The effect of the volume of film thickness is significant in influencing the Percentage Compacting Factor value. Although both mixes have a range of bitumen content, from 7 percent to 11.8 percent, mixes of Test Series 1 which have a particular range of film thickness, exhibit a wider range in value of Percentage Compacting Factor compared with mixes of Test Series 2, which have a constant volume of film thickness.

6.3.4 Data from material relating to Test Series 3

Figure 6.6 shows the relationships between Percentage Compacting Factor and temperature. There is a marginal increase in Percentage Compacting Factor value when the penetration value of the bitumen is increased. The difference between mixes decreases when a higher number of roll passages are applied. However, all mixes peak at approximately the same value of Percentage Compacting Factor, but at different temperatures. These temperatures represent the upper critical compaction temperature, which reduces as the penetration value of the bitumen increases. Changing the type of the bitumen alone and keeping all other ingredients and ingredient proportions constant will improve the Percentage Compacting Factor value but only at a low number of roller passages, whilst at a higher number of roll passages there is a possibility to compact at lower temperature by using a softer grade of bitumen to achieve a similar voidage content for mixes made with a stiffer bitumen and compacted at a higher temperature.

6.3.5 Data from material relating to test series 4

Mixes made with the modified binder [5 percent EVA replacement] exhibit a continuous increase in Percentage Compacting Factor value when the mix temperature or number of roller passages are increased. This series of mixes did not indicate any upper critical compaction temperature, but the profile of the relationships between Percentage Compacting Factor and temperature, as shown in Figure 6.7, shows an asymptotic trend at high temperature, suggesting an upper critical temperature at some higher temperature (above 160°C).

The modified mixes have a higher Percentage Compacting Factor value than that expected in light of the values of the components of internal resistance, particularly at a higher number of roll passages when compared with unmodified mixes which have similar, or even lower internal resistance. For example, modified mixes with 8.2 percent bitumen content using a 46 pen + 5 percent EVA replacement show significantly higher mix cohesion and mix viscosity values, and a slightly reduced angle of internal friction value compared with mixes made with 7 percent bitumen content in Test Series 1 or 2. The expectation would be that the Percentage Compacting Factor value would be much less for mixes made with 7 percent bitumen content of Test Series 1 and 2. The reason behind this apparent anomolous performance may come from the points raised in the discussion of the triaxial cell data with modified mixes in Chapter Five. The points relate to the shear susceptibility of the modified mixes exhibited in the time delay in response to a reduced cell pressure condition when measuring mix viscosity.

Shear susceptibility is signified apparently when the relationship between the cohesion value and rate of deformation is not a straight line, such as shown by other unmodified mixes. By taking the relationship as linear this over-estimates the true value of mix viscosity. The interpretation of this is that at high rates of shear (such as above 10^{-3} sec^{-1}) the viscous resistance is not increased as it would be with unmodified bitumens. The other factor concerning the time delay is the continuous reduction in void content (increase in Percentage Compacting Factor) when more roller passages are applied. This time delay may be significant if vibrating rollers are used for layer compaction. However, the use of EVA as a modifier did not improve workability even when a high penetration bitumen grade was used. Mixes with 68 pen + 5 percent EVA were not found to match the equivalent mix made with unmodified 46 pen bitumen as many investigators believed (105, 106, 114). It appears after the first pass of the roll that there are distinct differences between modified mixes and unmodified mixes, in spite of all the ingredient and ingredient proportions being the same, as shown in Figure 6.8. When the number of roll passages is increased, the differences between these mixes decrease and when 18 roller passes have been applied, mixes with 99 pen + 5 percent EVA are found to be closer in performance to those made with a straight 46 pen bitumen, the control mix. This is consistent, to some extent, with triaxial test results. It may be concluded that an EVA replacement to a bitumen may enhance stability and workability only by increasing the bitumen content with modified mixes, unless this is done, it may be that the EVA is not helpful as far as the compaction process is concerned.

6.4 COMPACTIBILITY OF HOT ROLLED ASPHALT

Many studies have been conducted to evaluate the compactability of bituminous materials. Some of these studies were carried out using the Marshall compacter as a tool; compactability being assessed by applying different compaction effort through a variable number of hammer blows (31, 32, 34, 115). This method compacts materials at one temperature, 60°C. A number of hammer blows cannot represent the action of a roller (in terms of type of loading) and the influence on the distribution of bitumen coating the mineral aggregate and filler. Also the wall effect of the Marshall mould has a potentially significant effect on the compaction procedure.

Other work has used a full scale roller, and different types of bituminous material have been assessed. Geller (110, 115) reported a typical compaction curve showing that mix density peaks at three roller passages. On the other hand, many other researchers have reported that layer density continues to increase, or layer void content continues to decrease, without any sign of decompaction when the number of roller passages is increased up to 13 passages, as reported in references (108, 117, 118, 119, 120) around 40 roller passages, as in references (122, 123, 124, 125, 126), and up to many hundreds of roller passages when a laboratory roller is used (126).

Other field studies have shown, in a few cases, that relationships between pavement layer density and number of roller passages have a peak point followed by a drop in layer density when the number of roller passages are increased (127, 128, 129). This peak point appears to lie between six to eight roller passages. Most of the cases of reduced pavement density, are caused apparently by over-compaction, but they lie within experimental error. Schmidt et al (108), for example, suggests that the decrease in pavement density that he measured after a particular number of roller passages [and which depends on the weight of the roller] did not actually show reduction, in spite of his field results.

Most of the studies carried out with a full scale roller did not incorporate any temperature control. Compaction was started immediately after the paver laid the material. The material temperature during compaction ranged from as high as 171°C, after laying, down to ambient air temperature as rolling proceeded (108, 118, 119, 120, 126, 127, 128, 129). Other groups of investigators carried out rolling at one temperature, such 100°C to 110°C (121, 125) or at a range of temperatures, 60°C to 100°C (117), and 85°C to 130°C (122, 123). All rolling trials used dense macadam, as a roadbase or a basecourse. There have been no definitive studies of the influence of different temperatures on the compactibility of hot rolled asphalt.

6.4.1 Discussion of data with material in Test Series 1 and 2

Figures 6.9 to 6.11 identify the influence of the number of roll passages on hot rolled asphalt over a series of controlled temperatures when the bitumen content and filler content is varied.

It is found that those mixes with high internal resistance continue to give an increase in Percentage Compacting

Factor with an increase in number of roll passages, as exemplified with the profiles of mixes made with 7 percent bitumen content. As the bitumen content increases the rate of increase in value of Percentage Compacting Factor decreases. Mixes with high bitumen content show the most compaction within the first or first few roller passsages. Such behaviour is found with the mixes in both Test Series 1 and 2.

The effect of filler is distinct in the mixes of Test Series 2: as the filler to bitumen ratio decreases layer compaction is completed within the first few roll passages.

The volume of film thickness not only influences the value of Percentage Compacting Factor in terms of its numerical value, its quantity, but also by its quality. When the volume of film thickness increases a mix becomes more compactable, as is the case with Test Series 1, which exhibits a wide range of Percentage Compacting Factor, compared with mixes of Test Series 2, which have a constant volume of film thickness.

In order to clarify this, a selected number of mixes from both Test Series 1 and 2 were plotted as shown in Figure 6.13. The Figure shows clearly that bitumen and filler content both increase the value of Percentage Compacting Factor over all ranges of temperature and all numbers of roll passages. Mixes with the same bitumen content produce a higher Percentage Compacting Factor value when the filler is increased. This is consistent with triaxial data, whilst the mixes with a high filler content show a low angle of inernal friction, low mix cohesion and low mix viscosity.

6.4.2 Discussion of data with Test Series 3 and 4

The effect of bitumen penetration grade is to impart a parallel profile between the Percentage Compacting Factor values and number of roller passages when three different penetration grade bitumens (46, 68 and 99 pen) are used. The differences in Percentage Compacting Factor values when unmodified bitumen were used was marginal when compared with those mixes with the same penetration grades of bitumen but modified with EVA, as shown in Figures 6.12 and 6.13.

The use of EVA appears to reduce the compactability of mixes, particularly during the early passages of the roller. Mixes with 46 pen + 5 percent EVA were found to be less compactable than those made with 68 pen + 5 percent EVA, and both were less compactable than mixes made with 99 pen + 5 percent EVA. Also, the modified mixes exhibited a continuous increase in Percentage Compacting Factor value when the number of roller passages increased, whilst unmodified mixes showed less improvement in Percentage Compacting Factor value after the first few roller passages. Figure 6.14 shows that the modified mixes are less influenced by the first roller passage compared with unmodified mixes, and the difference reduces after continuous rolling.

6.5 DATA WITH CHIPPED ASPHALT SAMPLES

The performance of chipped asphalt samples under the action of the roll was such that the void content of the material between the embedded chippings (upper sub-layer) is significantly higher than the bottom sub-layer. The difference between the upper and the lower sub-layers is greater with stiffer mixes.

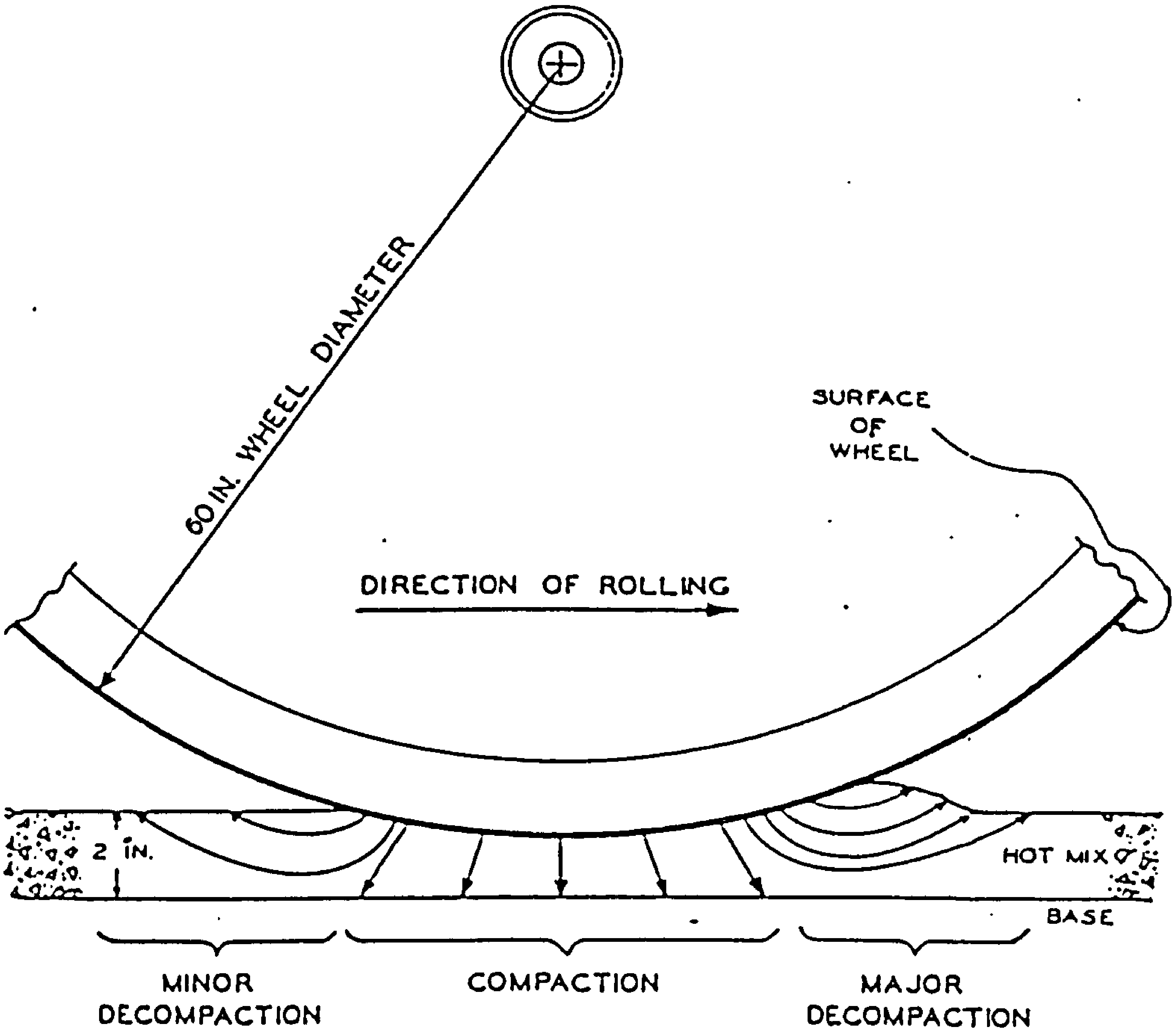
Figures 6.17 and 6.18 show that the upper sub-layer for mixes with low bitumen content or high filler to bitumen ratio, have a higher void content than the initial stages of rolling when compacted at low temperature, irrespective of the high number of roller passages used (18 passes). However it seems that when chippings are driven into the asphalt layer with a level of stress much higher than that produced with unchipped samples, as a result of the smaller contact area, this leads to a better compaction of the bottom sub-layer, and an extrusion of some dilated material to form a different material sub-layer between the chippings. This (highly) dilated material between the chippings will be subject to direct compaction when the chippings are well embedded, as is the case with soft mixes; here the difference in the voidage between the sub-layers is reduced markedly. The chippings divided the asphalt layer into two in terms of voidage, but, mixes with high bitumen content or low filler content, showed a disproportionate change between the voidage within the two sub-layers, which comes as a result of the direct contact of the top sub-layer with the surface of the roller.

As mentioned in Chapter Three, section 3.4.2, the Percentage Compacting Factor values of the top and bottom sub-layers are exagerated, to some extent, by the fact that the top sub-layer has more mortar content than the botom sub-layer, due to the easier movement of the mortar. This results in the top sub-layer possessing a marginally high bitumen content compared with the bottom sub-layer, subsequently the theoretical maximum density of the bottom sub-layer is greater than the top sub-layer.

Using the 'normal' theoretical maximum density, calculated assuming no difference in material composition between the upper and lower sub-layer, leads to a greater value of Percentage Compacting Factor value for the bottom sub-layer and lower value of Percentage Compacting Factor for the upper sub-layer. Having said that, this feature is not responsible for the whole difference between the upper and lower sub-layer voidage.

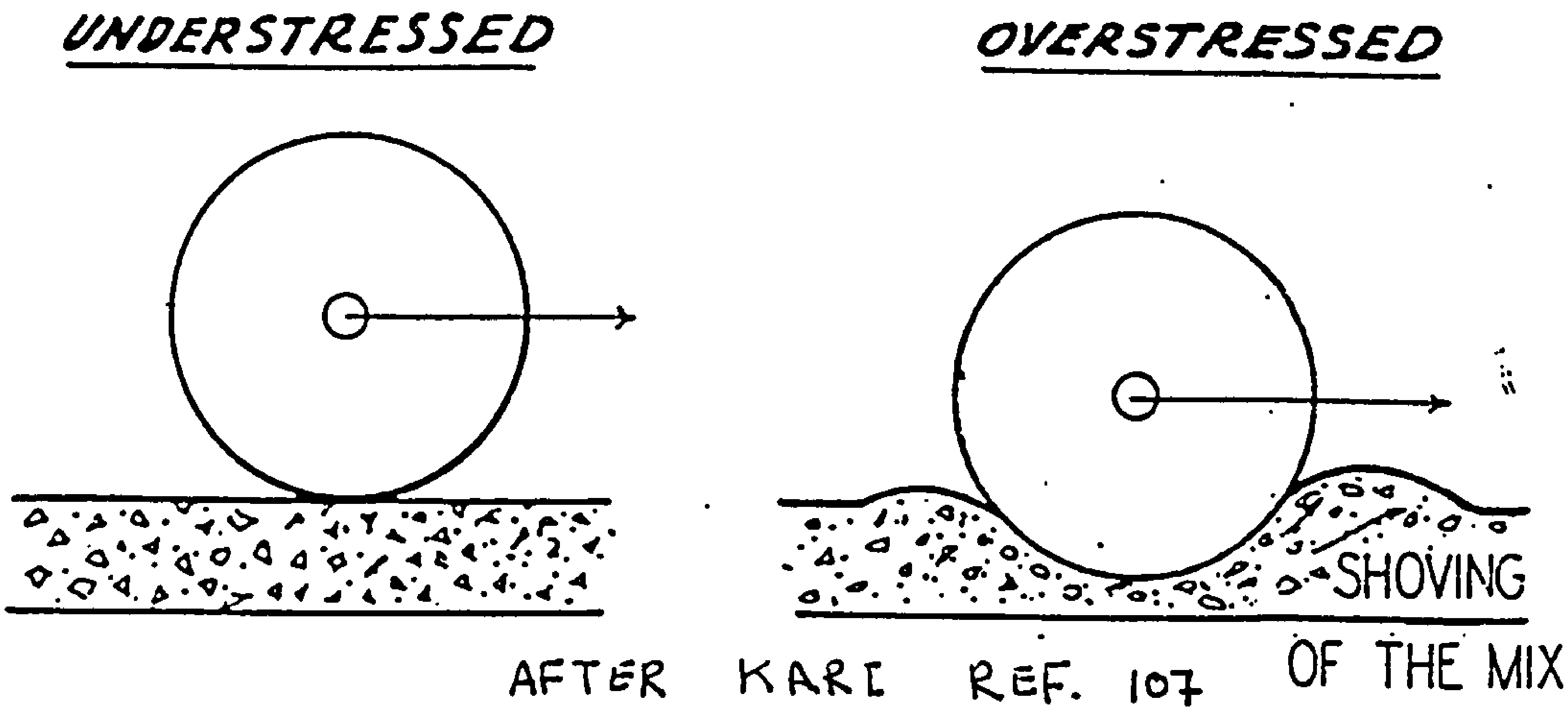
Figures 6.17 and 6.18 show that the voidage with unchipped samples are in close agreement with that of the lower sub-layer of chipped samples. The Percentage Compacting Factor values of unchipped samples exhibit profiles having higher numerical value than those of the whole layer with chipped samples.

The lower sub-layer densification through temperature changes, bitumen content and filler to bitumen ratio are very much in line with that for samples compacted without chippings, and are not far from the whole sample density, as can be seen in Figure 6.19. The agreement between the Percentage Compacting Factor values with unchipped samples and those with the lower sub-layers of chipped samples both define an upper compaction temperature, upper bitumen content and the lower filler-bitumen ratio.



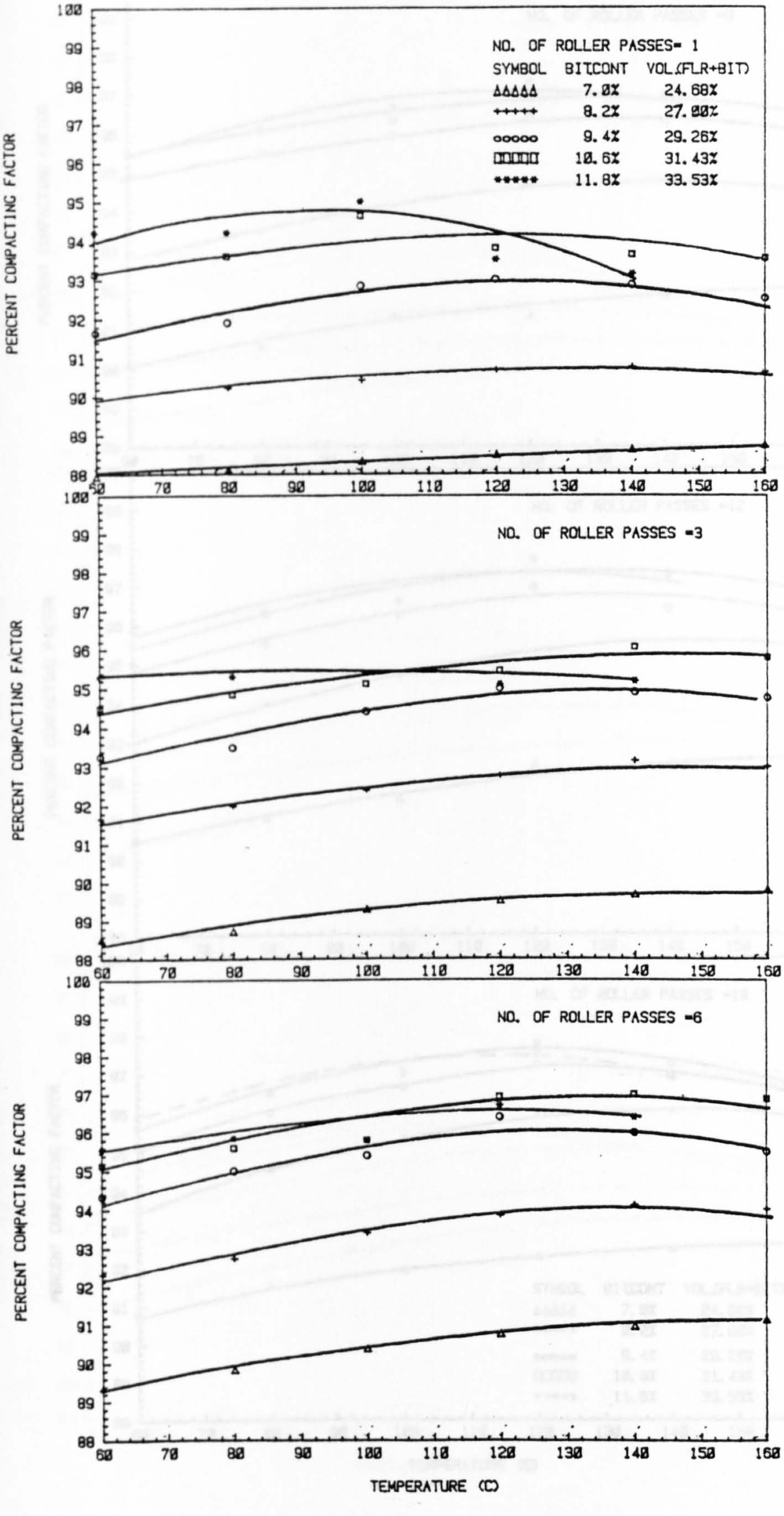
AFTER SCHMIDT, KARI, BOWER & HEIN - REF. 108

Fig. 6.1 Compaction Process.

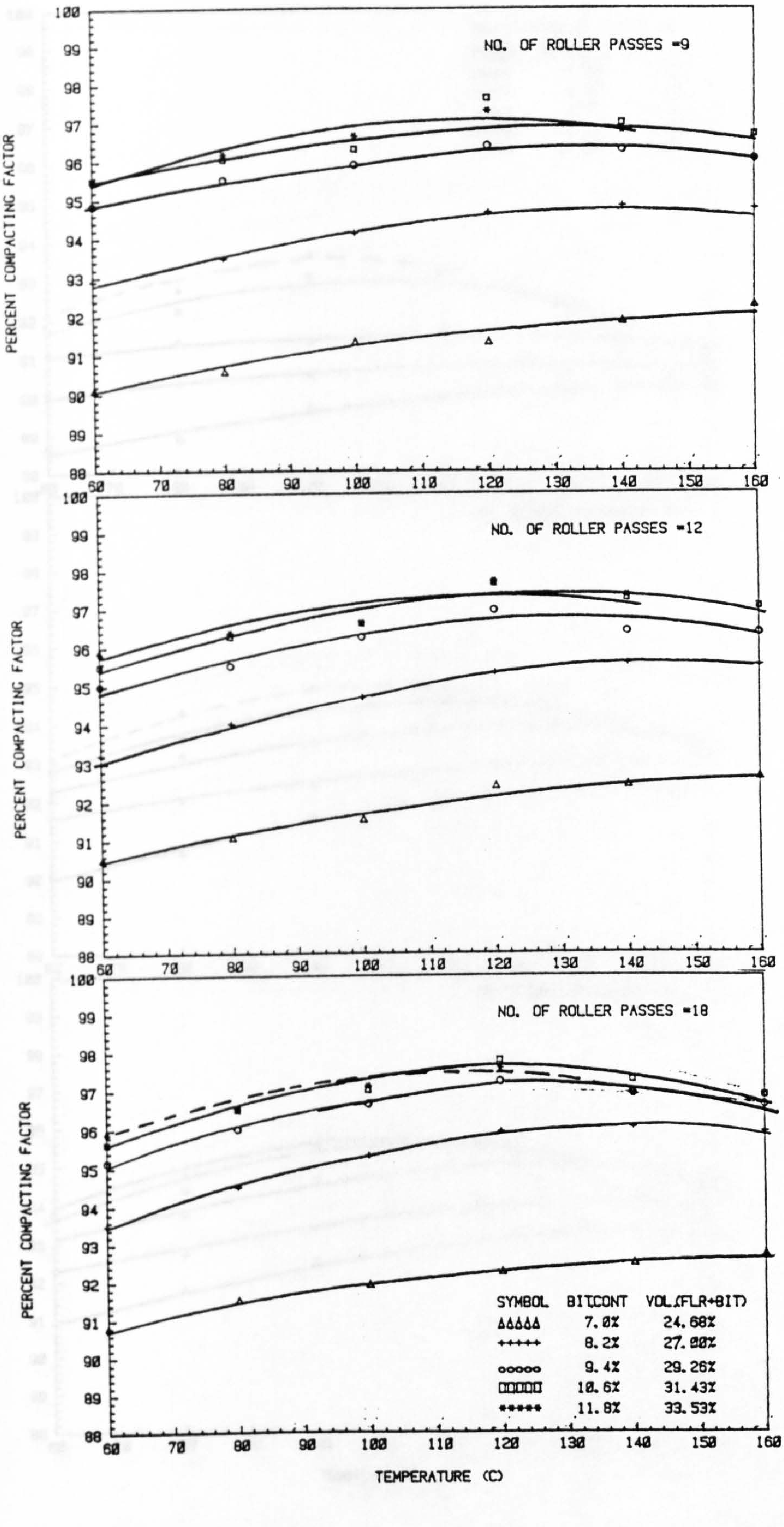


AFTER KARI REF. 107

Fig. 6.2 Types of Mixes Under Compaction.



Figures 6.3: The relationship between Percentage Compacting Factor and temperature for mixes with Test Series 1.



Figures 6.3: The relationship between Percentage Compacting Factor and temperature for mixes with Test Series 1, continued.

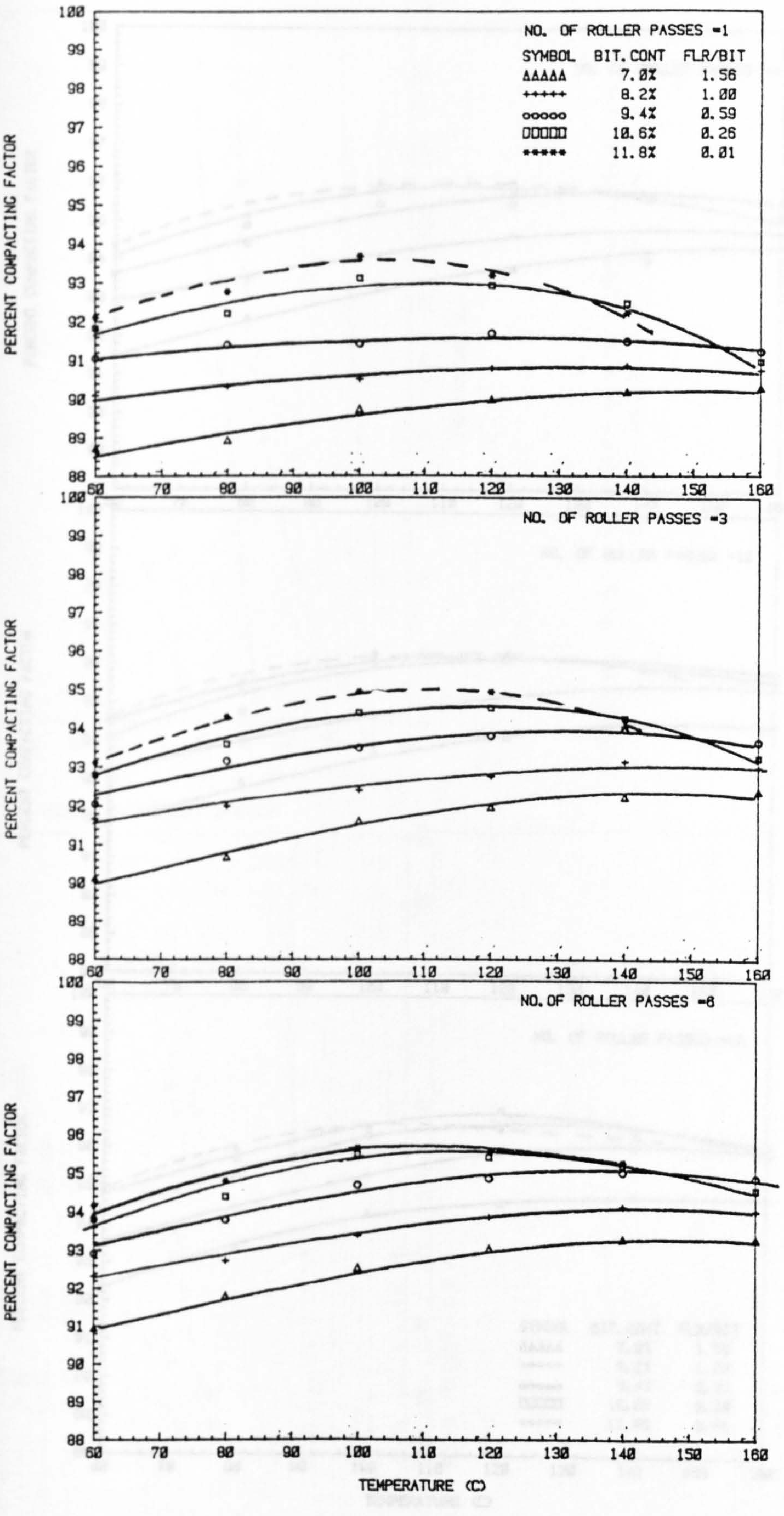


Figure 6.4: The relationship between Percentage Compacting Factor and temperature for mixes with Test Series 2.

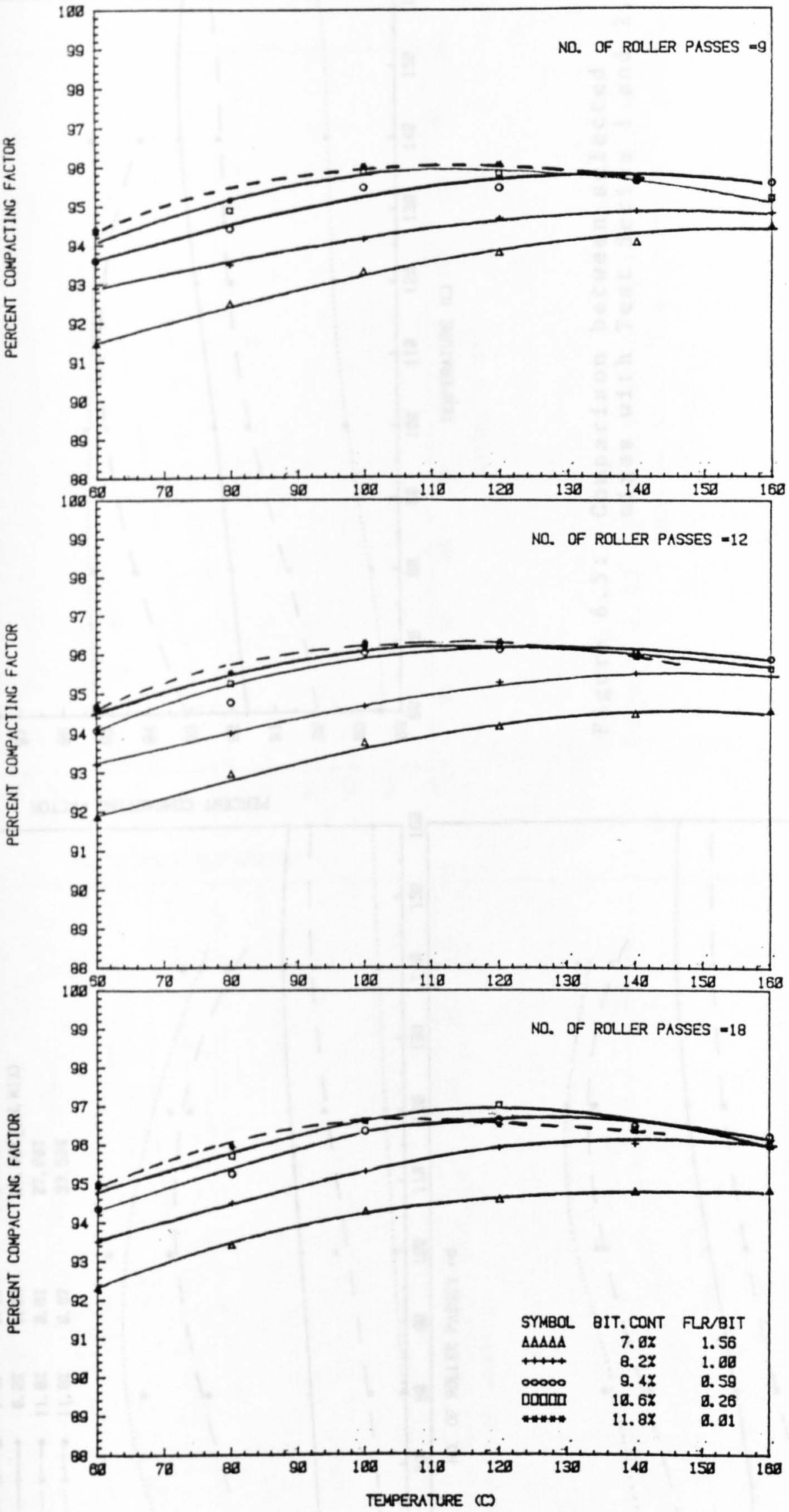


Figure 6.4: The relationship between Percentage Compacting Factor and temperature for mixes with Test Series 2, continued.

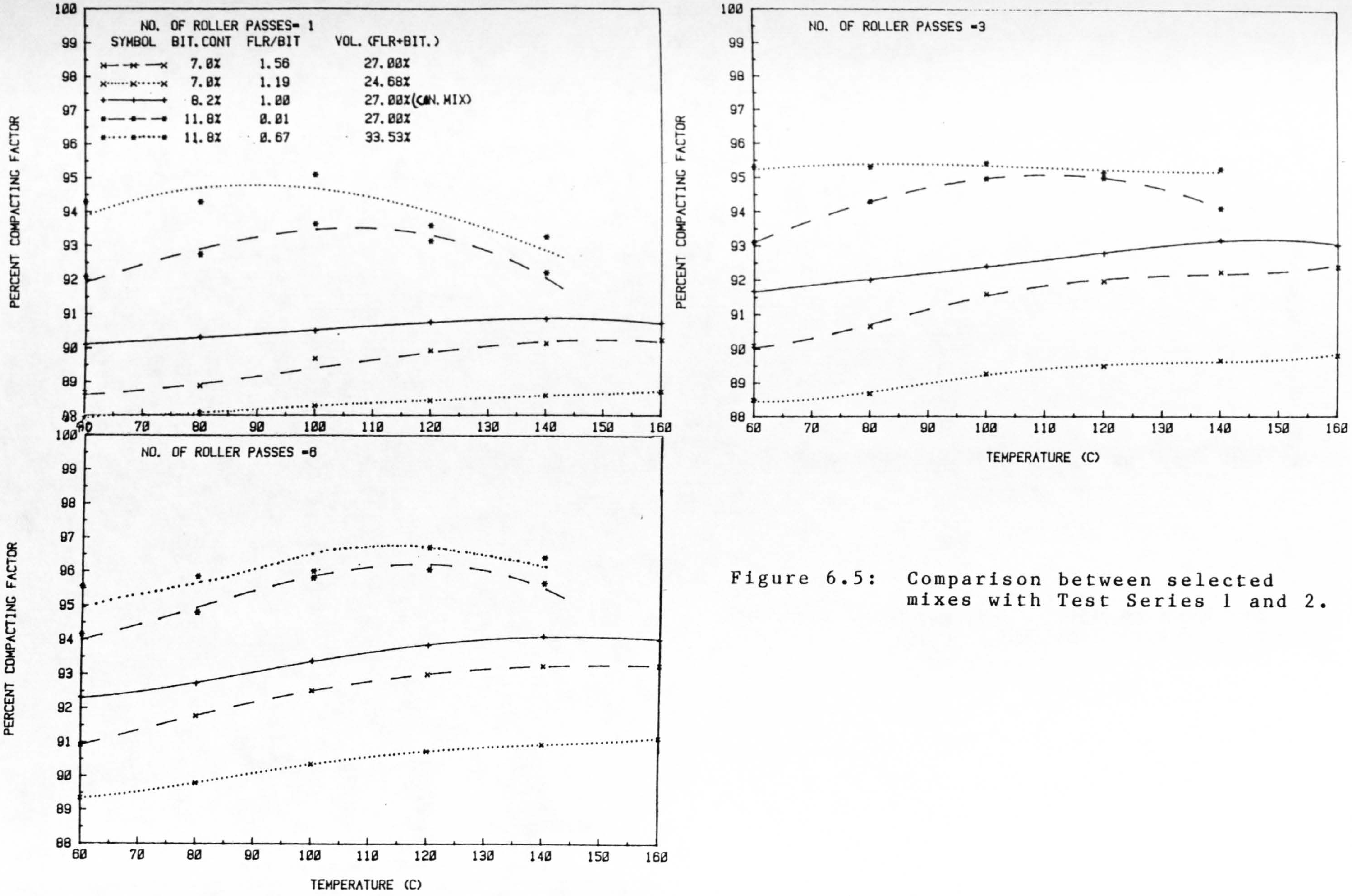


Figure 6.5: Comparison between selected mixes with Test Series 1 and 2.

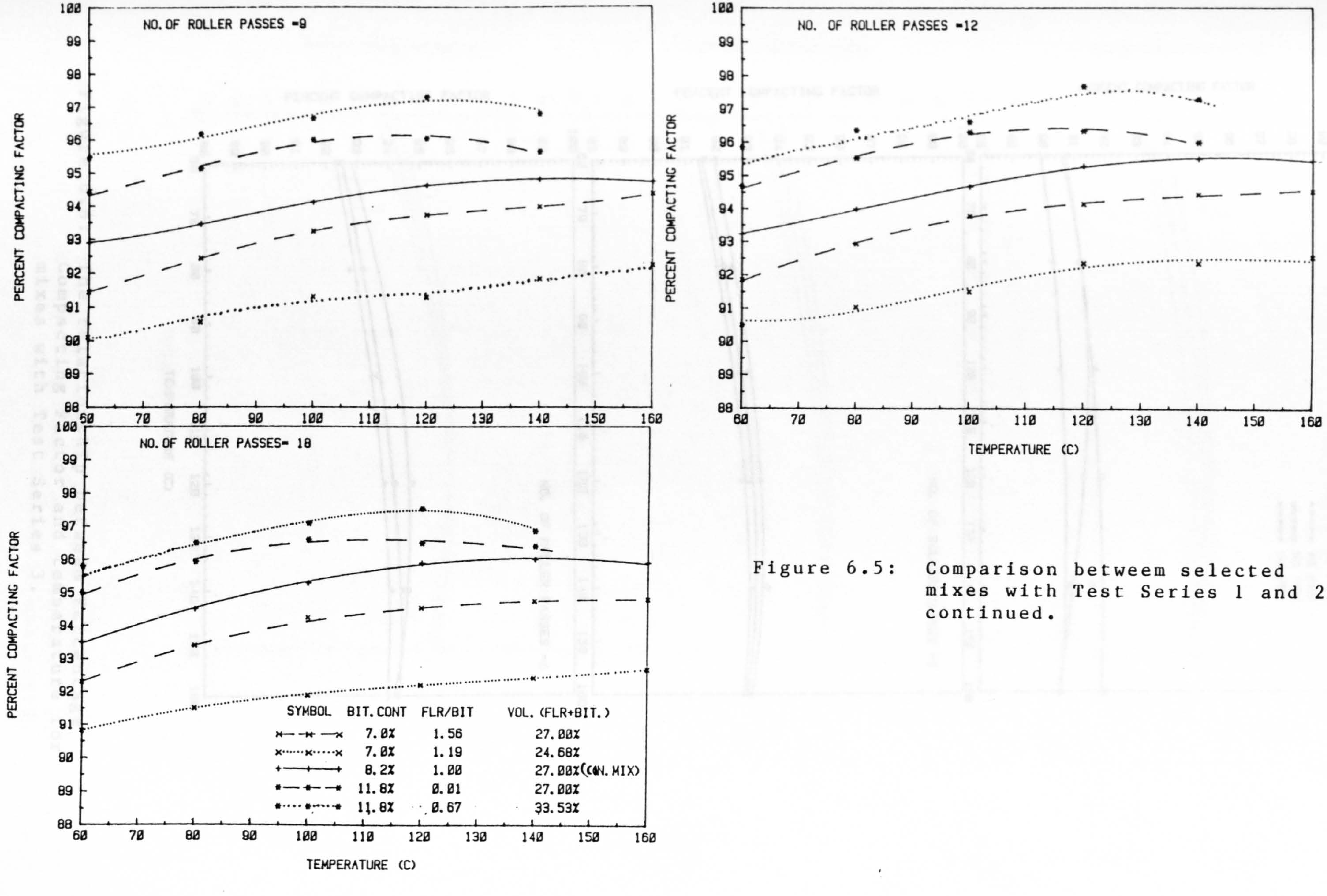


Figure 6.5: Comparison betweem selected mixes with Test Series 1 and 2, continued.

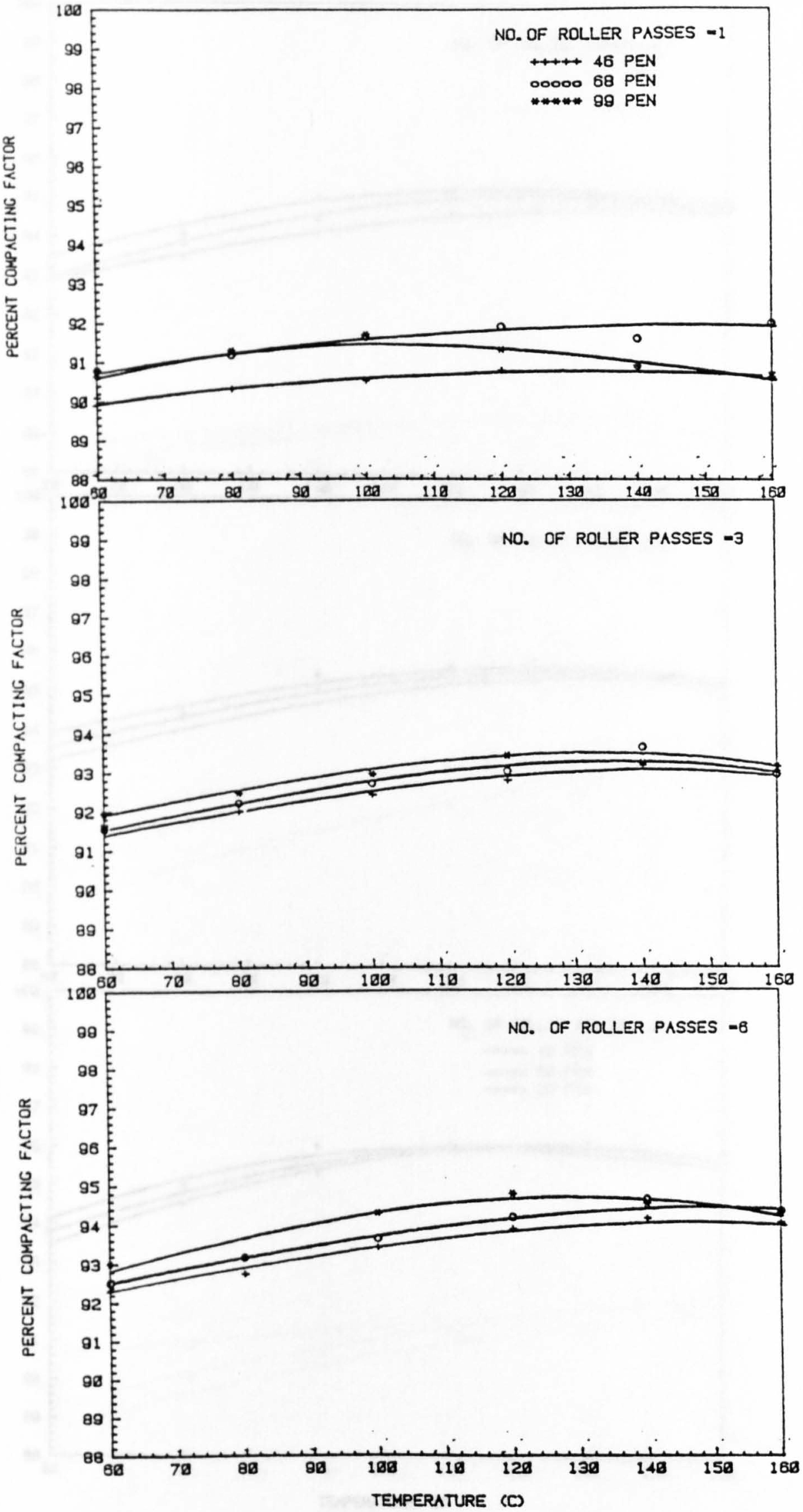


Figure 6.6: The relationship betweem Percentage Compacting Factor and temperature for mixes with Test Series 3.

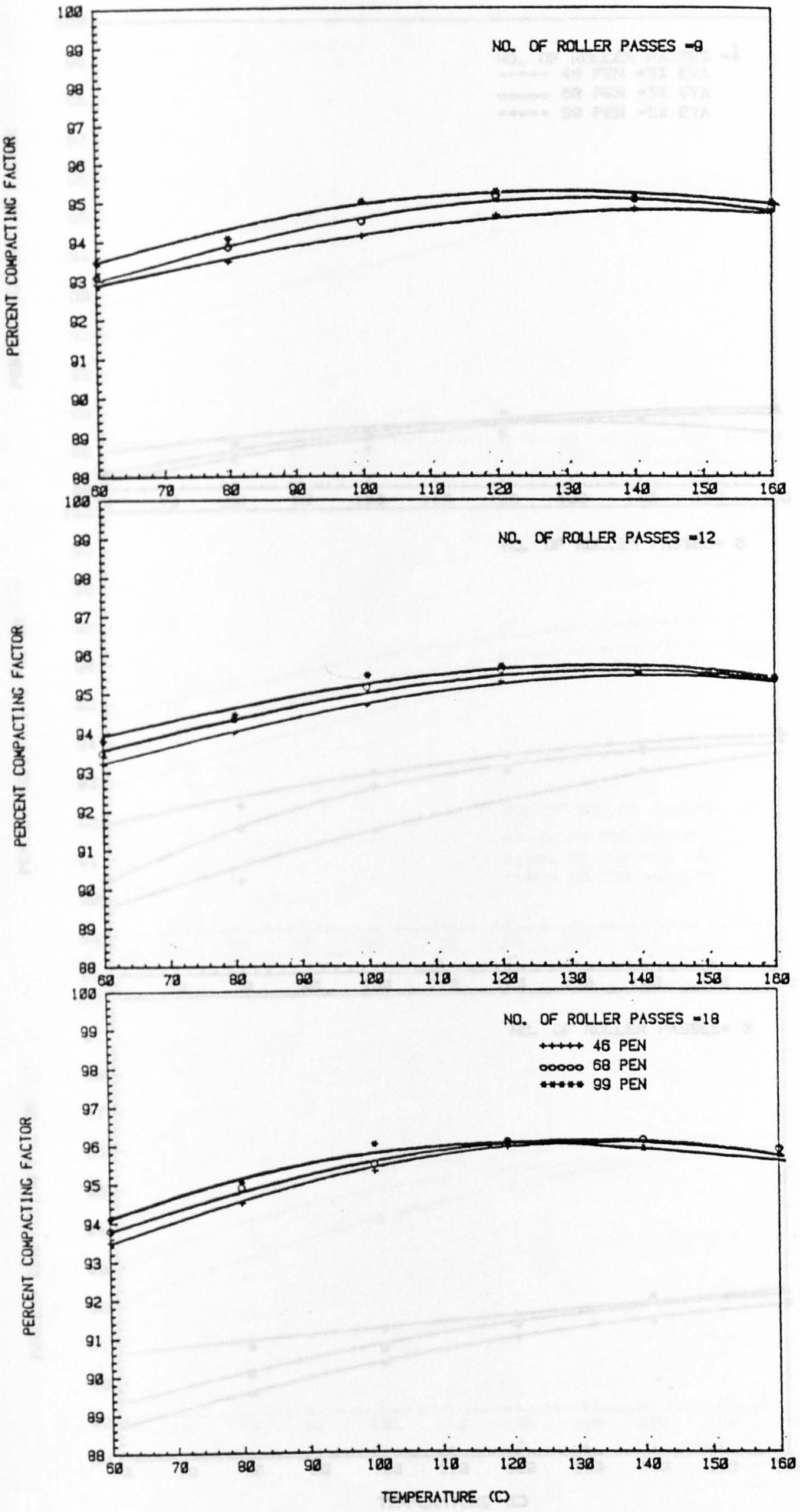


Figure 6.6: The relationship between Percentage Compacting Factor and temperature for mixes with Test Series 3, continued.

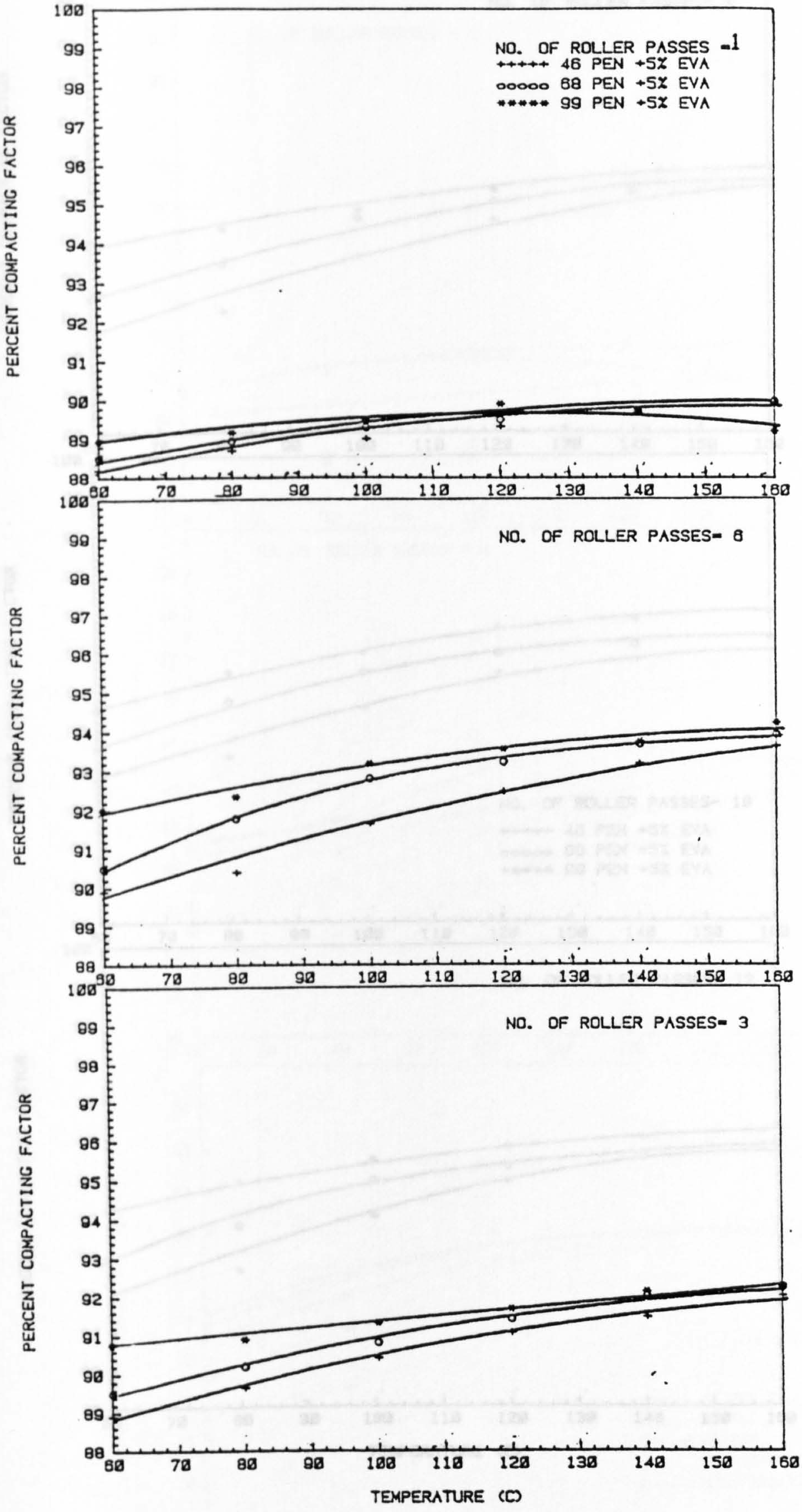


Figure 6.7: The relationship between Percentage Compacting Factor and temperature for mixes with Test Series 4.

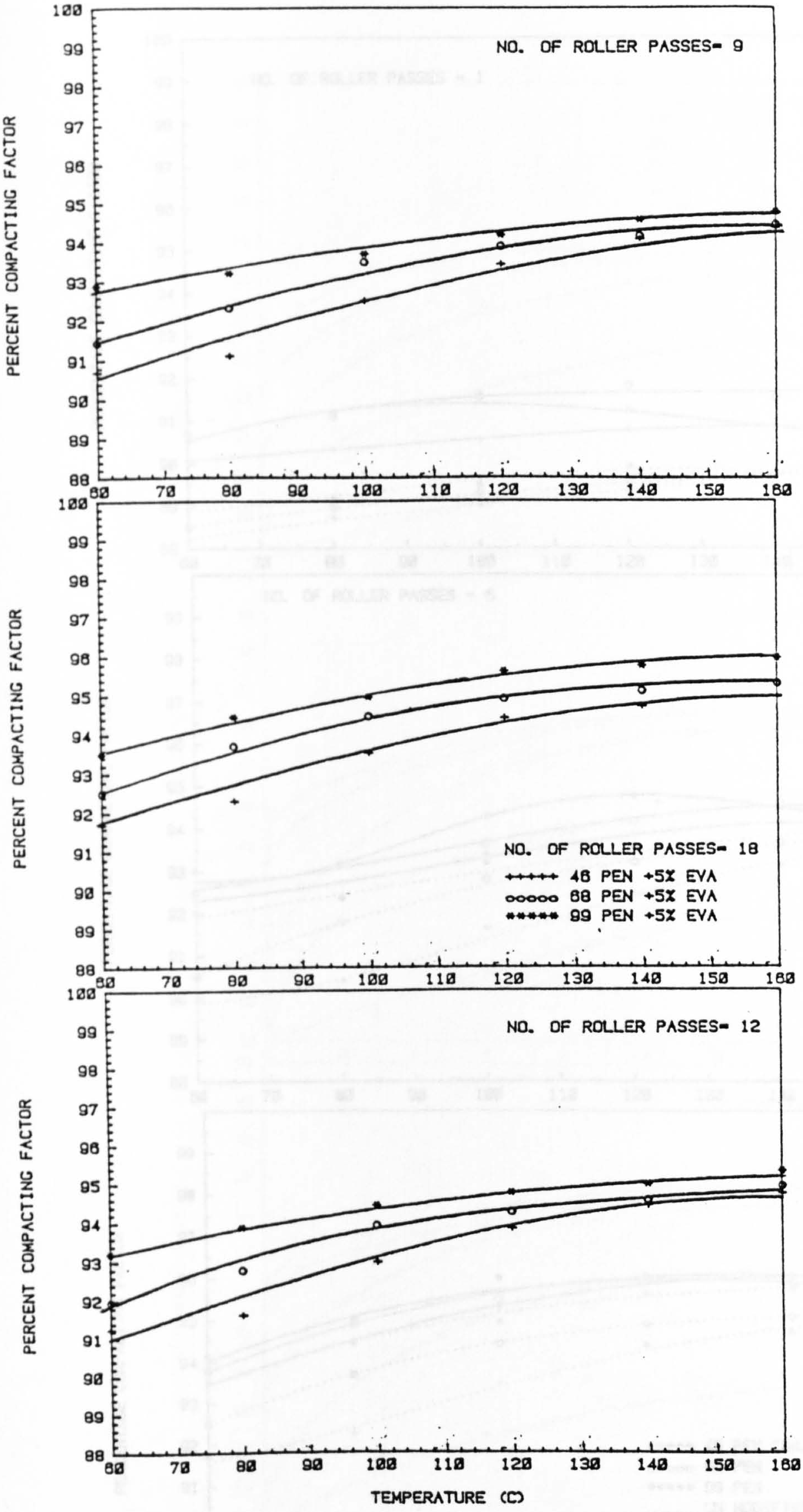


Figure 6.7: The relationship between Percentage Compacting Factor and temperature for mixes with Test Series 4, continued.

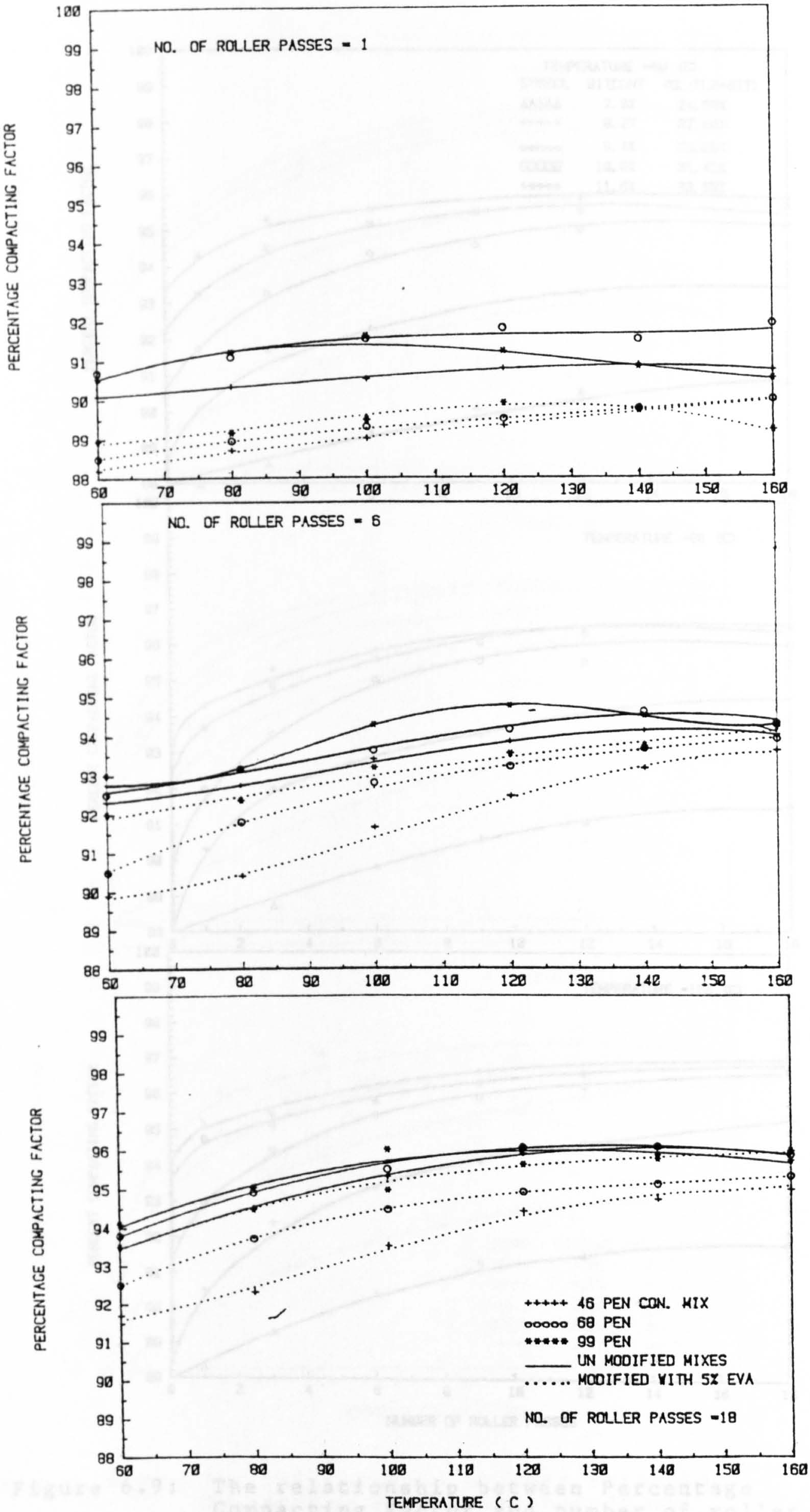


Figure 6.8: Comparison between mixes of Test Series 3 and Test Series 4 at selected numbers of roller passages.

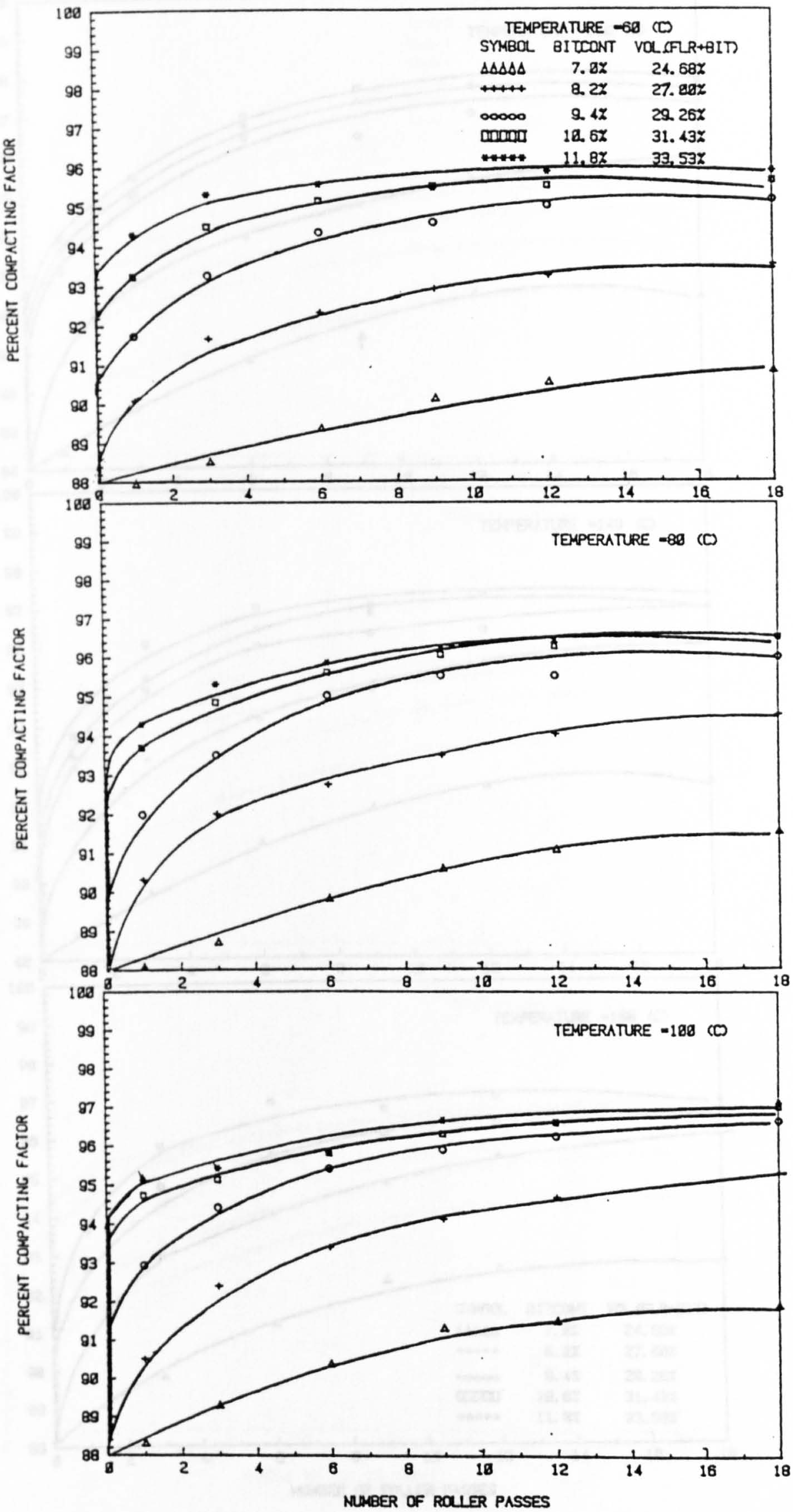


Figure 6.9: The relationship between Percentage Compacting Factor and number of roller passes for mixes with Test Series 1.

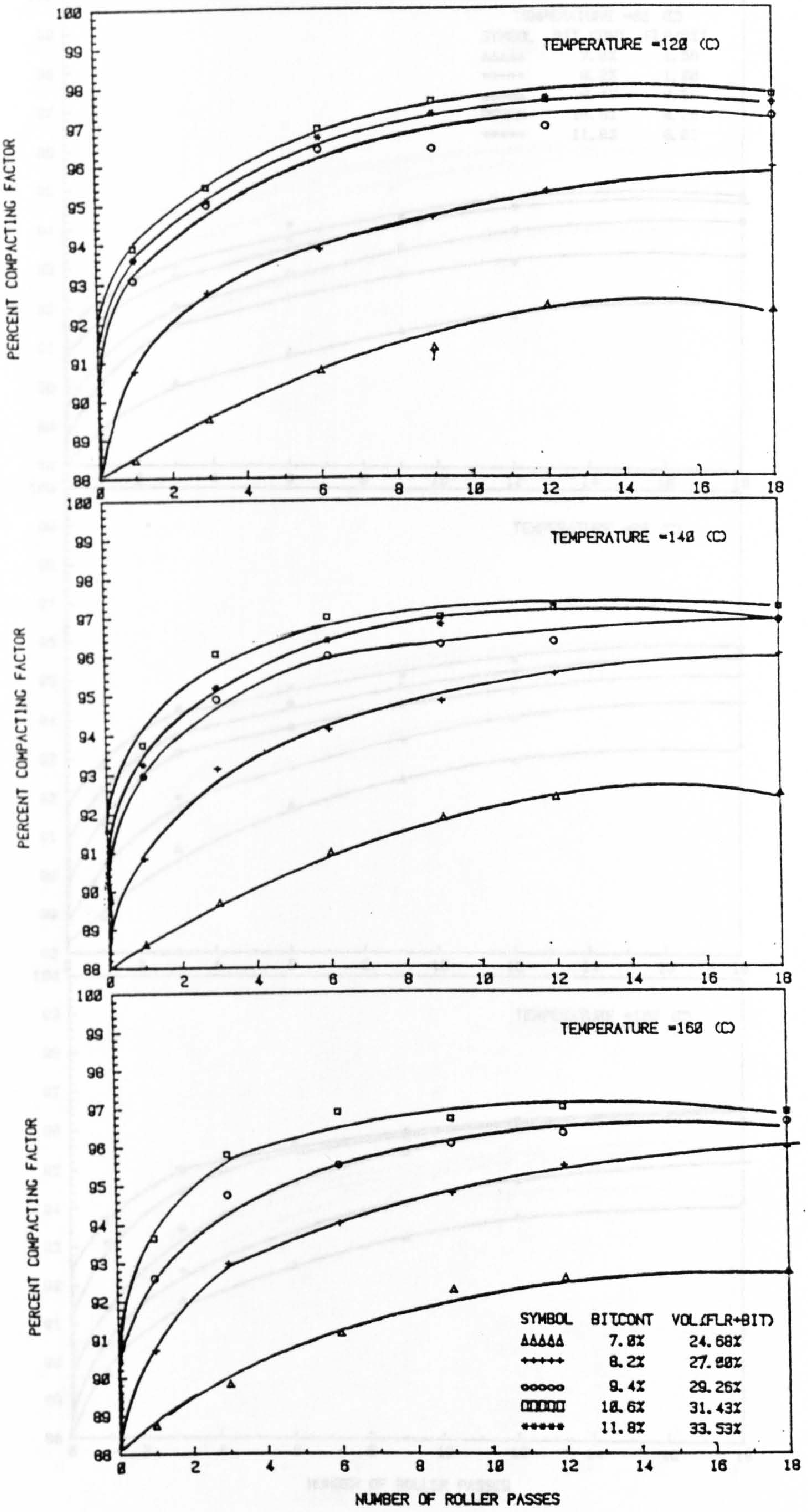


Figure 6.9: The relationship between Percentage Compacting Factor and number of roller passes for mixes with Test Series 1, continued.

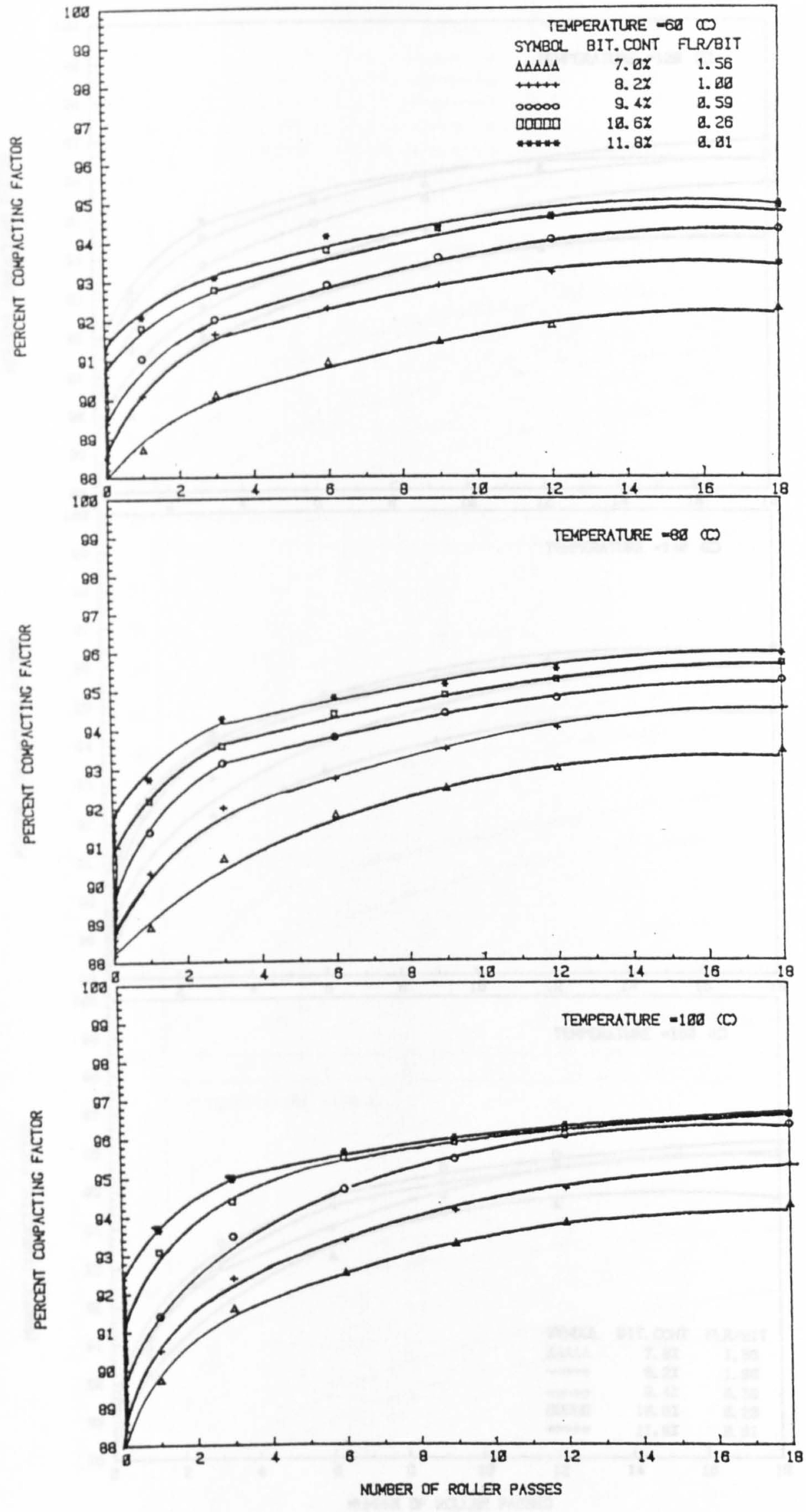


Figure 6.10: The relatonship between Percentage Compacting Factor and number of roller passes for mixes with Test Series 2.

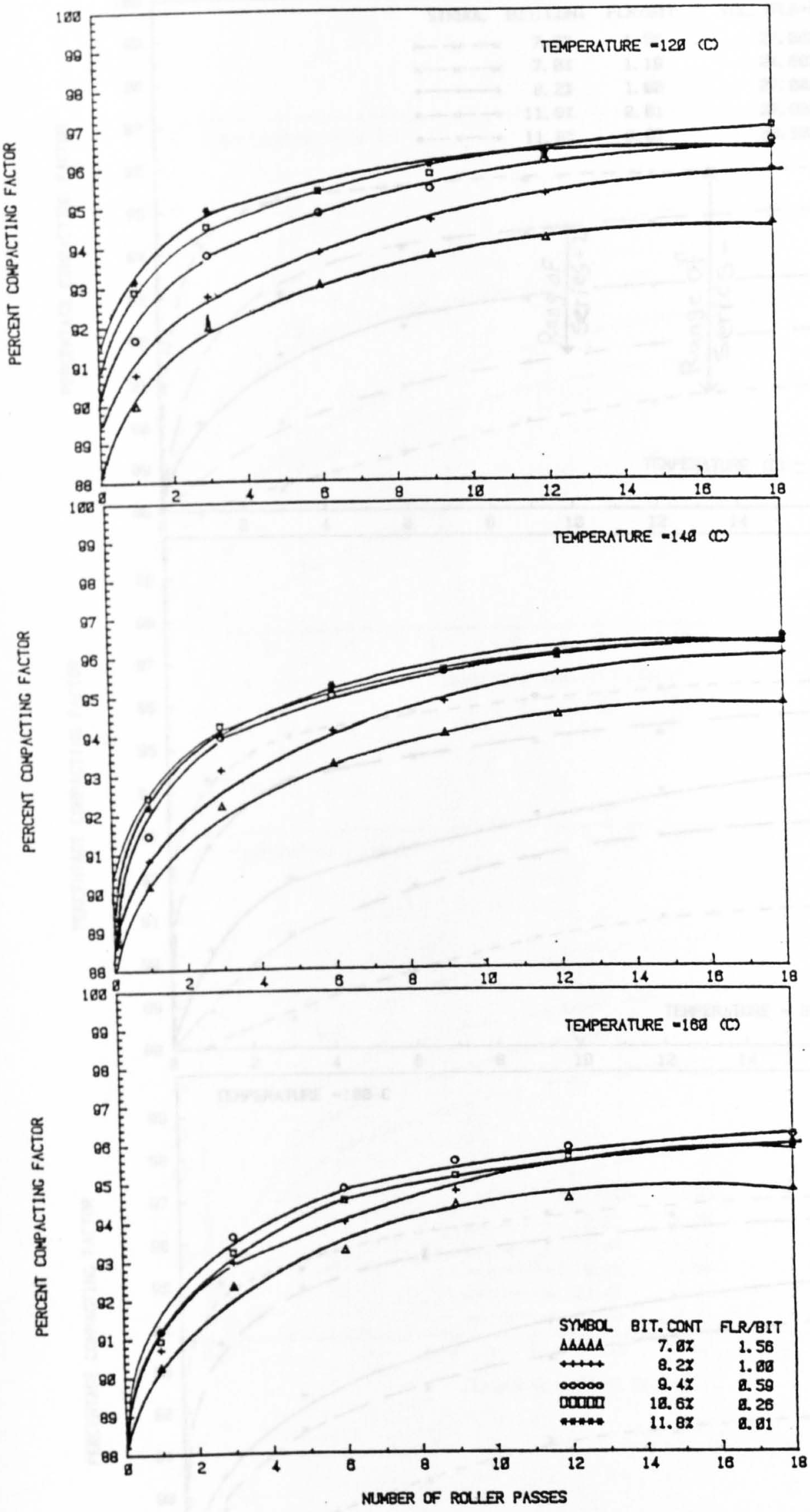


Figure 6.10: The relationship between Percentage Compacting Factor and number of roller passes for mixes with Test Series 2, continued.

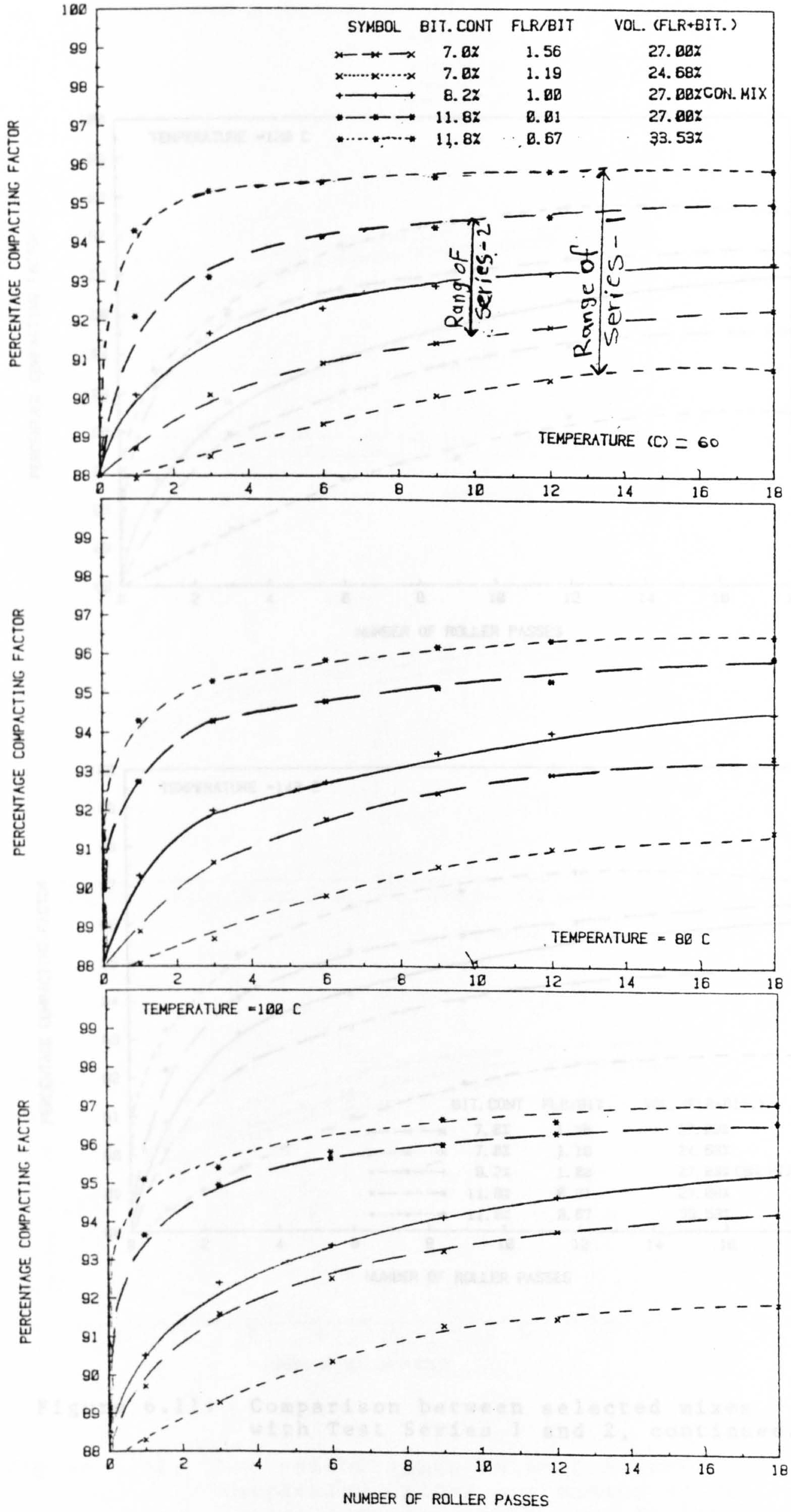


Figure 6.11: Comparison between selected mixes with Test Series 1 and 2.

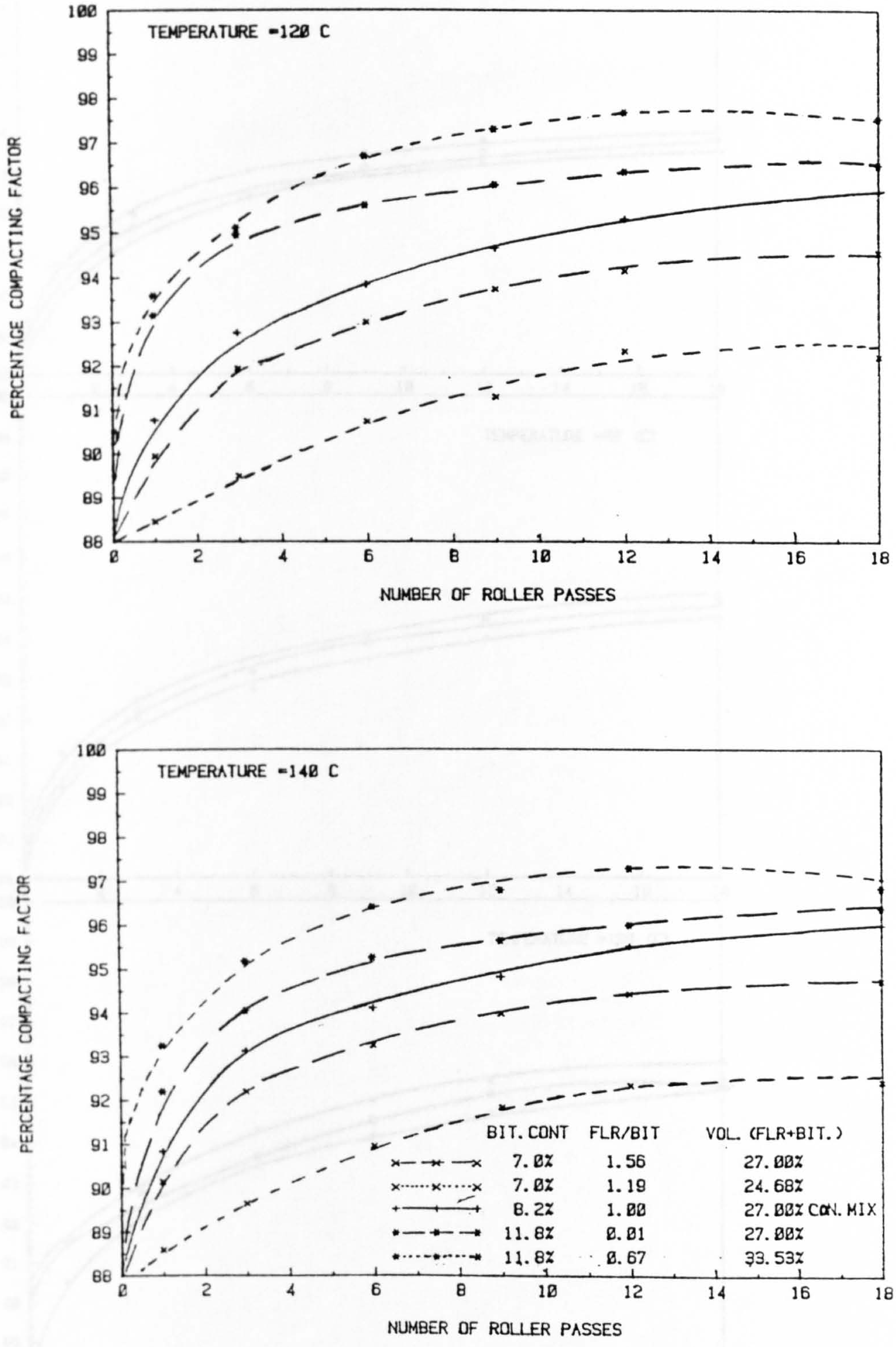


Figure 6.11: Comparison between selected mixes with Test Series 1 and 2, continued.

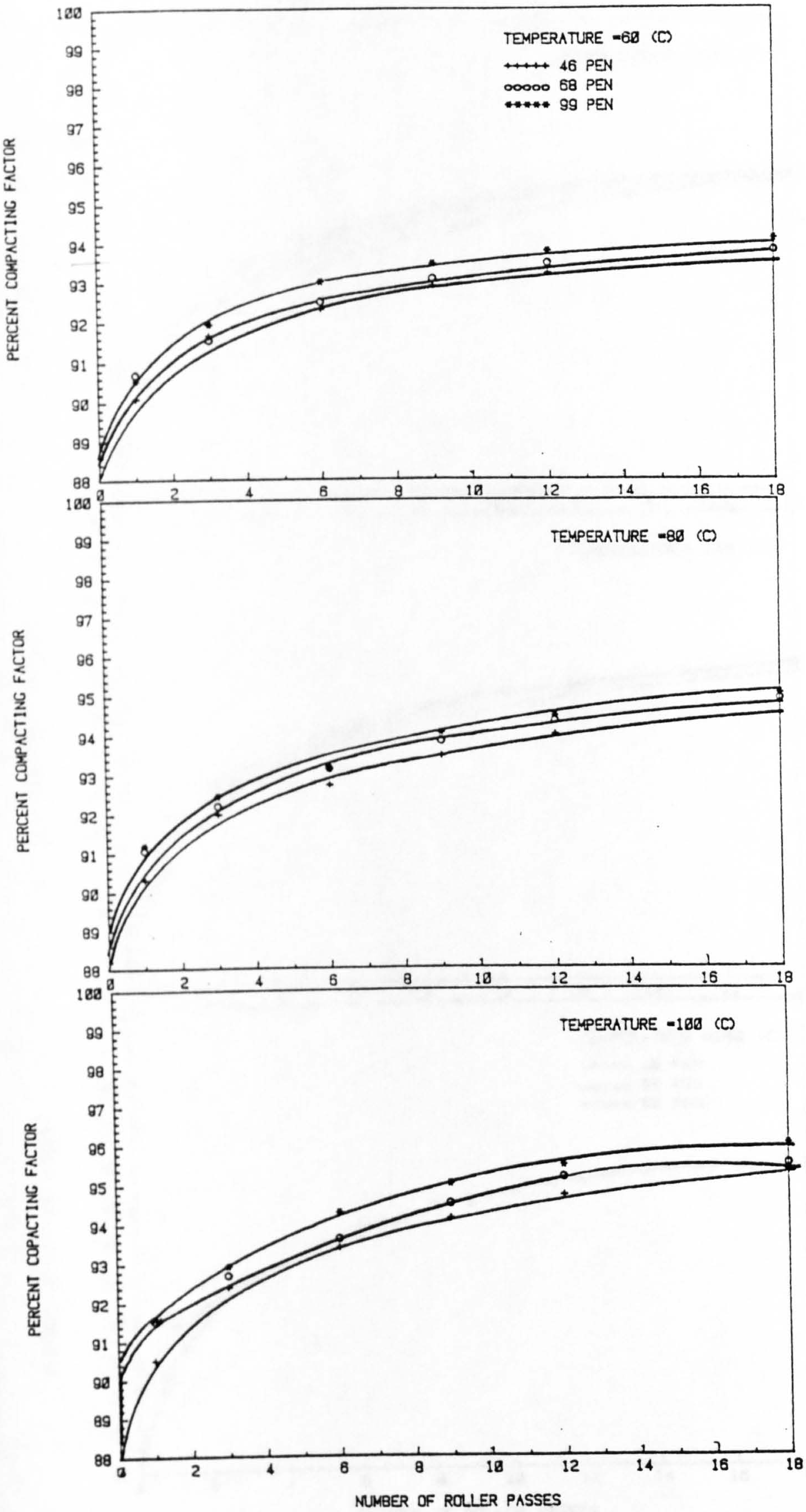


Figure 6.12: The relationship between Percentage Compacting Factor and number of roller passes for mixes with Test Series 3.

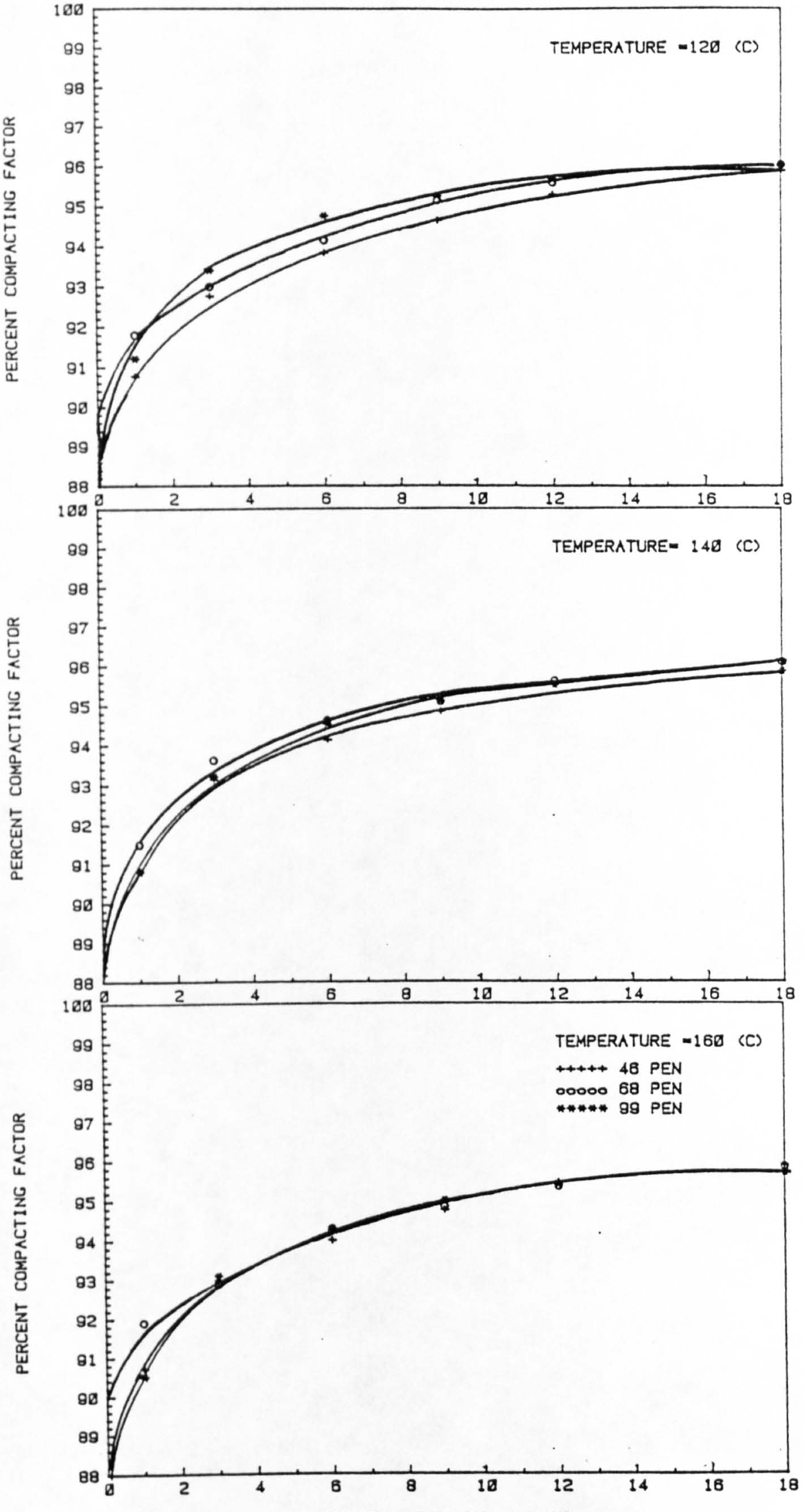


Figure 6.12: The relationship between Percentage Compacting Factor and number of roller passes for mixes with Test Series 3, continued.

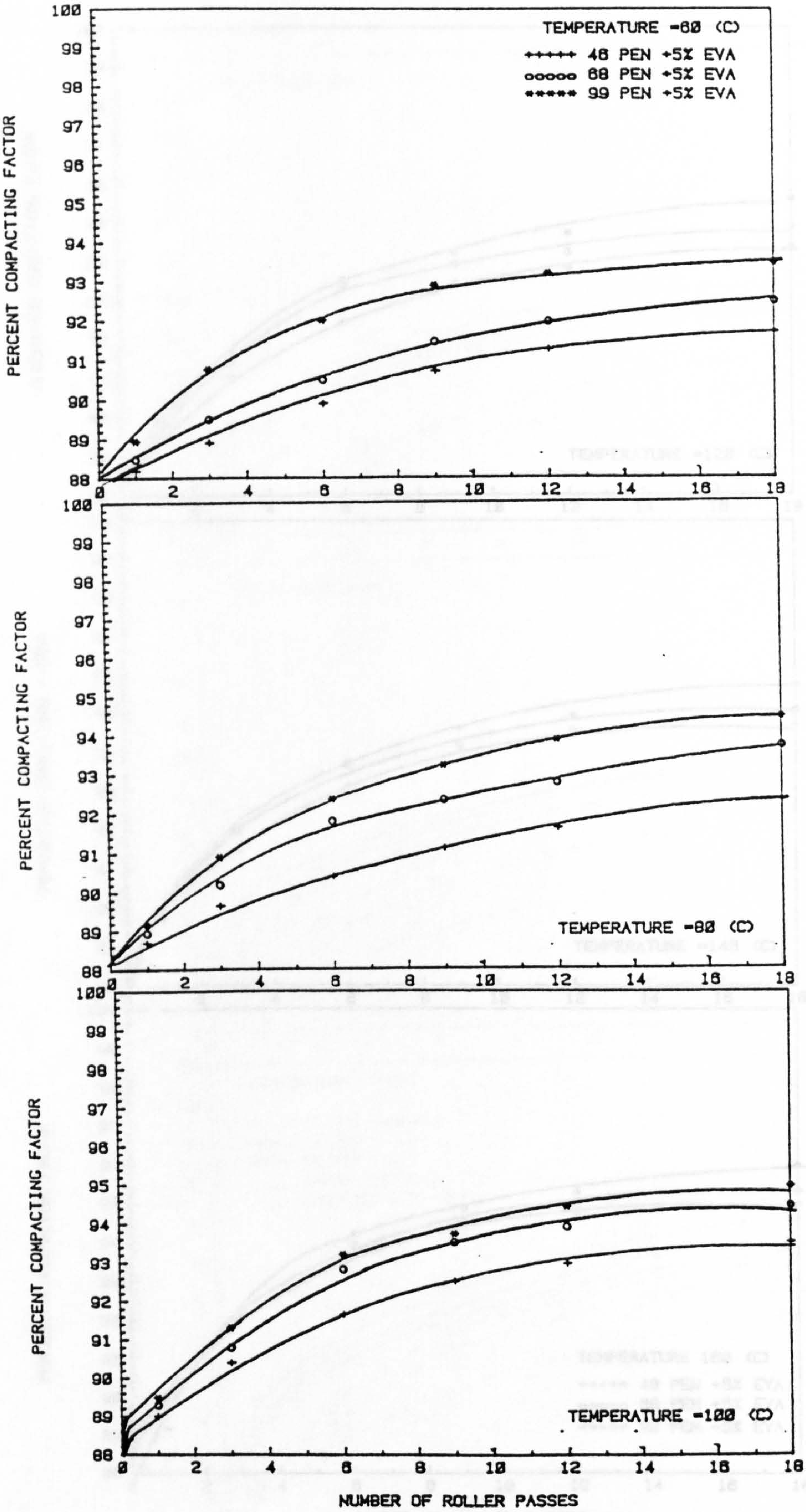


Figure 6.13: The relationship between Percentage Compacting Factor and number of roller passes for mixes with Test Series 4.

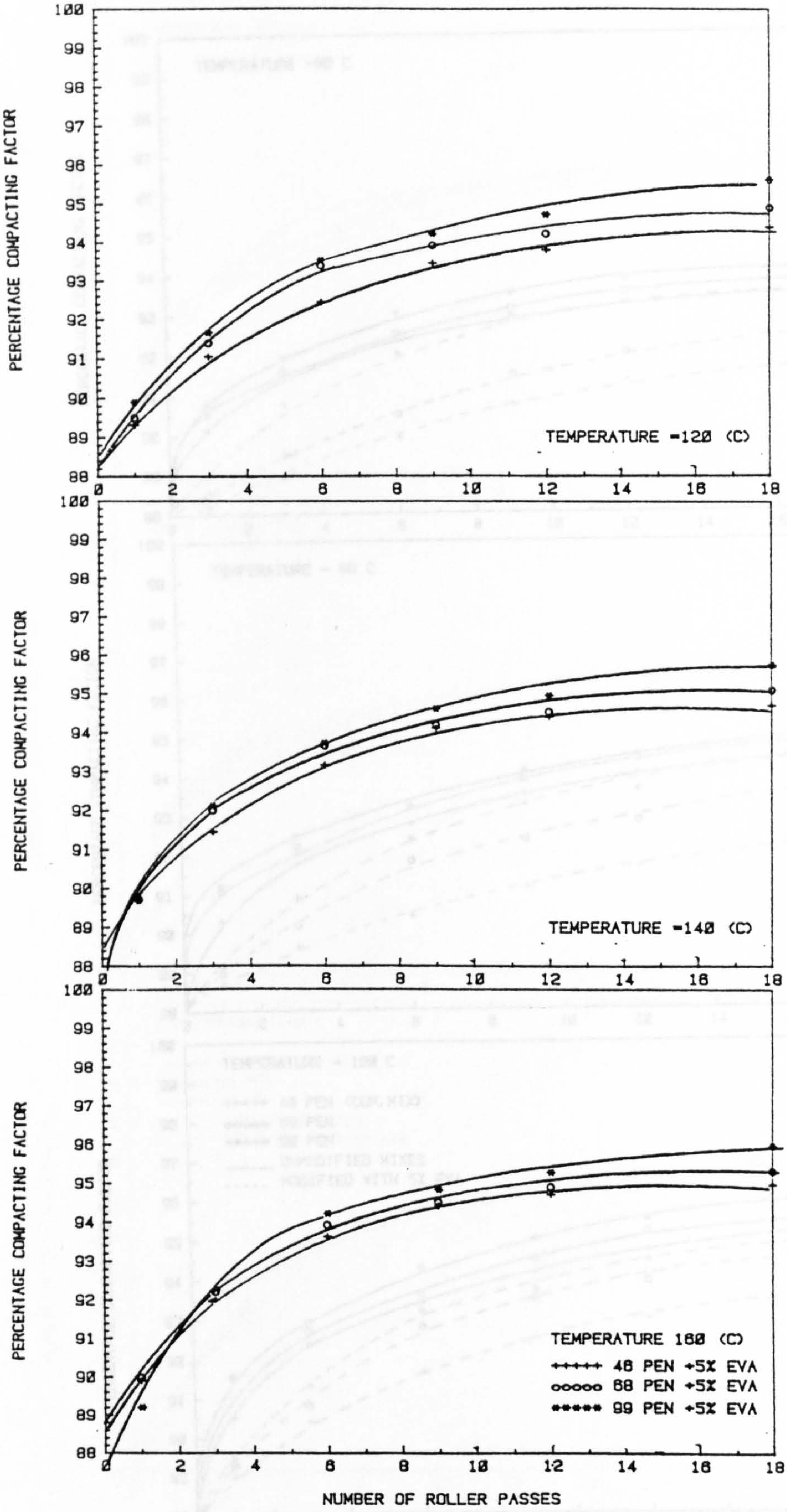


Figure 6.13: The relationship between Percentage Compacting Factor and number of roller passes for mixes with Test Series 4, continued.

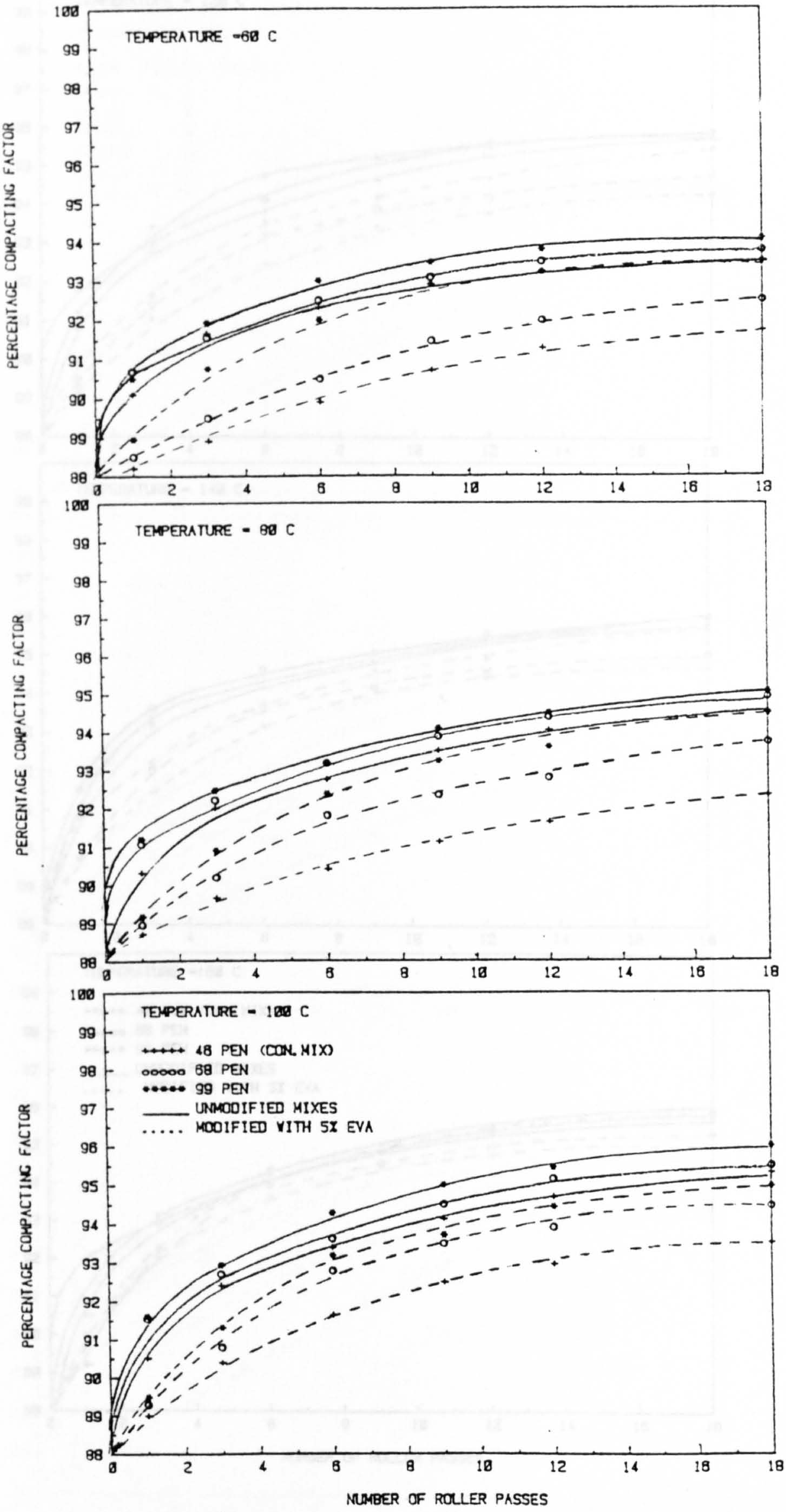


Figure 6.14: Comparison between mixes with Test Series 3 and Test Series 4.

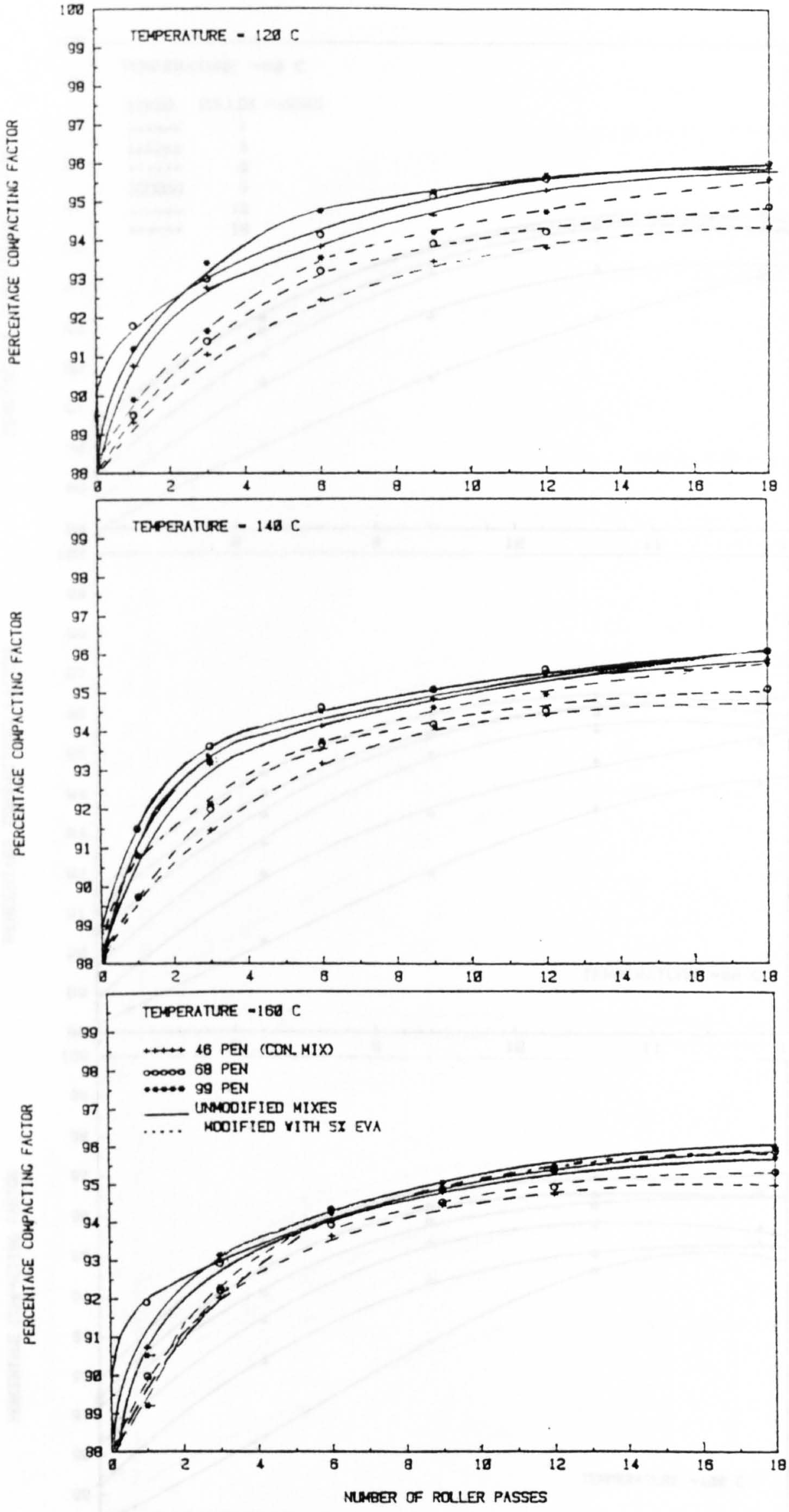


Figure 6.14: Comparison between mixes with Test Series 3 and Test Series 4, continued.

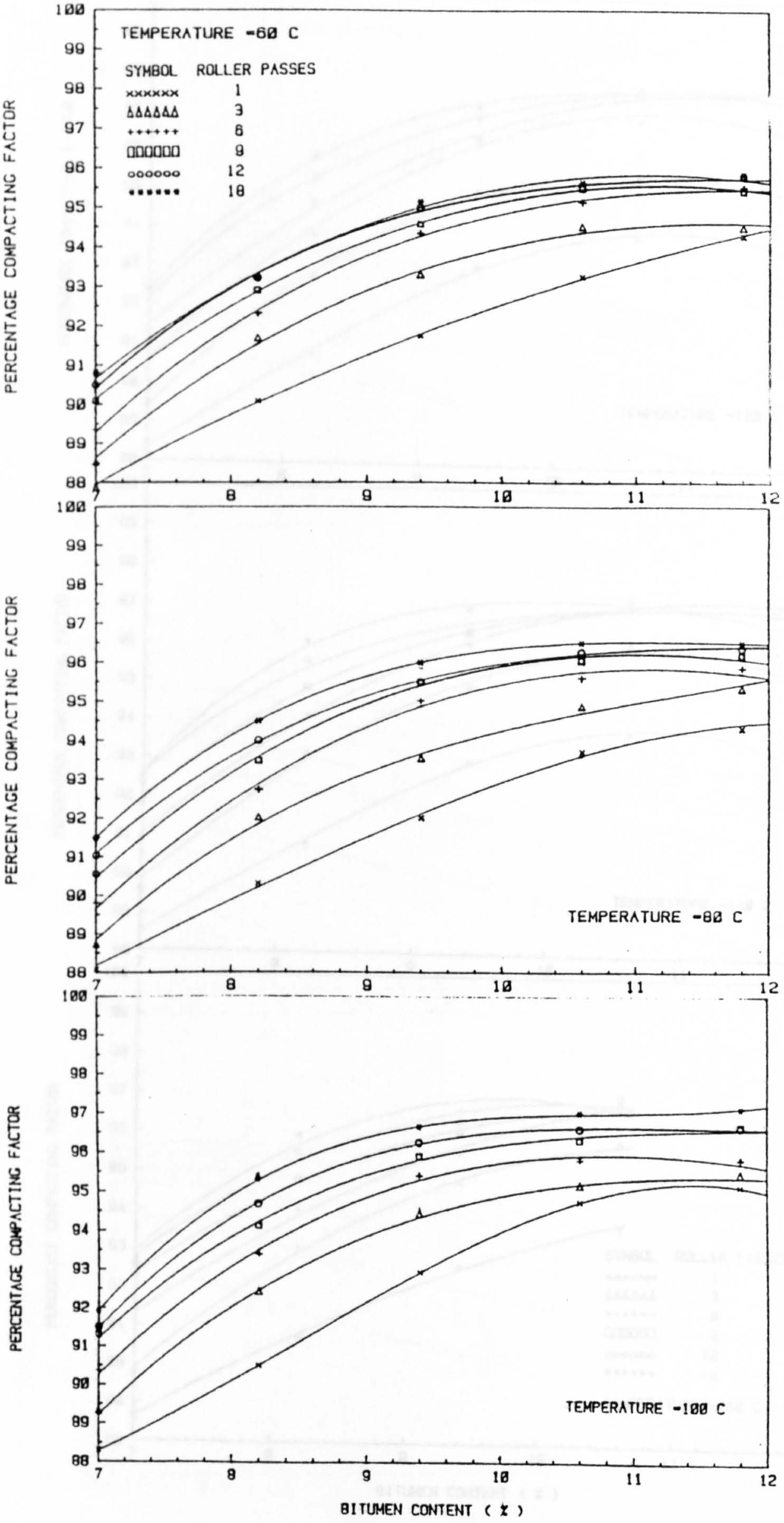


Figure 6.15: The relationship between Percentage Compacting Factor and bitumen content for mixes with Test Series 1.

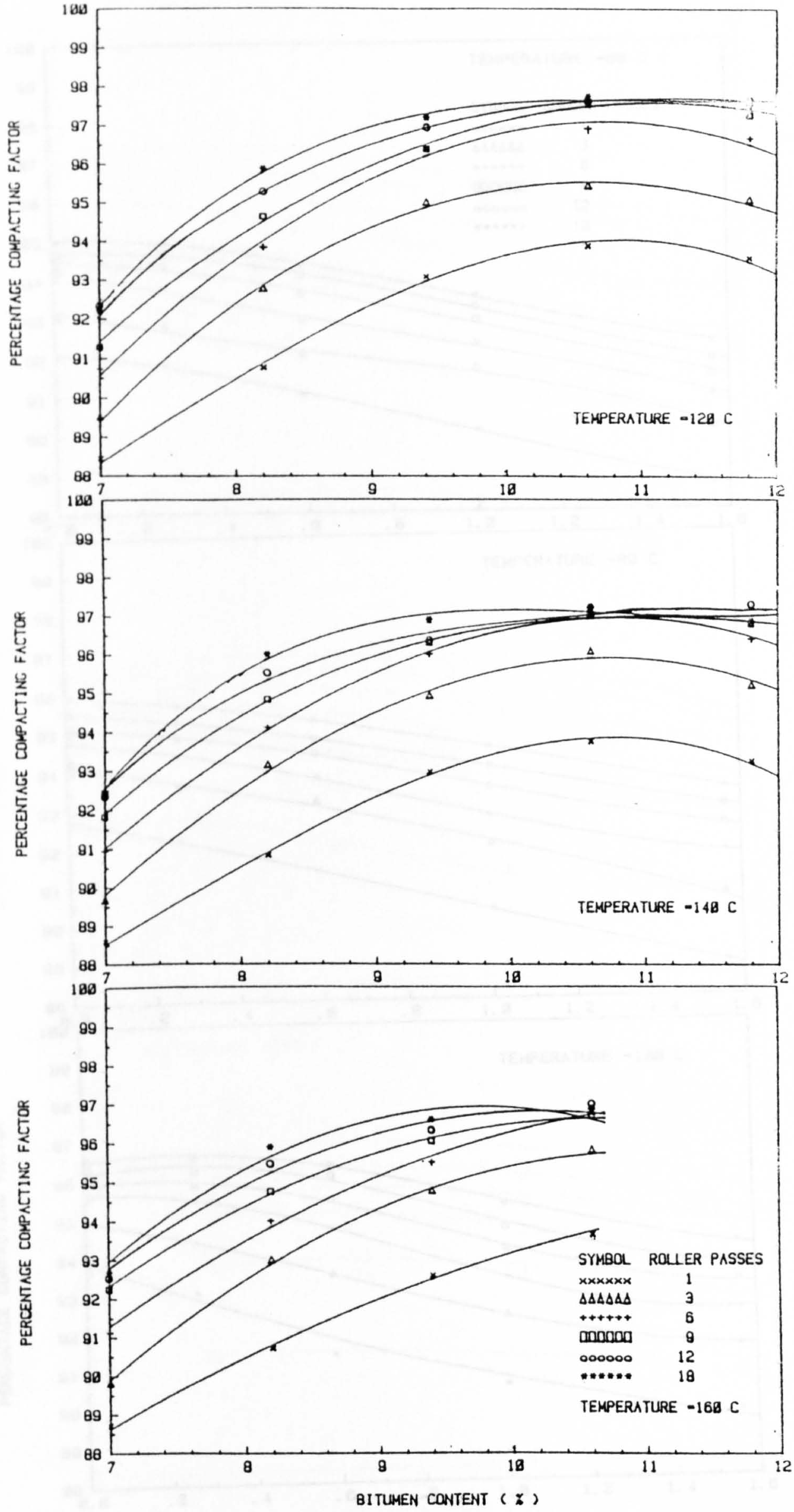


Figure 6.15: The relationship between Percentage Compacting Factor and bitumen content for mixes with Test Series 1, continued.

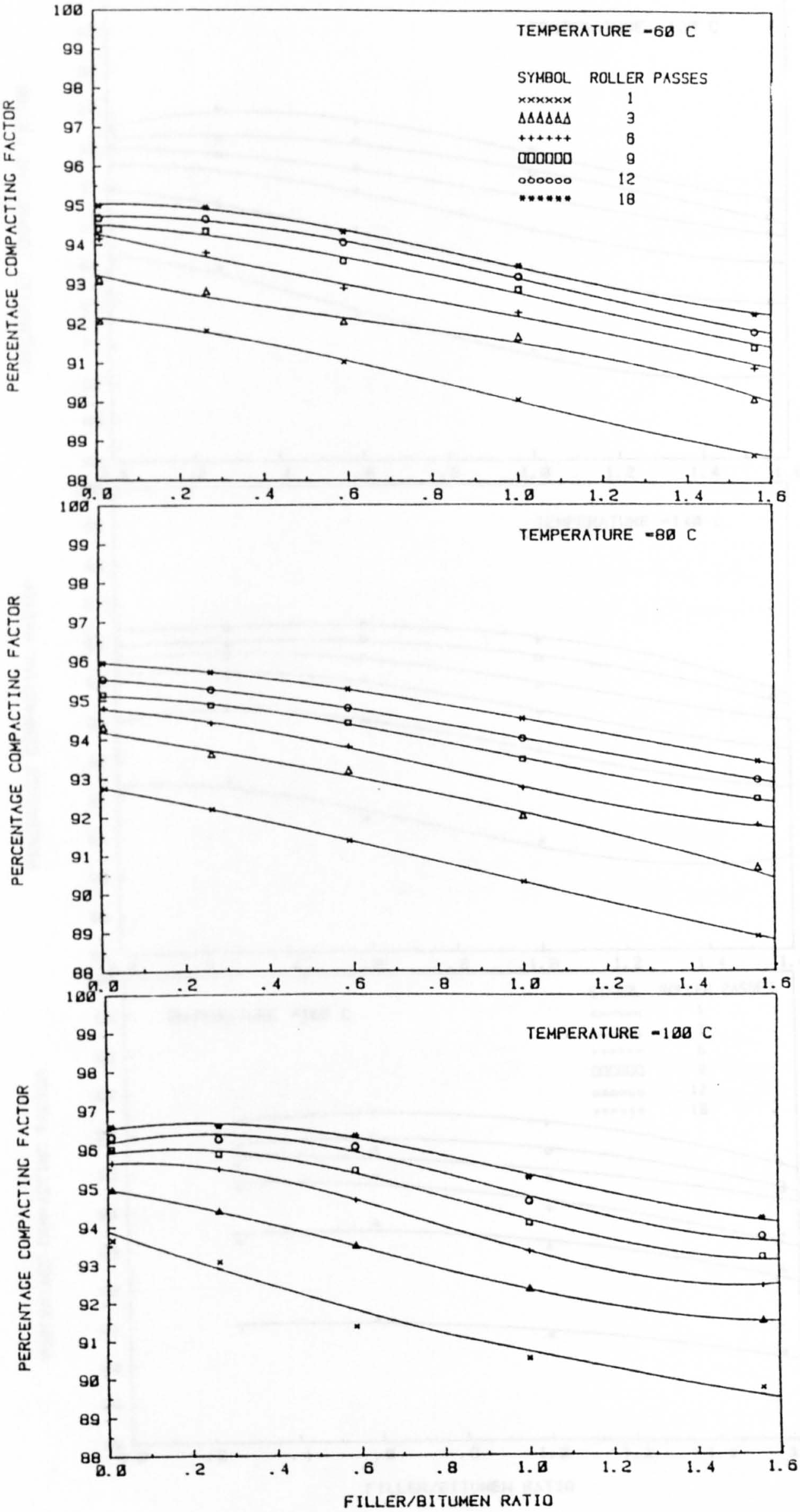


Figure 6.16: The relationship between Percentage Compacting Factor and filler/bitumen ratios for mixes with Test Series 2.

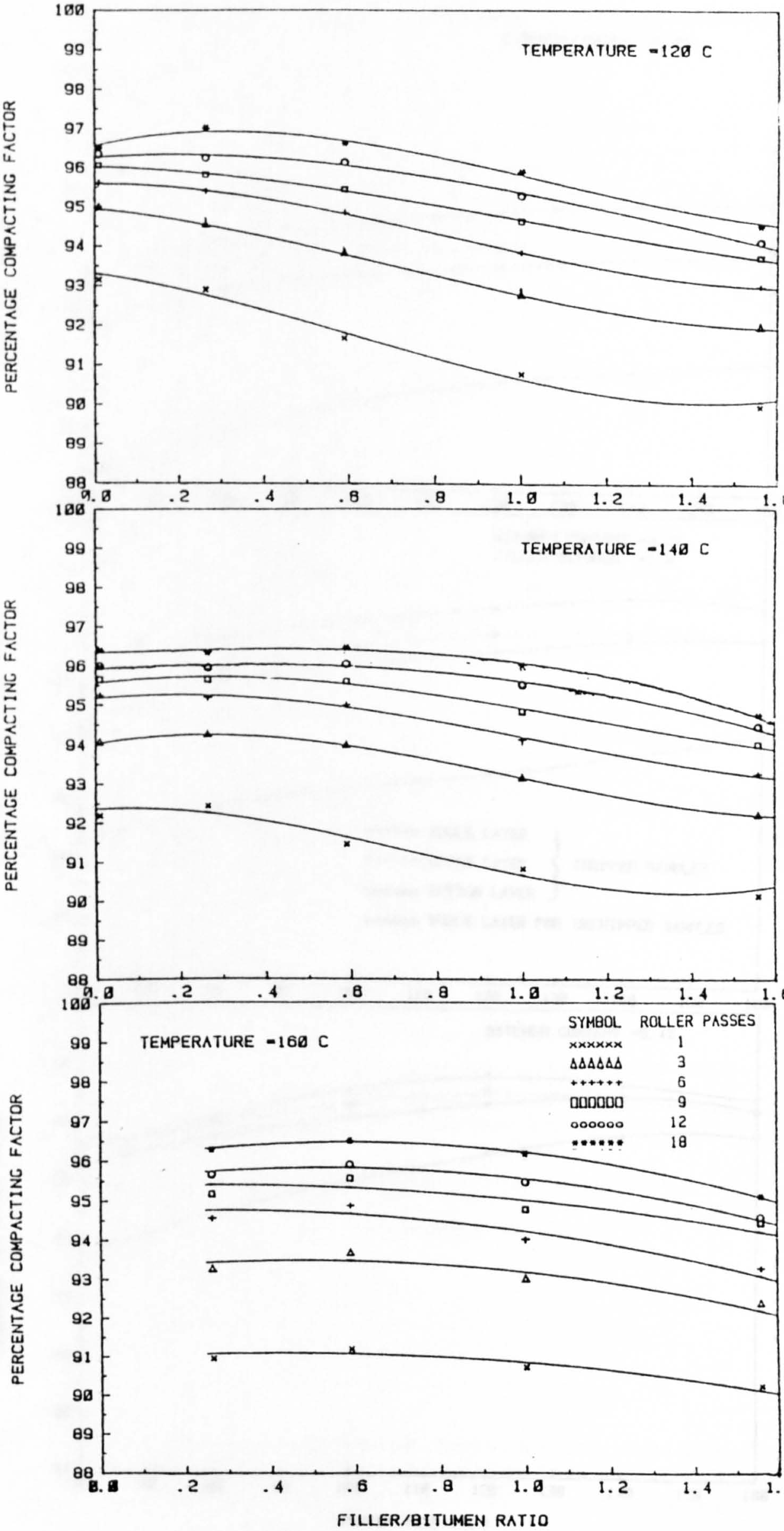


Figure 6.16: The relationship between Percentage Compacting Factor and filler/bitumen ratio for mixes with Test Series 2, continued.

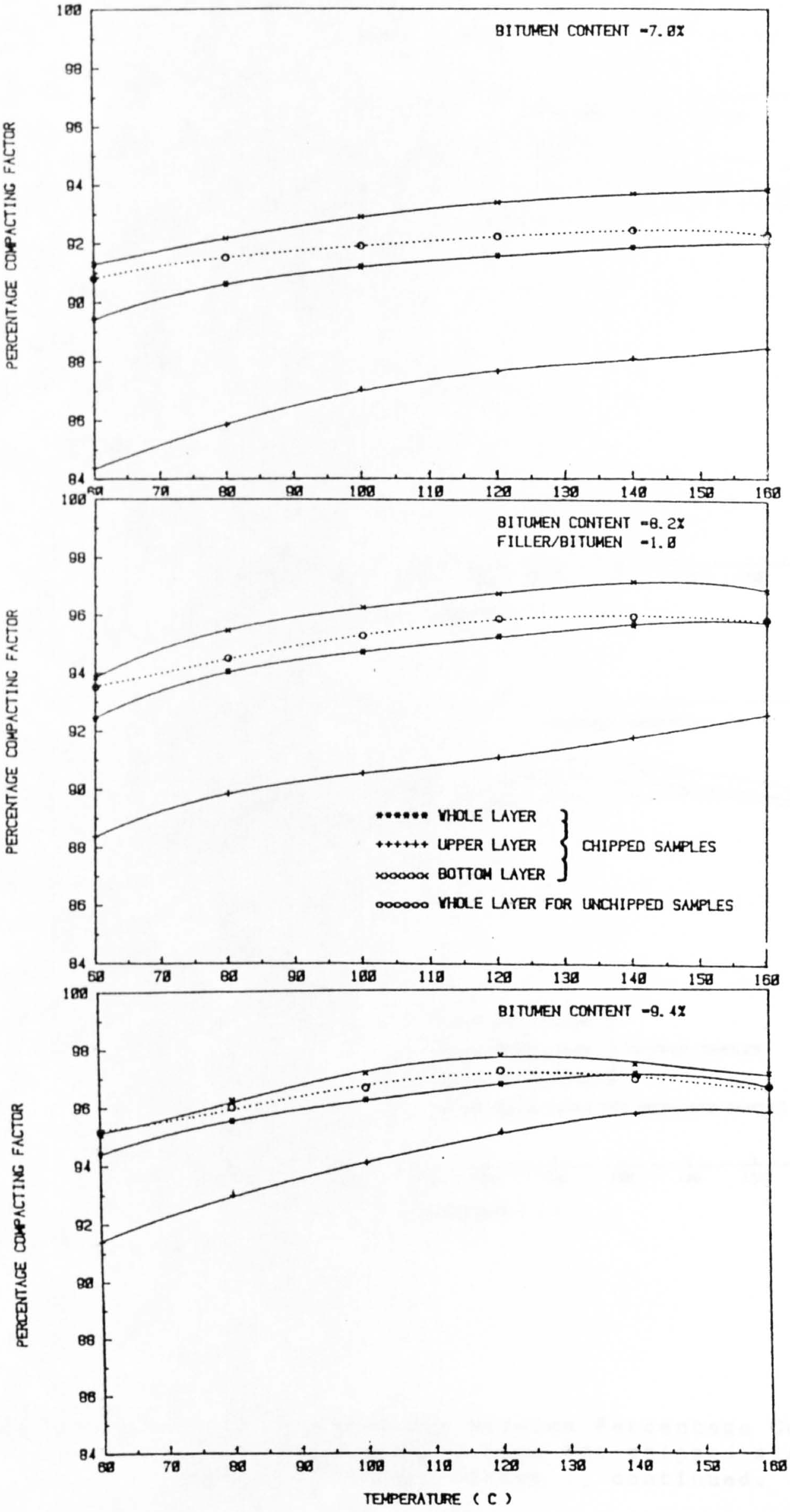


Figure 6.17: The relationship between Percentage Compacting Factor and temperature for chipped slab for mixes with Test Series 1.

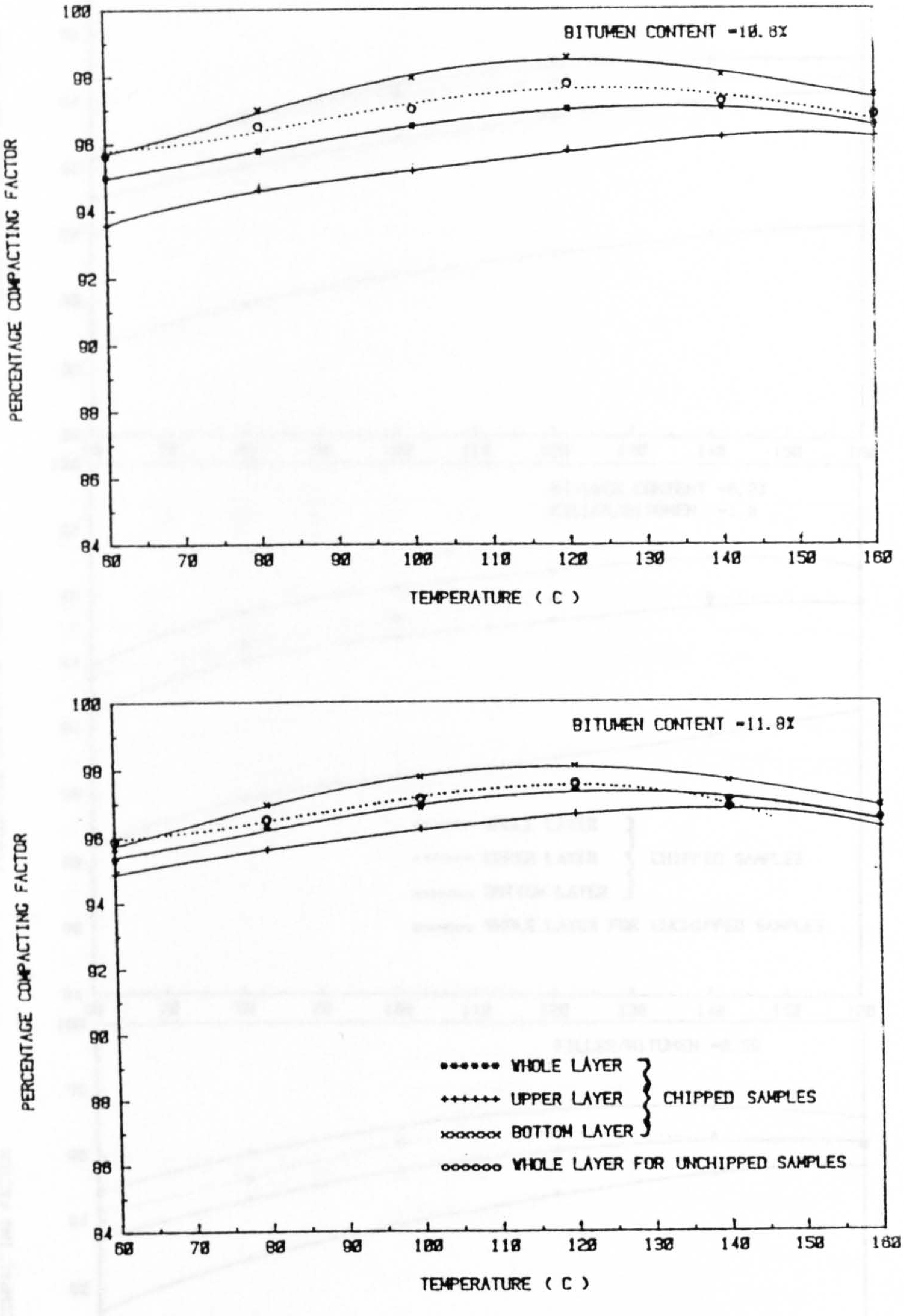


Figure 6.17: The relationship between Percentage Compacting Factor and temperature for chipped slab for mixes with Test Series 1, continued.

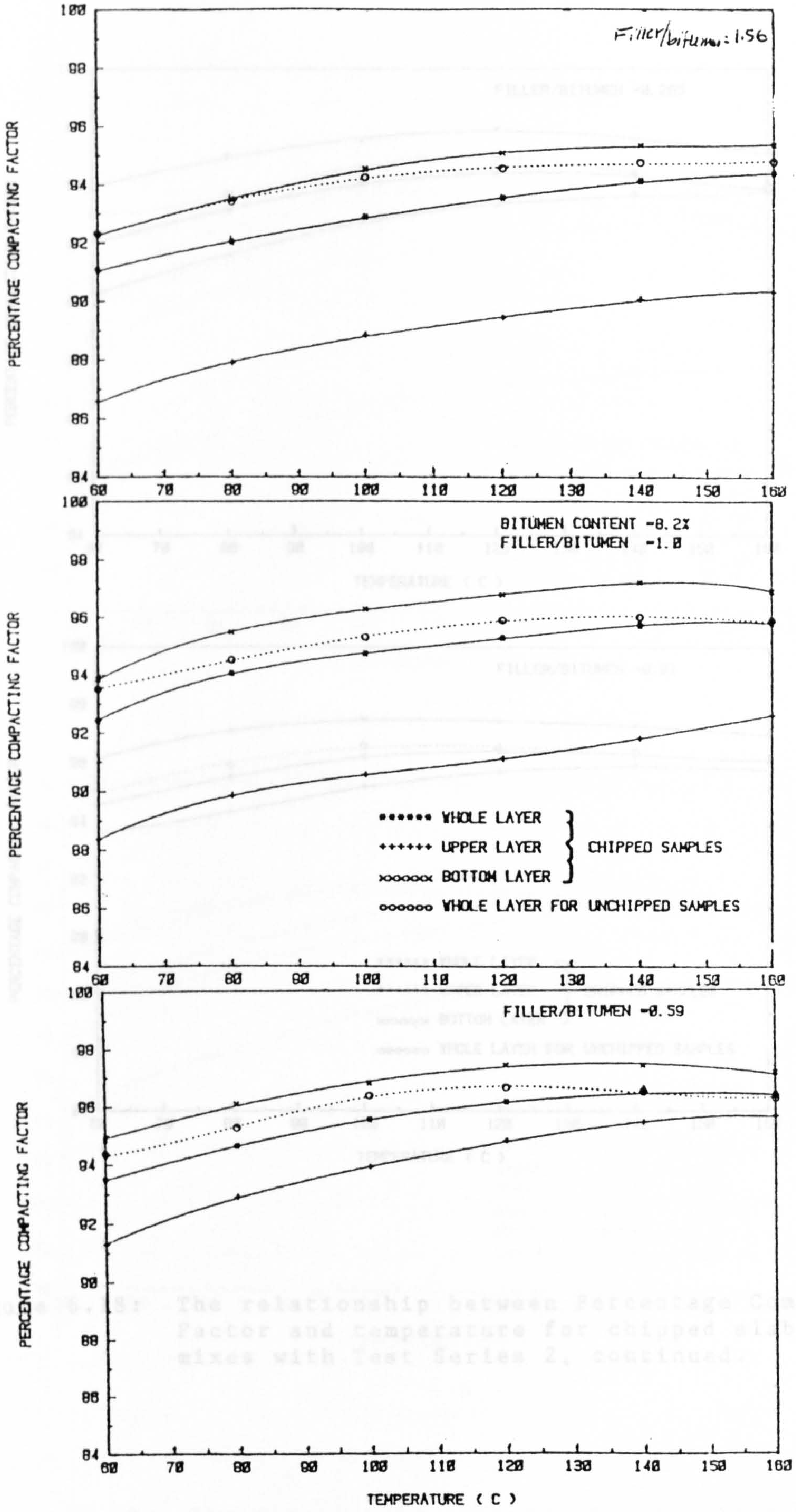


Figure 6.18: The relationship between Percentage Compacting Factor and temperature for chipped slabs for mixes with Test Series 2.

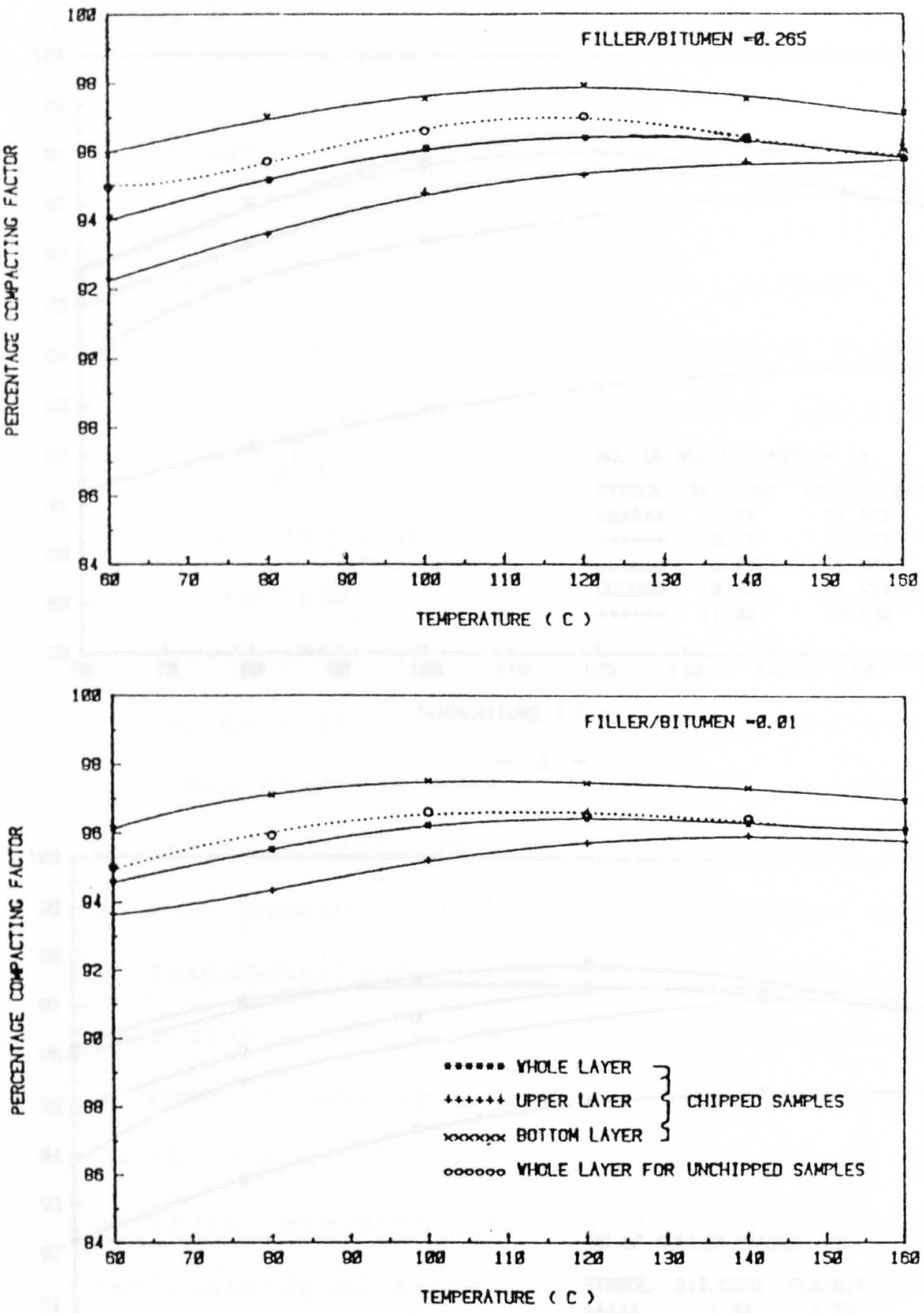


Figure 6.18: The relationship between Percentage Compacting Factor and temperature for chipped slabs for mixes with Test Series 2, continued.

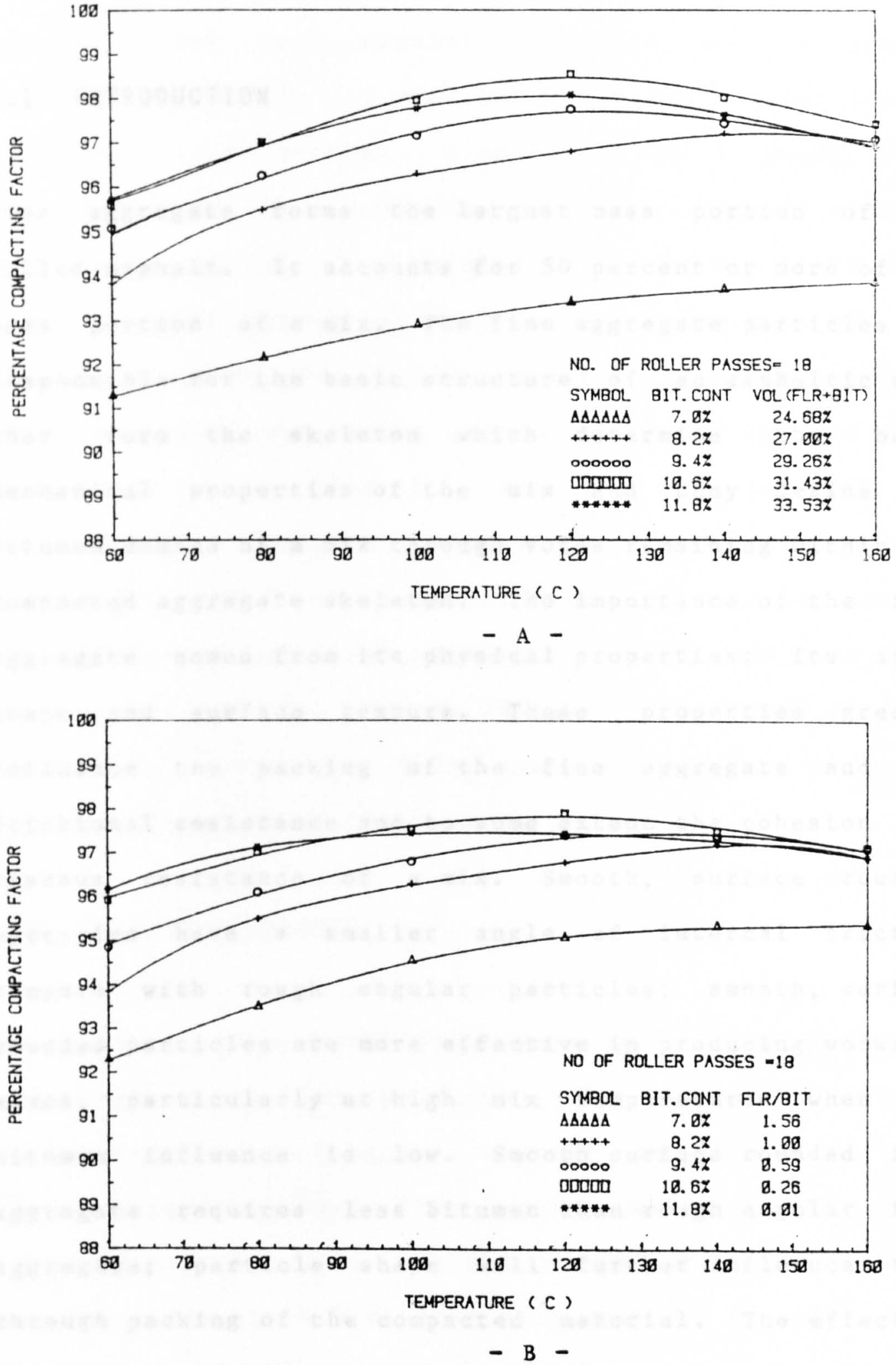


Figure 6.19: The relationship between Percentage Compacting Factor and temperature for the bottom sub-layer with chipped samples of: A - mixes with Test Series 1, and B - mixes with Test Series 2.

7.0 THE INFLUENCE OF FINE AGGREGATE ON ASPHALT WORKABILITY

7.1 INTRODUCTION

Fine aggregate forms the largest mass portion of hot rolled asphalt. It accounts for 50 percent or more of the mass portion of a mix. The fine aggregate particles are responsible for the basic structure of an asphaltic mix; they form the skeleton which determine the basic mechanical properties of the mix and they define the bitumen demand of a mix through voids remaining within the compacted aggregate skeleton. The importance of the fine aggregate comes from its physical properties; its size, shape and surface texture. These properties greatly influence the packing of the fine aggregate and the frictional resistance and to some extent the cohesion and viscous resistance of a mix. Smooth, surface rounded particles have a smaller angle of internal friction compare with rough angular particles; smooth, surface rounded particles are more effective in producing workable mixes, particularly at high mix temperatures when the bitumen influence is low. Smooth surface rounded fine aggregate requires less bitumen than rough angular fine aggregate; particle shape will further influence this through packing of the compacted material. The effect on bitumen demand between such materials may go as far as 4 percent, and even more. Duthie (130) stated that mixes made with rounded fine aggregate have stability and density maxima at bitumen content of about 6 percent, whereas mixes with angular particles show a gradual increase in density and stability over the bitumen content range of 4 to 12 percent. Szatkowski (131) using wheel tracking data, showed that at the same rate of tracking four fine aggregates included a bitumen content which differed over a range of four percent. The work of this chapter is an adjunct to main research programme which was used to explore the nature of the test data obtained using commercial mixes, and it was used to identify the influence of the fine aggregate on the resistance to internal movement of an asphalt mix. Data on the quality of two additional fine aggregate blends and the site performance of four commercial mixes is reported. The four mixes used two fine aggregate blends; each fine aggregate blend used two bitumen contents.

7.2 TESTING PROGRAMME

Four mixes were tested which were two variants of two commercial mixes from two plants. The plants were located in the South-east of England and used local material. The coarse aggregate and filler were crushed limestone; the fine aggregates were natural sands and came from four sources. The mixes have been labelled M1, M2, M3 and M4. Mixes M1 and M2 were made with fine aggregate labelled sand type B; mixes M3 and M4 were made with fine aggregate labelled sand type C. Sand types B and C were each a blend of fine aggregate from two different sources. The components of sand type B were a fine 'sand' labelled B1 and a coarse 'sand' labelled B2; the components of sand type C were (also) a fine 'sand' labelled C1 and a coarse 'sand' labelled C2. As a basis of comparison data with the fine aggregate of the main test programme is presented, this fine aggregate is labelled A.

All mixes using the blended fine aggregates were mixed by commercial plants. Batches from one day's production were bagged and transferred to the laboratory. The materials were reheated using a microwave oven of 20 Kg capacity to a temperature of around 170°C. The use of a microwave oven reduced the time of heating of mixes substantially, to about 15 minutes. Such time is unlikely to put a mix at any serious risk of oxidation or embrittlement through evaporaton of volatiles.

Each pair of mixes made with one type of fine aggregate incorporated two nominal binder contents: 7.1 percent and 6.5 percent. The average percentage of ingredients with each mix is shown in Table 7.1 The values in Table 7.1 are based on the average of analysed site samples.

Table 7.1: Percentage of mixes ingredients

Ingredients	Sand type B		Sand type C	
	M1	M2	M3	M4
Bitumen	7.13	6.56	7.06	6.53
Filler	8.96	8.53	9.9	9.00
Fine aggregate	50.96	52.56	53.06	56.17
Coarse aggregate	32.95	32.35	29.98	28.3
Filler/bitumen	1.26	1.3	1.4	1.38

Samples for triaxial testing were prepared with a void content between 4 and 5 percent. The method of sample preparation and testing was the same as described in Chapter 3. The samples were tested over the temperature range 80°C to 150°C. A second series of samples were prepared for roller compaction with a pre-compaction void content of 12 percent + 0.5 percent. The samples were compacted using a surface applied chipping rate of 70 percent and 18 passes of the laboratory roller.

To quantify the characteristics of the fine aggregates two measures were used: the voidage of a semi-compacted blend of fine aggregate and filler; and, the angle of internal friction of blends of fine aggregate and filler. The measures were made to describe the packing of the fine aggregates as a mechanism to explain the triaxial test data with the asphalt mixes.

Samples of dry unwashed fine aggregate were blended with different percentages of filler; the filler being that used in the main test programme. Using a 'standard' added filler enabled the fine aggregate properties to be defined and compared. The blends were tested by triaxial testing, using the standard procedure and after semi-compaction. The test provided a measure of angle of internal friction as well as void content. The latter was calculated by determining the blend density and its specific gravity. The blend density was defined by dividing the weight of material that occupied the sample container by the volume of the container. Scanning electron microscope (SEM) photographs were made of the four fine aggregates and the filler. These photographs provided important qualitative information on the shape and surface texture of the fine aggregate, and an appreciation of the grading of the filler. Samples of the filler and fine aggregates were prepared for the SEM photographs by extracting specific fraction sizes: material lying in the size range 300μm and 150μm, a size fraction used by many investigators (132, 133, 134); and, material passing the 75μm sieve size, which does not necessarily have the same properties as other size fractions, particularly with natural fine aggregate. A sample of the filler added to all mixes was also photographed.

7.3 RESULTS AND DISCUSSION

7.3.1 General

Triaxial and rolling test data are shown in Figures 7.1 and 7.2. The results show low values of internal resistance components (angle of internal friction, mix cohesion and mix viscosity) when compared with the values obtained with the laboratory prepared mixes of the main test programme, in spite of the low bitumen contents, high filler to bitumen ratios and similarity in aggregate proportions. As a result of the low values of internal resistance the Percentage Compacting Factor values are higher than those for corresponding mixes in the main test programme.

However, the important differences between the measured components of internal resistance to movement with mixes M1, M2, M3 and M4 and the four series in the main programme is the nature of the fine aggregates. The 'nature' of the fine aggregates have been characterised in the data of the triaxial and Scanning Electron Microscope (SEM) on the fine aggregate samples.

7.3.2 Data from the scanning electron microscope

Plates 7.1 to 7.18 show the SEM photographs for the fine aggregate and filler fractions used in mixes M1, M2, M3 and M4. For comparison, sand type A used in the main test programme are shown in Chapter 5. From the SEM photographs the following points can be made:

a) the components of fine aggregates B and C, as indicated by the 300 μm to 150 μm fraction, are rounded and relatively surface smooth.

b) the filler fraction of the four mixes was generally not as surface rough as that of the included filler and that used in the main programme.

c) the filler fraction of sand type C1 appears to be of small size (microfines),. its surface roughness is equivalent to that of the filler used with sand type A in the main test programme.

7.3.3 Data from triaxial testing of the fine aggregate-filler samples

The main feature of the fine aggregate particles is their frictional properties. A dry loose sample of fine aggregate type B gave a measured angle of internal friction of 42.6° and that of type C of 41°; both of them less than that of type A at 45.6°. The results of the triaxial testing of fine aggregate-filler blends are shown in Figure 7.3.

The profile of angle of internal friction with percentage blends of fine aggregate and filler exhibits a continuous decrease in value when the filler percentage increases with samples made with sand type A and B. This phenomena was explained in Chapter 5, section 5.2.1. Sand type C exhibits a concave upward profile. Although sand type C has the lowest measured value of angle of internal friction, when filler is added the measured angle of internal friction increases markedly to a peak value before it decreases. The increase in value of angle of internal friction with increase in filler content may be related to the presence of the 'natural' filler portion of sand type C (material less than 0.075mm). This portion of the fine aggregate is very fine material, and angular, as shown in Plates 7.13 and 7.14. The angularity of the filler fraction of this fine aggregate is markedly more than the bulk material. The maximum particle size of the natural filler fraction of sand type C is much less than 0.075mm; the fine aggregate/filler blend is consequently gap graded, at the fine fraction end of the fine aggregate grading. With no added filler (giving a more complete grading less than 0.075mm) the influence of the natural filler fraction is limited. As filler is added to sand type C the influence of the included (and angular) filler fraction is 'mobilised', resulting in an increase in measured angle of internal friction. Above a volume percentage of added filler, when it 'floods' the free voids in the fine aggregate, the measured angle of internal friction reduces as with the control fine aggregate.

The reasoning put forward for the angle of internal friction profile is also valid for the voidage profile. Figure 7.4 shows that the addition of crushed limestone filler to sand type C decreases the void content as a consequence of the more complete grading of the fine aggregate filler blend. The added filler percentage at the lowest void content closely relates that of the highest angle of internal friction value.

7.3.4 Packed void content measurements

Table 7.2 shows the values of voidage within loose dry samples and wet semi-compacted samples of fine aggregate. The voidage of fine aggregate samples were calculated using the moulds for preparing triaxial samples. With dry loose samples fine aggregate was poured carefully into the mould until it was filled. The mould was weighed when empty and when filled with fine aggregate. The bulk density, the specific gravity and the voidage of the sample was calculated using this procedure. With semi-compacted samples the moulds were agitated whilst being filled with fine aggregate which had been immersed under water for 24 hours. Water was added to the moulds during the process of filling and agitating. The principal applied was that a flooded fine aggregate assumes a minimum arrangement of particles, as with a fully compacted dry sample. The volume of added water was considered the volume of voids within the fine aggregate. The data is shown in Table 7.2

Table 7.2: Voidage and angle of internal friction data of sand type A, B and C

Sand Type	voidage (percentage)		angle of internal friction
	dry loose	wet semi-compacted	
A	42.3	35.6	45.6
B	39.1	32.8	42.6
C	33.8	30.8	41.0

Sand type C appears to more readily compact itself the loose compacted voidage is the lowest measured and it indicates the least additional compaction. This is possibly an indication of the ability of this fine aggregate to self compact as a result of its shape, surface texture and grading.

7.3.5 Discussion of triaxial and rolling results

Before making observations and drawing conclusions from the profiles of angle of internal friction, mix cohesion, mix viscosity and compaction, it is important to comment on the scatter of points on the graphs. This is as a result of the differences between the mixes tested. Four tonnes of material were brought to the laboratory in more than 100 bags. One or more bags represented a batch of material. Although bags of material were warmed for remixing before sampling, more than one bag could not be remixed. Each point therefore represents, to the best of laboratory procedures, tests on a batch of material. But, from mix analysis batch mix proportions show significant variation, although the variations are within the limits of the British Standard Specification, as shown in Table 7.3. The reasons are most likely to be plant variation, sampling on site and filling of bags. However the proportions of any commercial material are different from weighing the exact amount of each ingredient and mixing them in the laboratory.

Comparing the triaxial data for the four mixes, the most significant feature is the profile of angle of internal friction. All mixes show low values of this parameter. The optimum temperature for the mixes are lower than mixes of equivalent bitumen content and filler to bitumen ratio within the main test programme. As in the main test programme the profiles of angle of internal friction are very similar to the profiles of Percentage Compacting Factor, measured with asphalt below the chippings. Although the profiles of angle of internal friction are not a direct measure of the compaction of materials, which is also a function of mix cohesion and mix viscosity, the profiles do suggest, it is believed, the temperature sensitivity of the materials. The profiles of Percentage Compacting Factor have gradients in the same ranking order as angle of internal friction profiles, although they are more 'peaky'. The optimum temperature indicated by the angle of internal friction profiles appear similar to those suggested by the Percentage Compacting Factor profiles. The high values of Percentage Compacting Factor reflect the low values of mix cohesion and mix viscosity.

Mixes M3 and M4 show concave upward profiles with mix cohesion. These type of profiles reflect a mix with an imbalance in its mix proportions. The profiles of mix cohesion with mixes M3 and M4, which are both made with sand type C, are similar to those mixes made with no filler for Test Series 2 in the main test programme. This similarity may be the result of the gap grading in the filler/fine aggregate system within the mix. It may be that the added filler does not reduce the pore size within the system to trap the natural included filler fraction. This material will therefore form part of the bitumen phase. For the system the filler fraction is not effective, but the stiffness of the bitumen will be increased, leading consequently to the upward concave profile.

The type of fine aggregate used in mixes M1 to M4 is responsible, to some extent, for the low mix cohesion values, which come from the low interlocking resistance of these fine aggregate.

The filler percentage is relatively high for the type of fine aggregate used in mixes M1 to M4. The filler reduces the effective interlocking resistance of the fine aggregate; possibly because of the fineness of the filler (Plates 7.17 and 7.18).

The change in bitumen content between mixes M1 and M2 and between mixes M3 and M4 has only a small influence on mix cohesion. Many researchers report that mix cohesion value peak at bituminous content between 4 percent to 7.1 percent (45, 62, 72).

Mix viscosity profiles are also low for the same reason as for mix cohesion. Mix viscosity profiles show a flat profile for a considerable range of temperature which may be an indication of the high compaction potential of those mixes. Mixes M1 and M3 exhibit higher mix viscosity values than mixes M2 and M4, in spite of mixes M1 and M3 having a higher bitumen content. This abnormal behaviour may be in line with the finding of Pfeiffer (41) who stated that the excess of bitumen - the volume of the bitumen by which it exceeds the voids of the aggregate - strongly reduces the internal friction and completely eliminates the cohesion and increase the viscous resistance. In his explanation he reported that when a mineral mixture is deformed the particles shift over each other, but they will also try to roll and turn - when particles turn over and shift in the material it makes all the difference whether there is a layer of air between the moving parts or viscous mass which is bound to the mineral aggregate by cohesion forces.

7.4 General points about the effect of the fine aggregate on asphalt workability

a) The optimum compaction temperature of rounder, more surface smooth fine aggregates reduces by 30°C when compared with similar mixes made with more angular, surface rough fine aggregates. This is understood when the relationships shown in Chapter 9, Figure 9.1, which represent the optimum temperature when bitumen content, filler to bitumen ratio and the grade change, is considered. The optimum compaction temperature with such fine aggregate will reduce further when the bitumen content increases, filler to bitumen ratio reduces and the penetration grade values increase.

b) Sand type C produce the highest percentage compacting factor values. This comes from the higher mastic volume relative to small fine aggregate's voids values, which is a direct result of the packing ability and well grading sand.

c) The reduction in bitumen content enhances temperature susceptibility as shown in mix M2 while the effect diminishes in mix M4 due to the type of sand and due to high filler to bitumen ratio which overcomes the reduction in bitumen content.

d) The type of fine aggregate very much influences the bitumen demand. Mixes in which the bitumen content is as little as 6.5 percent of the content of a mix have been shown to exhibit a similar level of internal resistance to movement, or Percentage Compacting Factor, as mixes made with other types of fine aggregate made with bitumen content of 10.6 percent or even 11.8 percent. This finding confirms the fact that different fine aggregate may produce similar properties when bitumen content varies 4 to 5 percent. This fact is needed to be acknowledged in the Standard Specification.

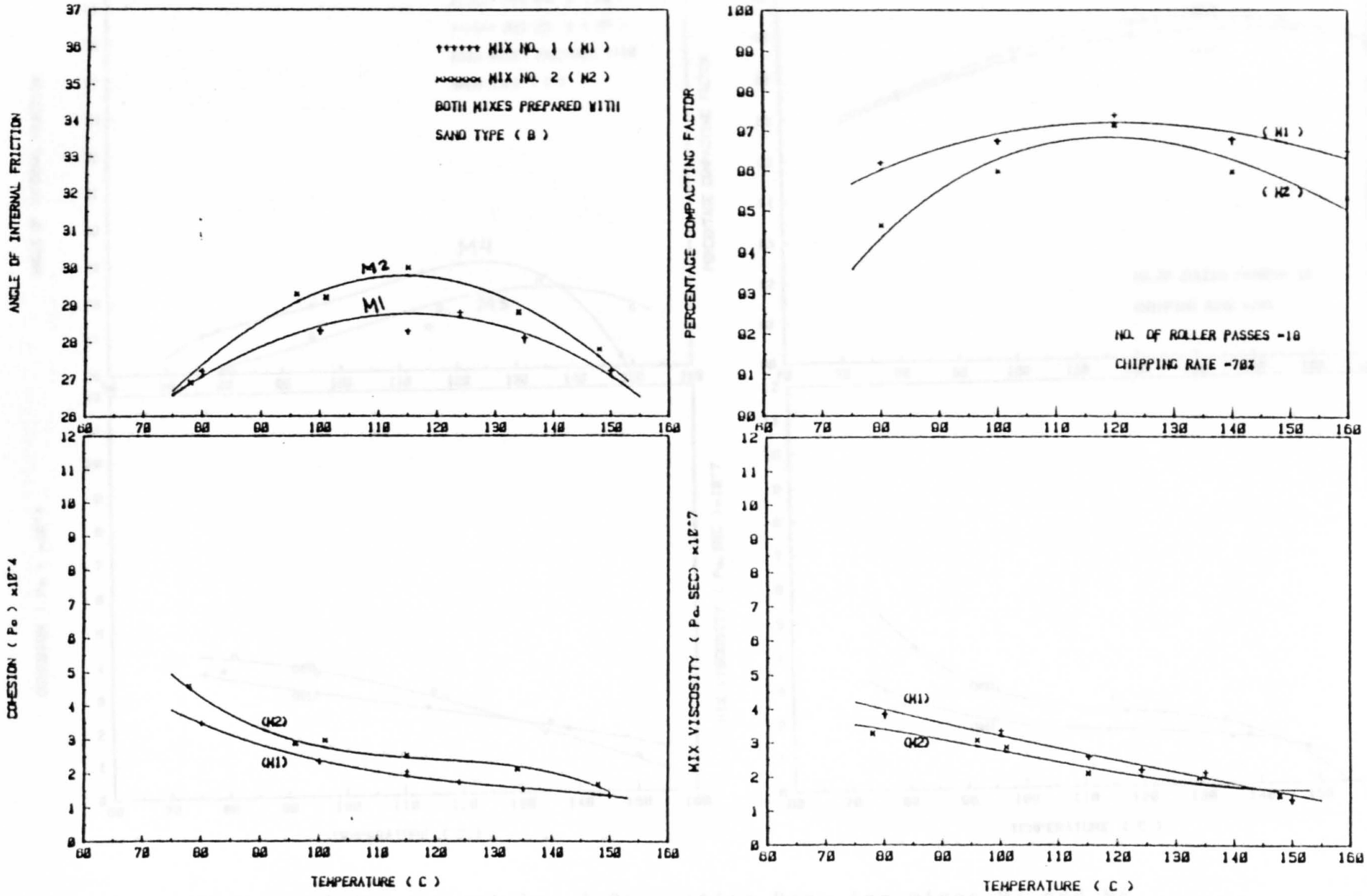


Figure 7.1: Triaxial and compaction data for mixes M1 and M2

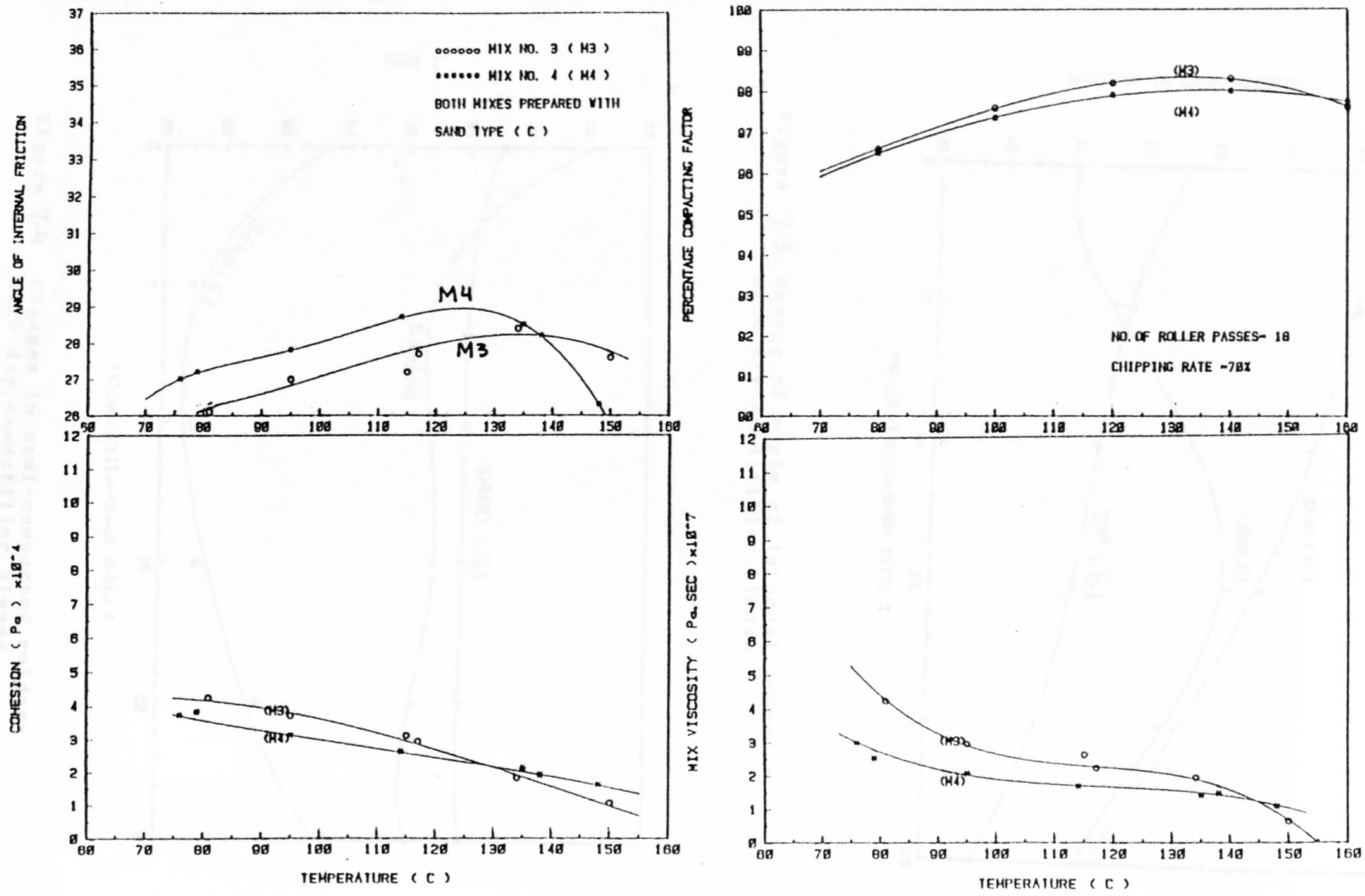


Figure 7.2: Triaxial and Compaction Data for mixes M3 and M4

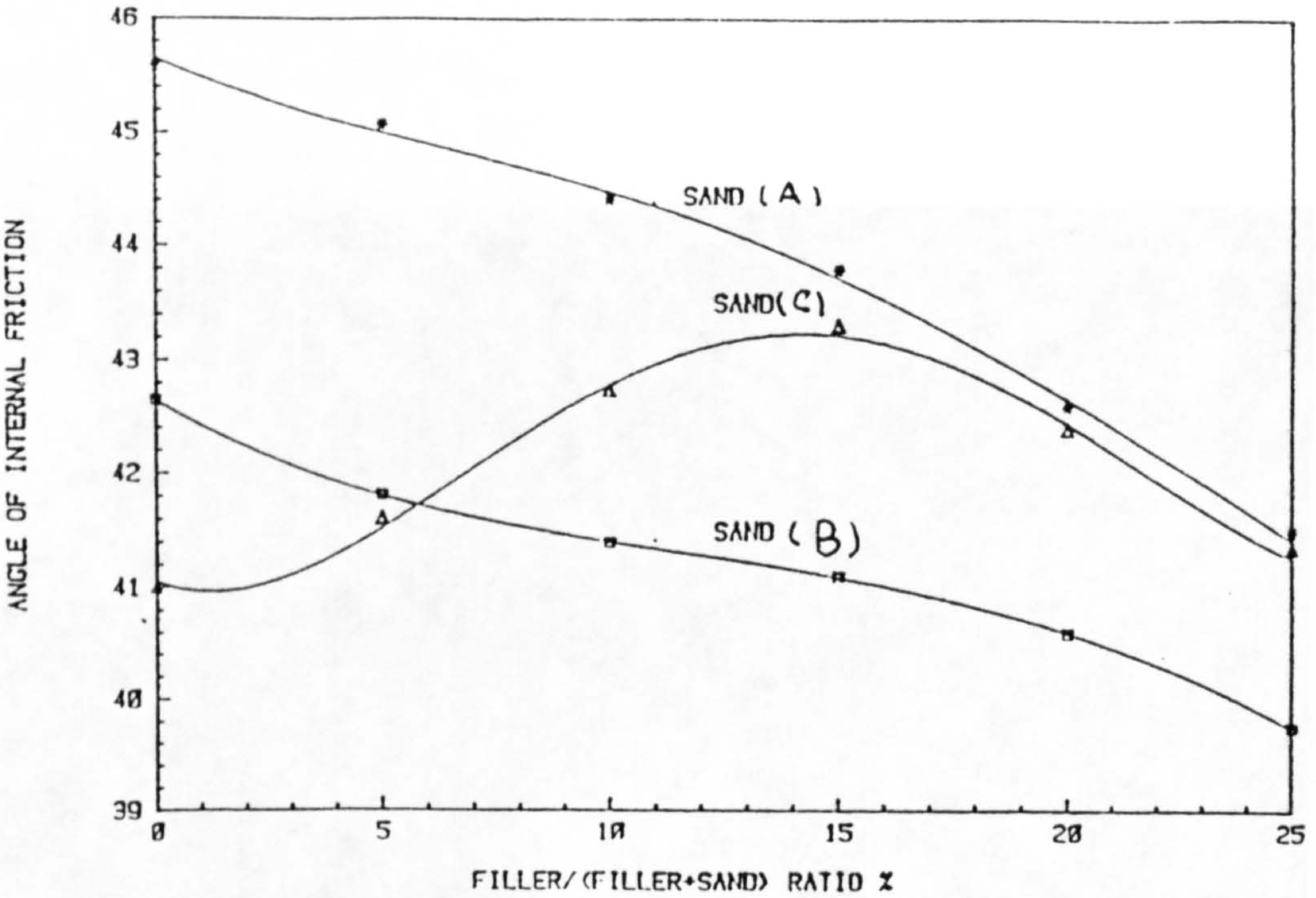


Figure 7.3 Change of angle of internal friction with dry sand:filler blends

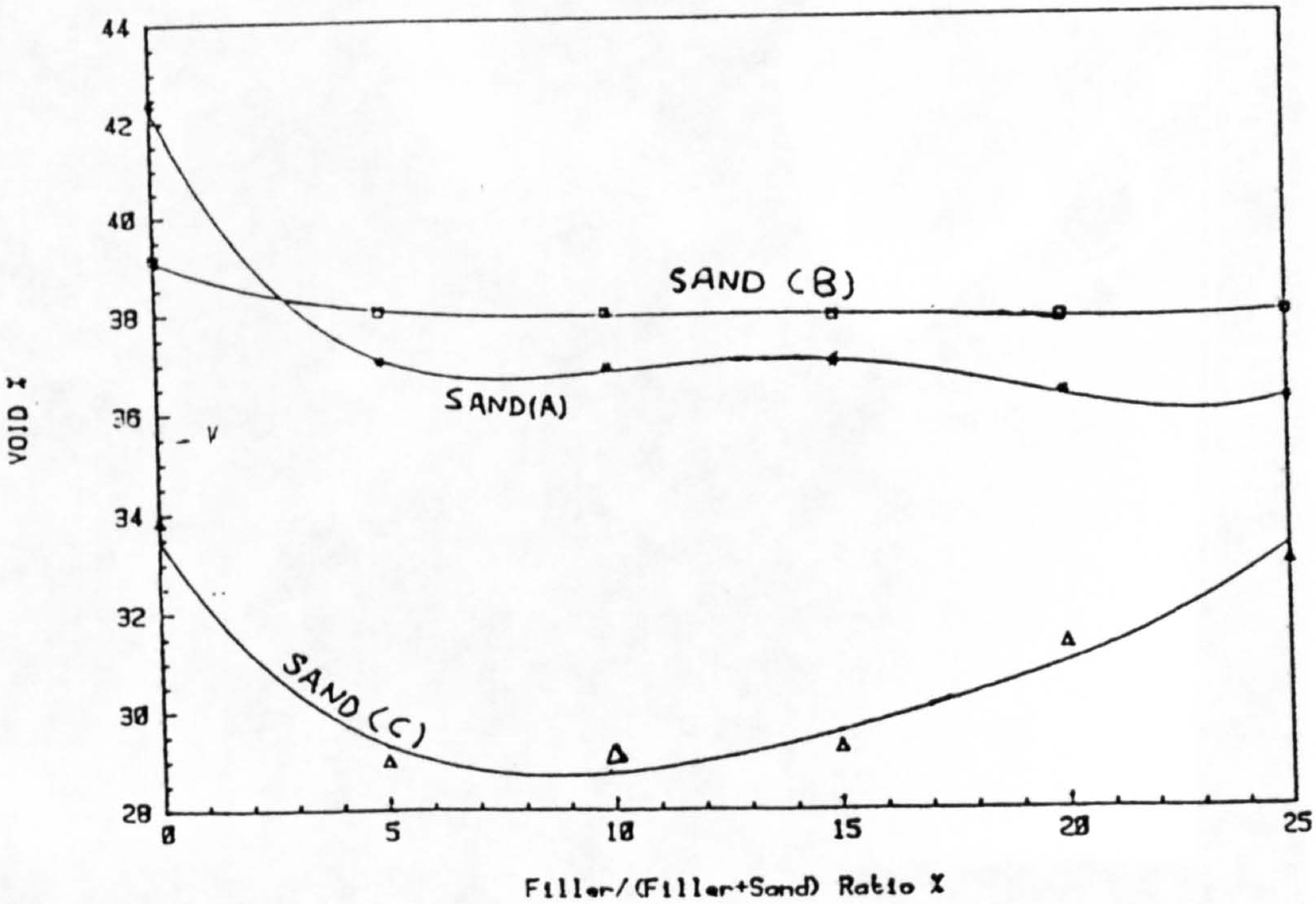


Figure 7.4 Changes in semi-compacted voidage with dry sand:filler blends

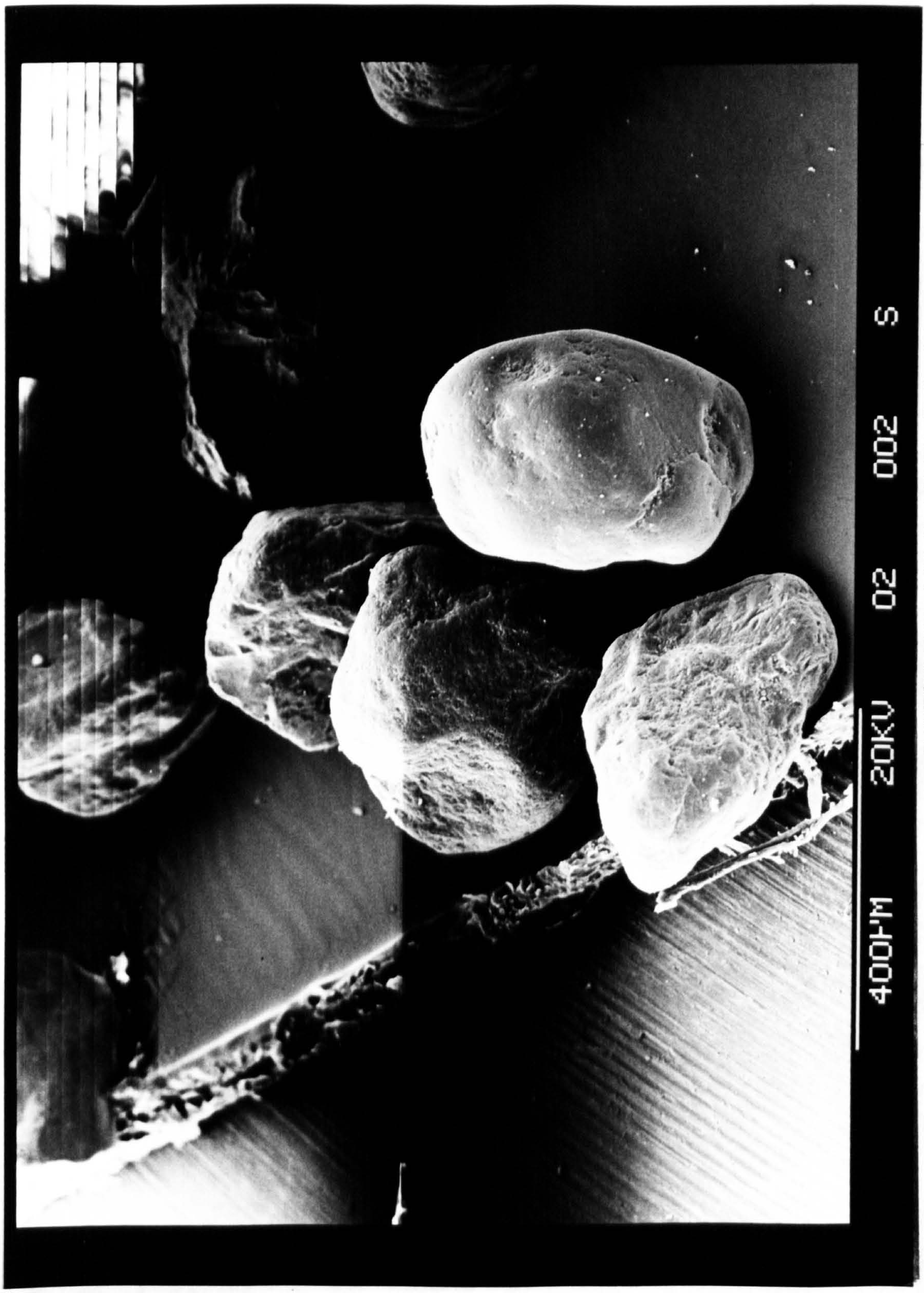


PLATE [7-1] SAND TYPE (B1) PARTICLES SIZE(0.15 TO 0.3 MM)

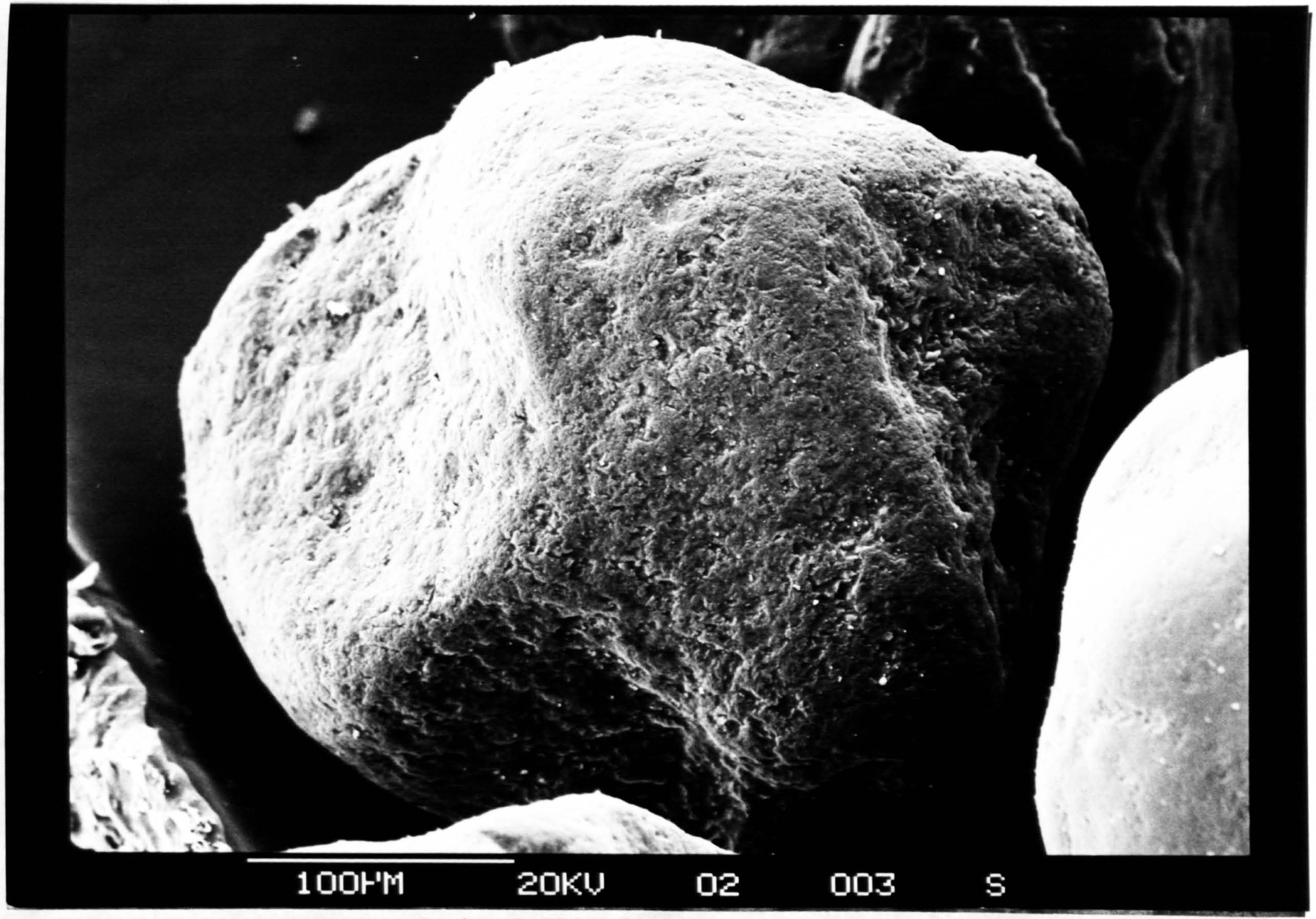


PLATE [7-2] SAND TYPE (B1) PARTICLES SIZE (0.15 TO 0.3 MM)

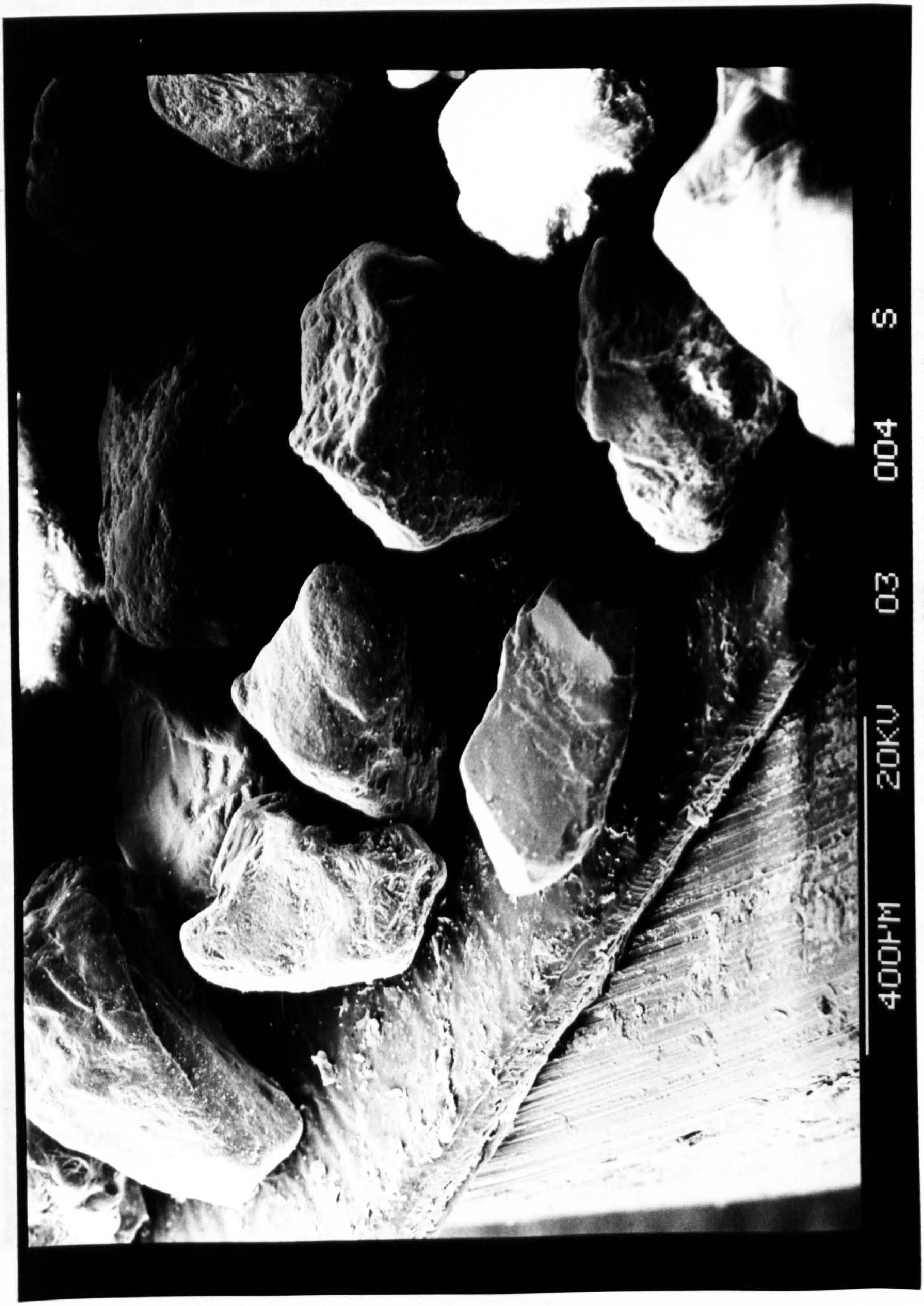


PLATE [7-3] SAND TYPE (B2) PARTICLES SIZE (0.15 TO 0.3 MM)

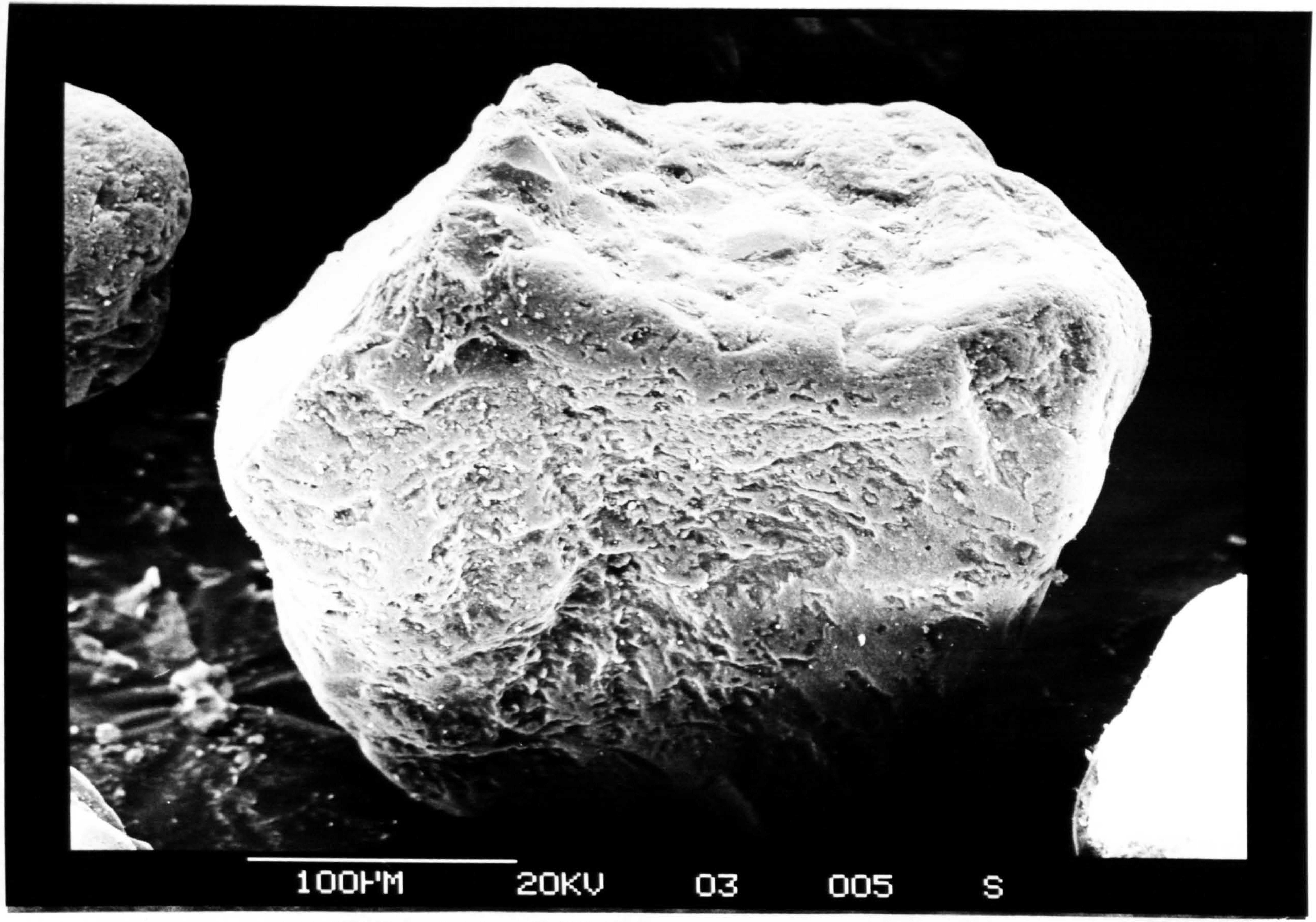


PLATE [7-4] SAND TYPE (B2) PARTICLES SIZE (0.15 TO 0.3 MM)

PLATE [7-5] SAND TYPE (C1) PARTICLES SIZE (0.15 TO 0.3 MM)

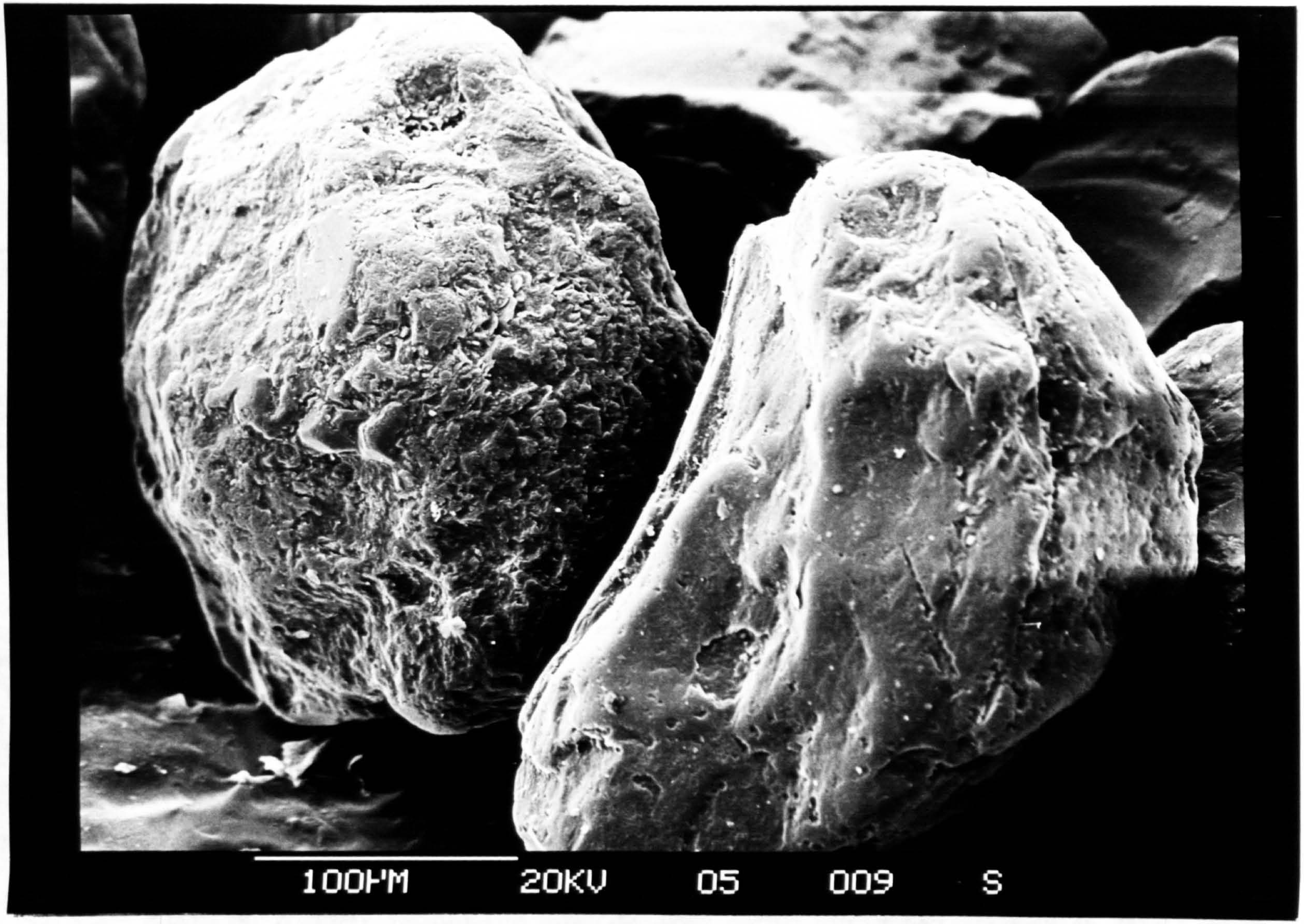


PLATE [7-6] SAND TYPE (C1) PARTICLES SIZE (0.15 TO 0.30 MM)

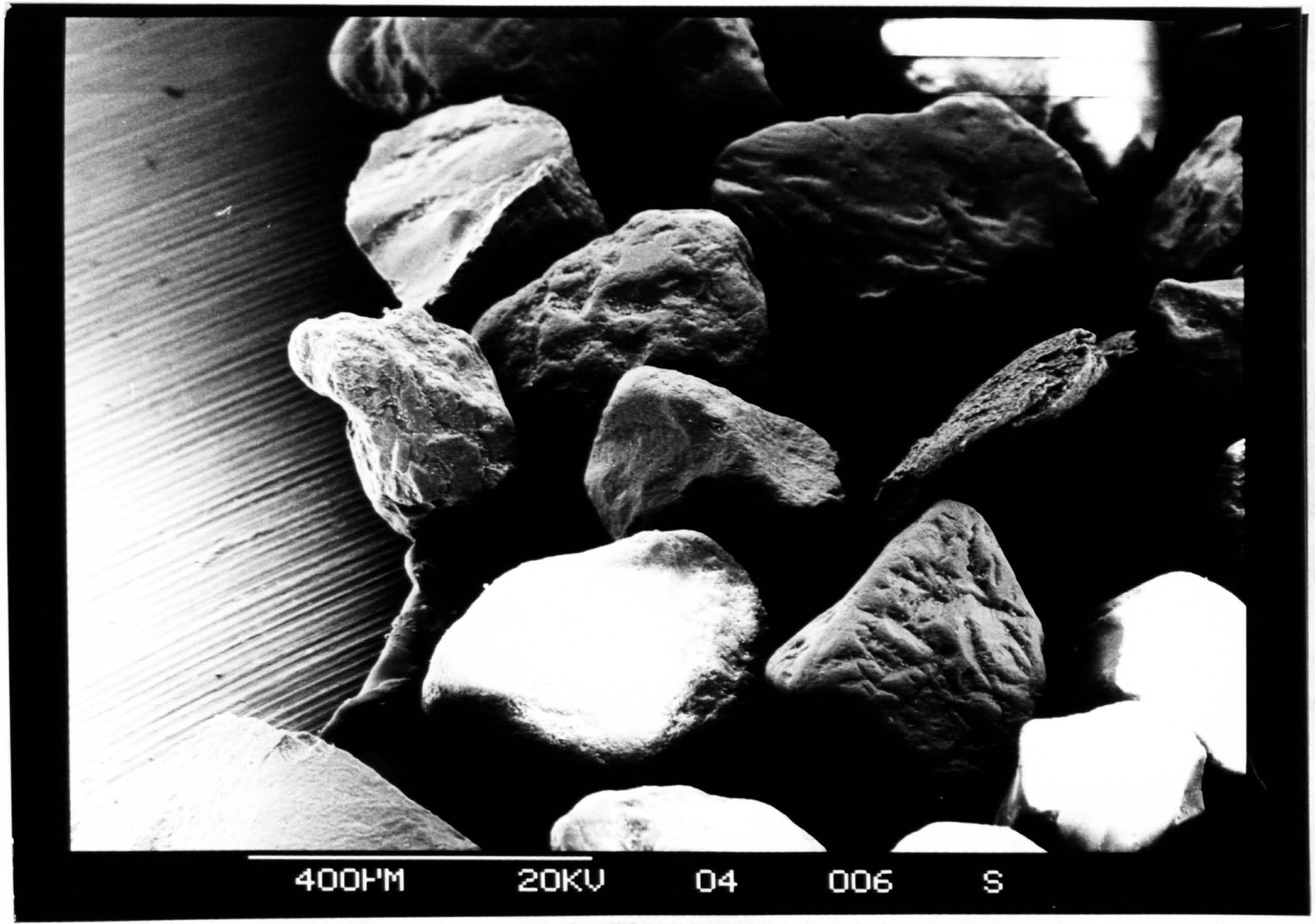


PLATE [7-7] SAND TYPE (C2) PARTICLES SIZE (0.15 TO 0.3 MM)

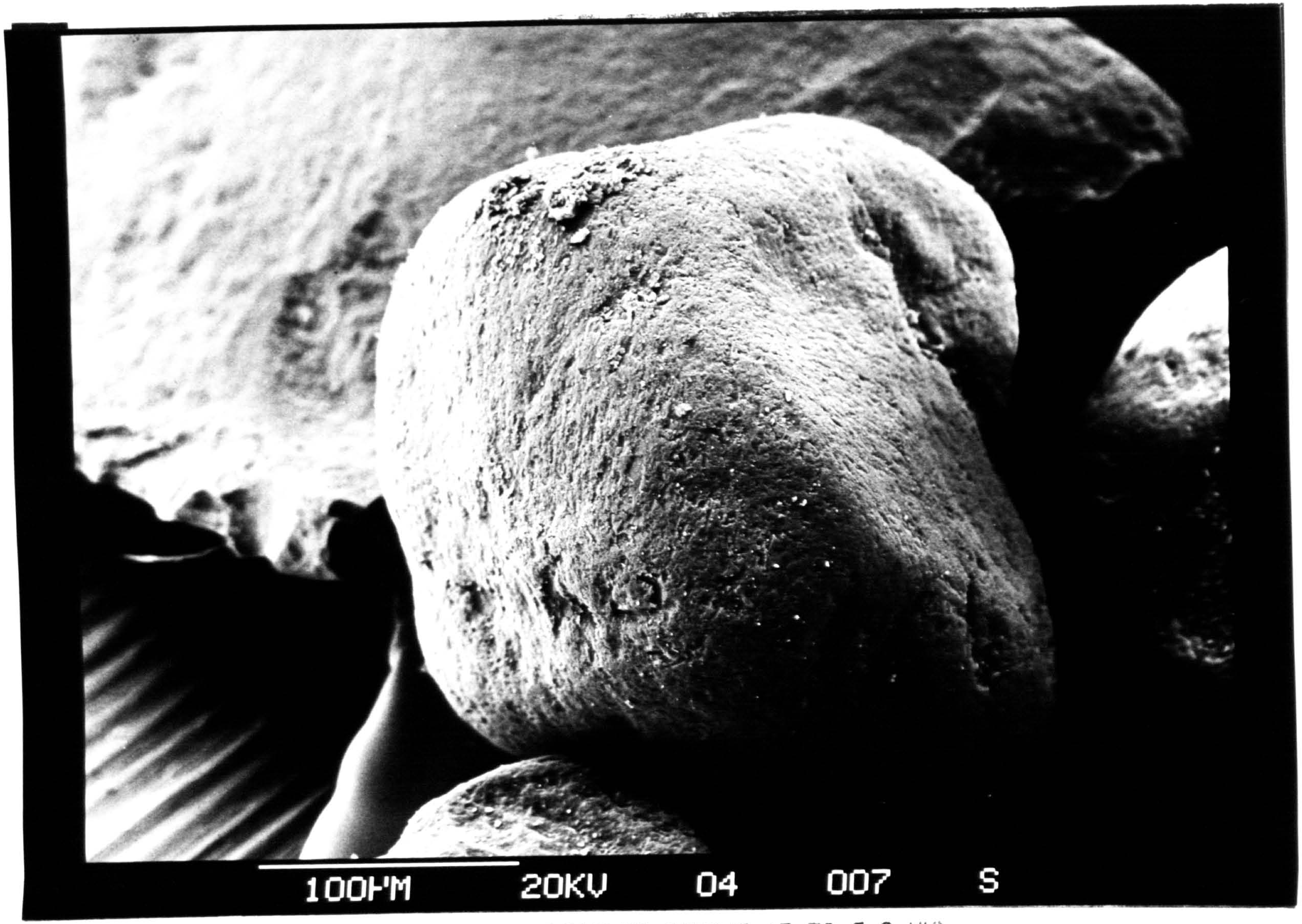


PLATE [7-8] SAND TYPE (C2) PARTICLES SIZE(0.15 TO 0.3 MM)

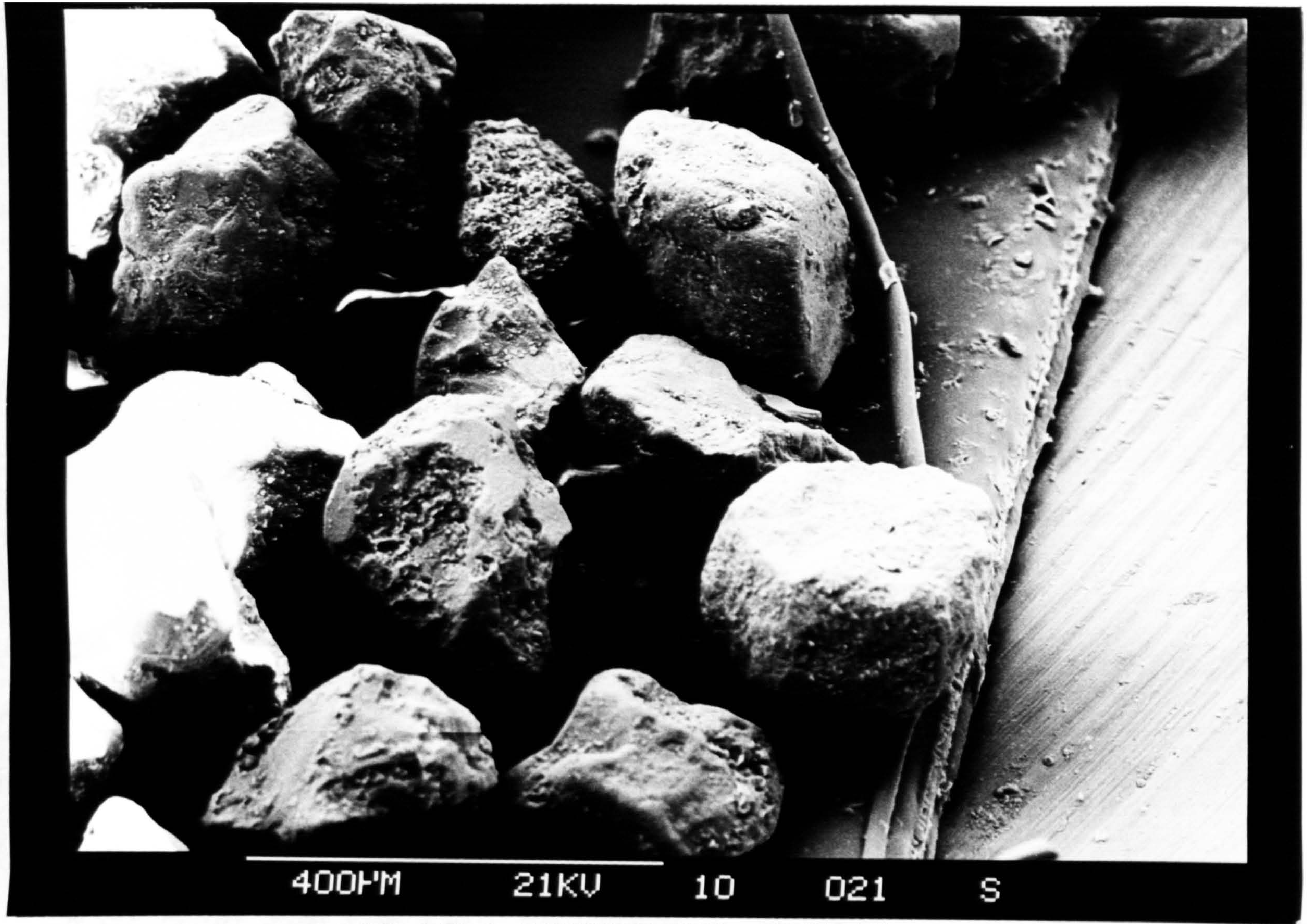


PLATE [7-9] SAND TYPE (B1) PARTICLES SIZE < 0.075 MM

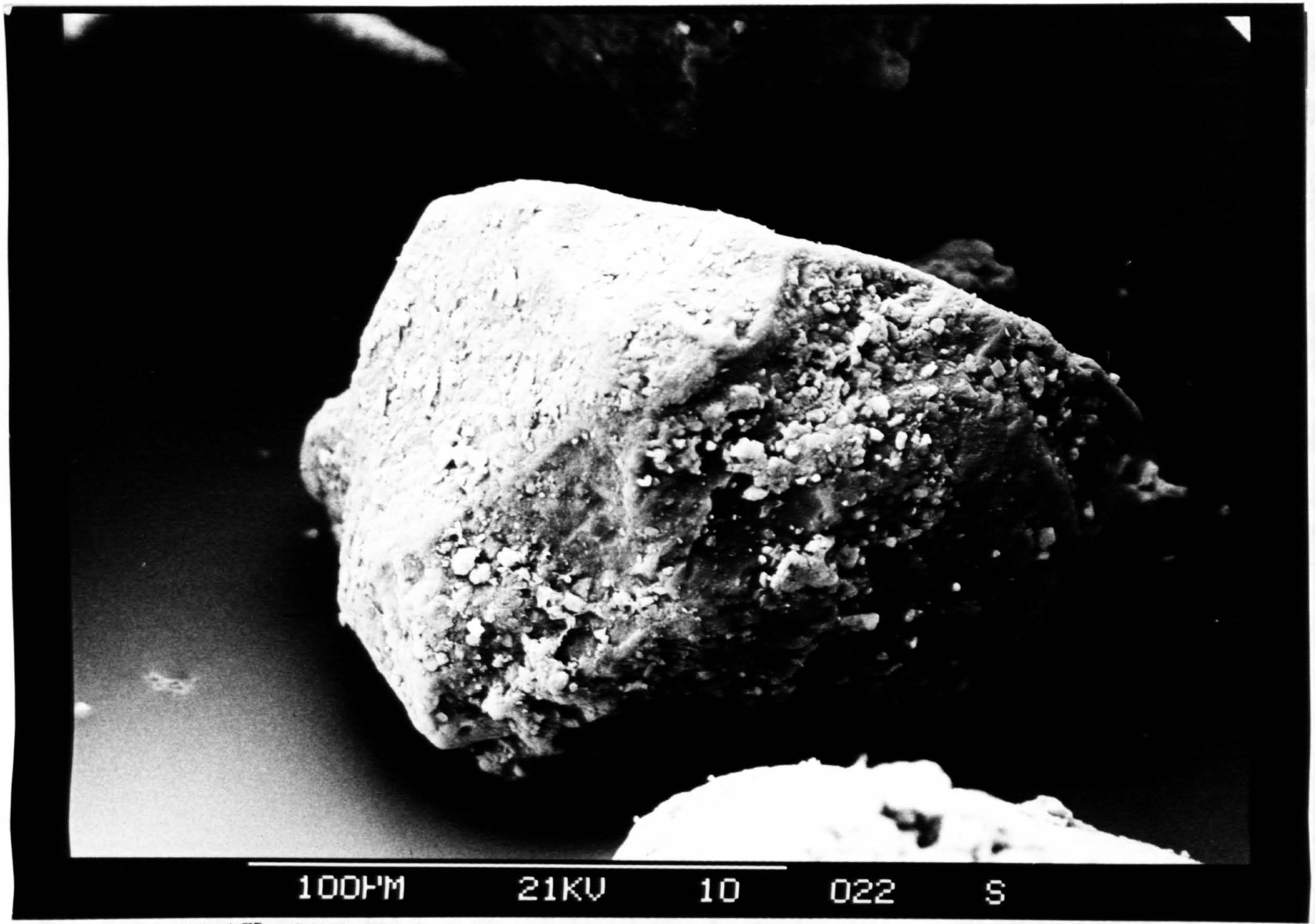


PLATE [7-10] SAND TYPE (B1) PARTICLES SIZE < 0.075 MM

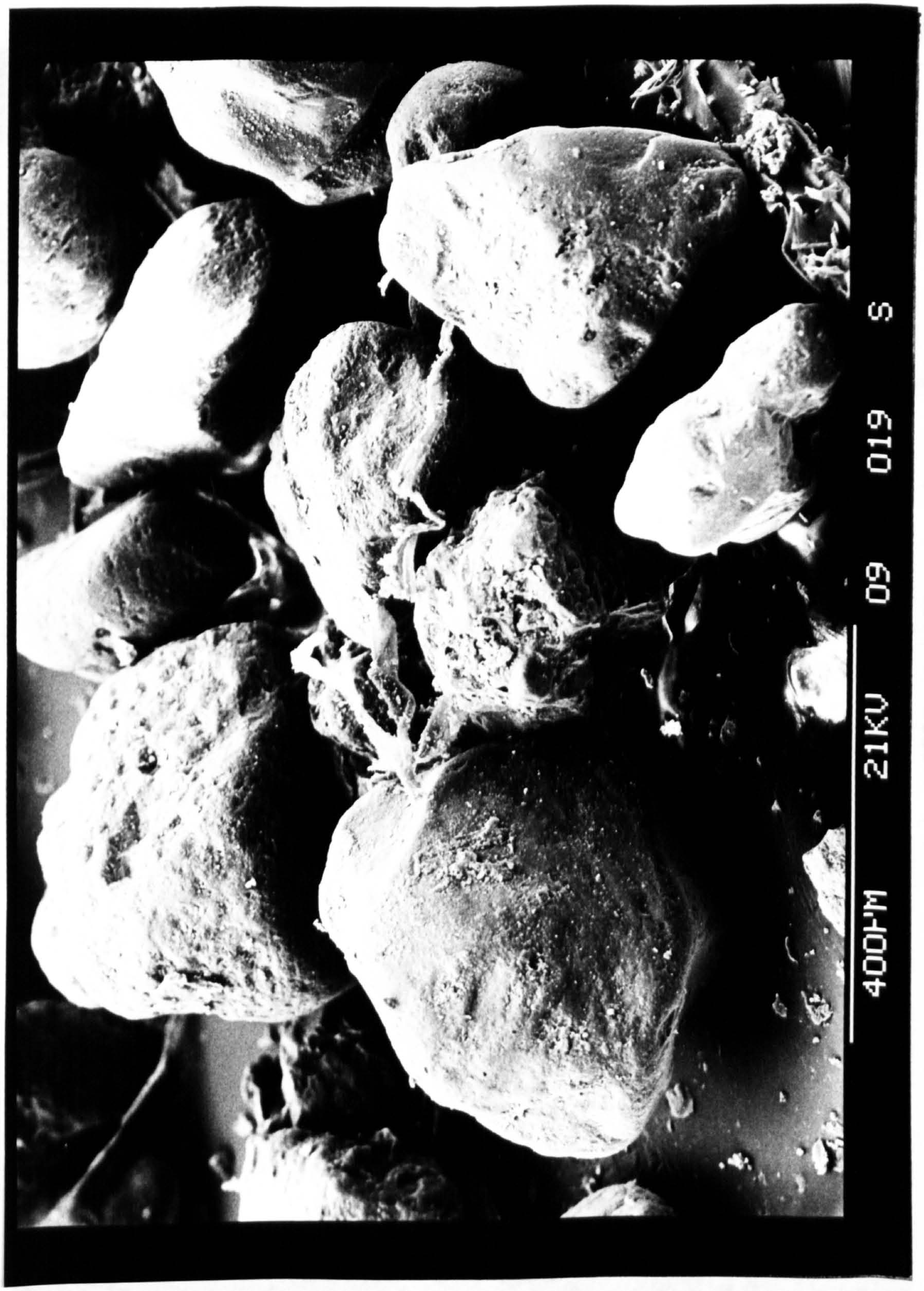


PLATE [7-11] SAND TYPE (B2) PARTICLES SIZE < 0.075 MM

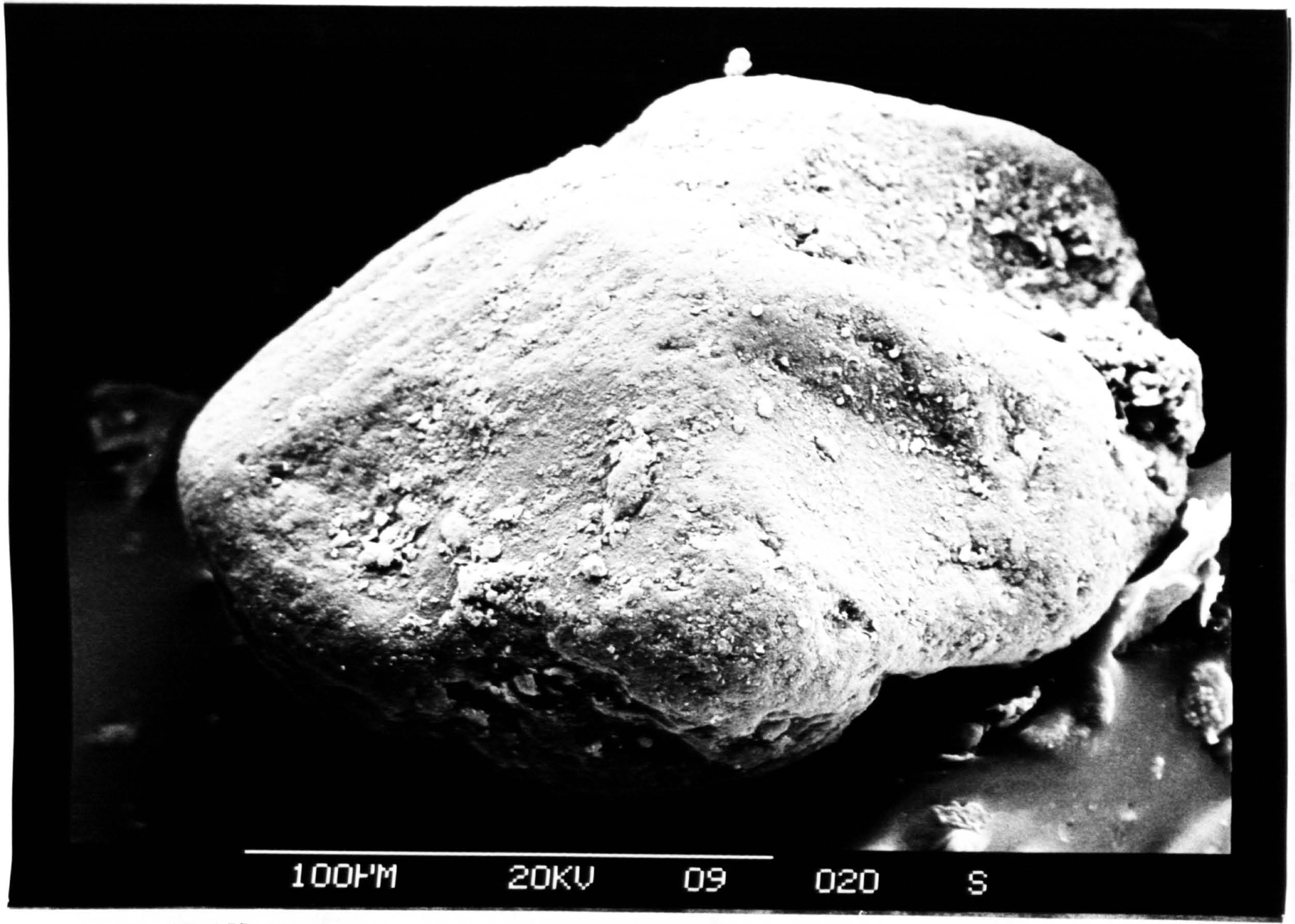


PLATE [7-12] SAND TYPE (B2) PARTIVLES SIZE < 0.075 MM

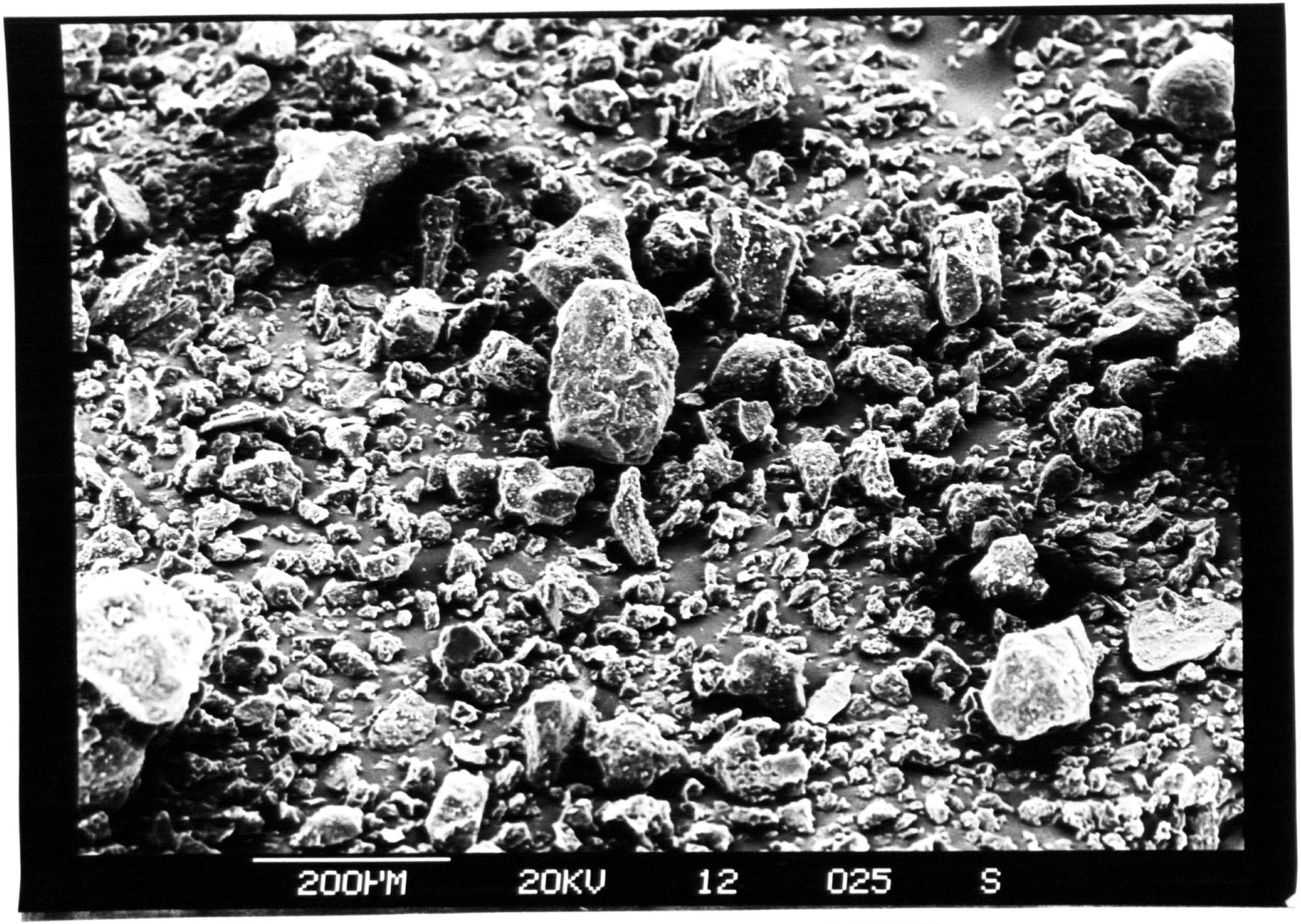


PLATE [7-13] SAND TYPE (C1) PARTICLES SIZE < 0.075 MM

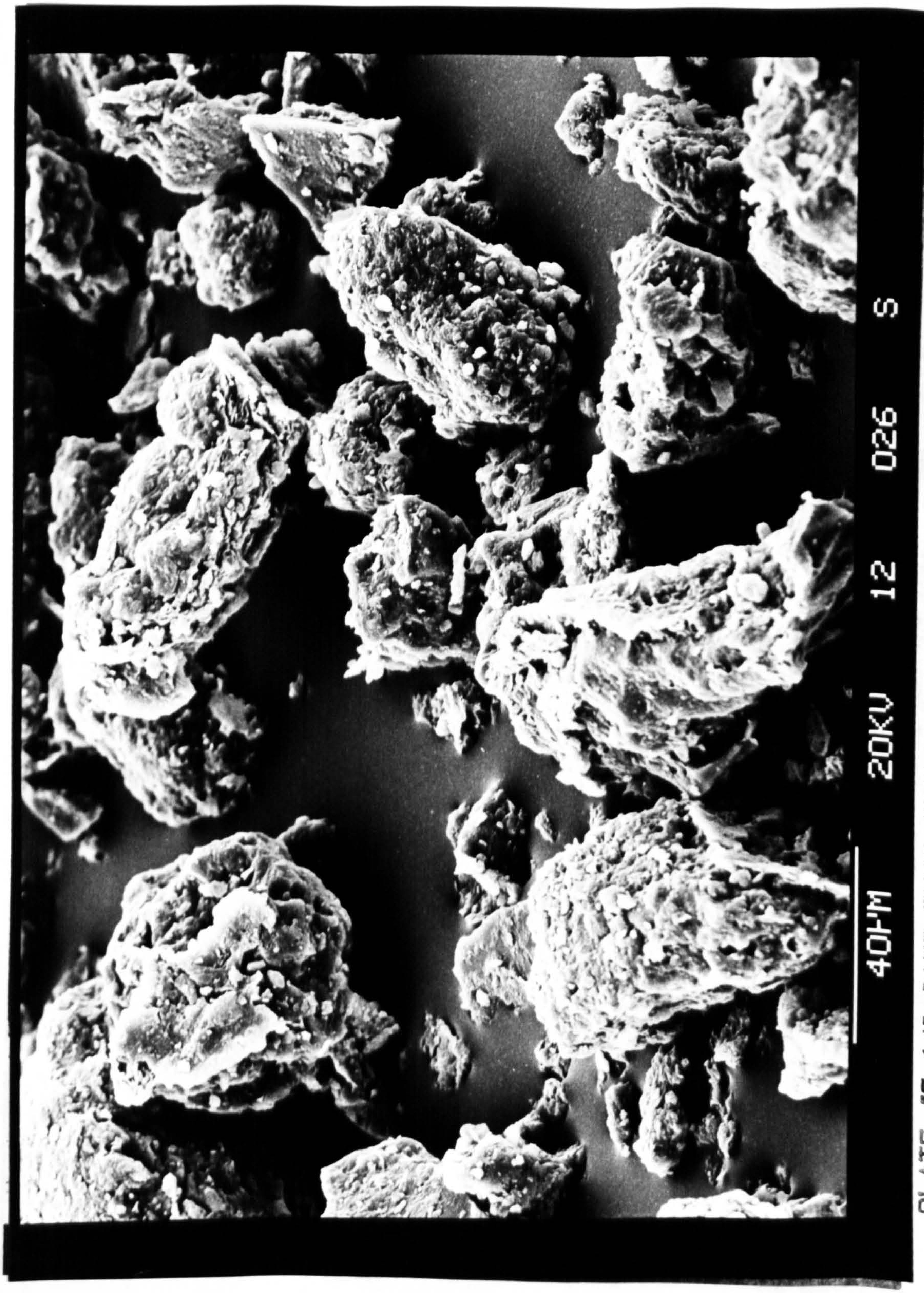


PLATE [7-14] SAND TYPE (C1) PARTICLES SIZE < 0.075 MM

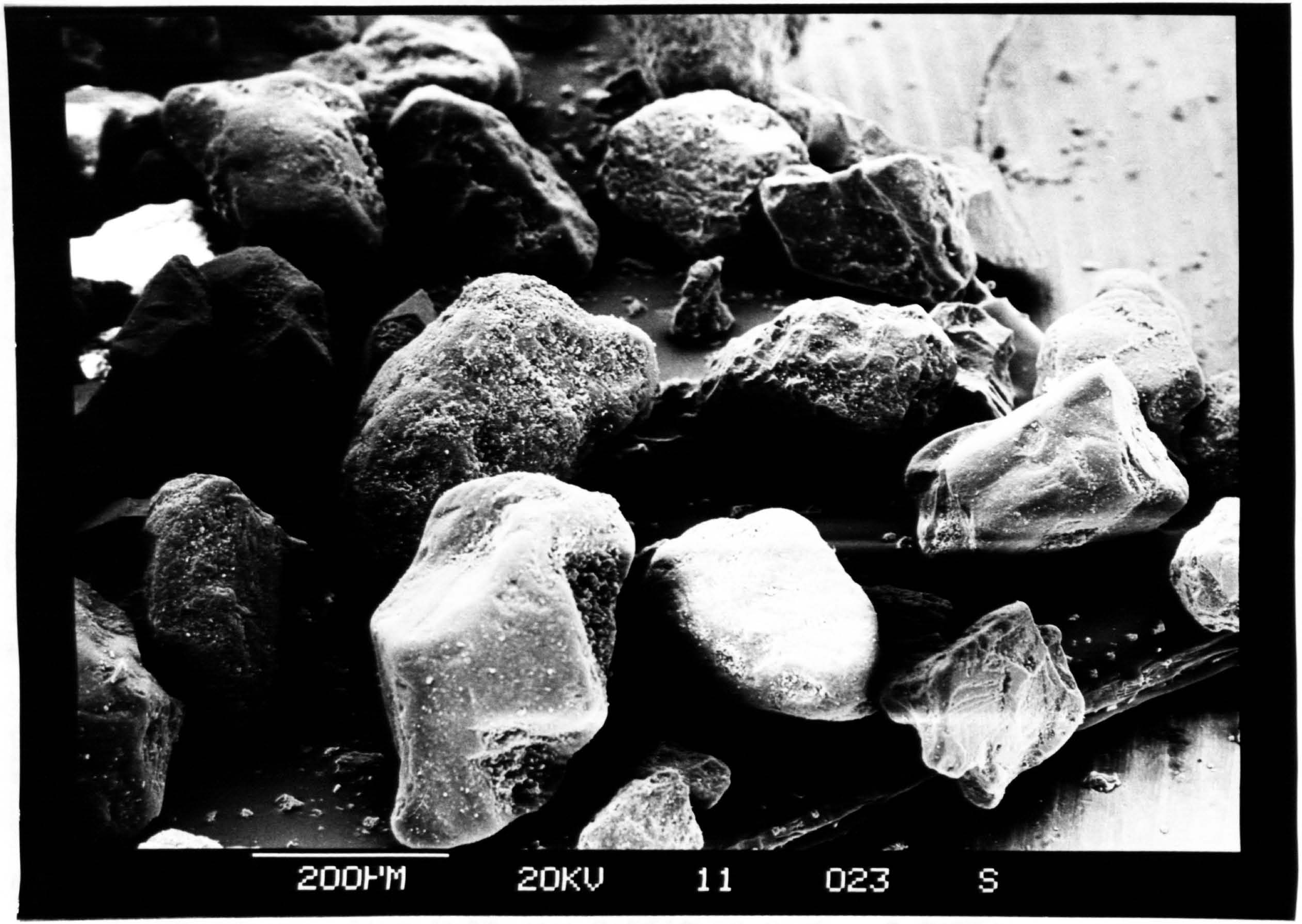


PLATE [7-15] SAND TYPE (C2) PARTICLES SIZE < 0.075 MM

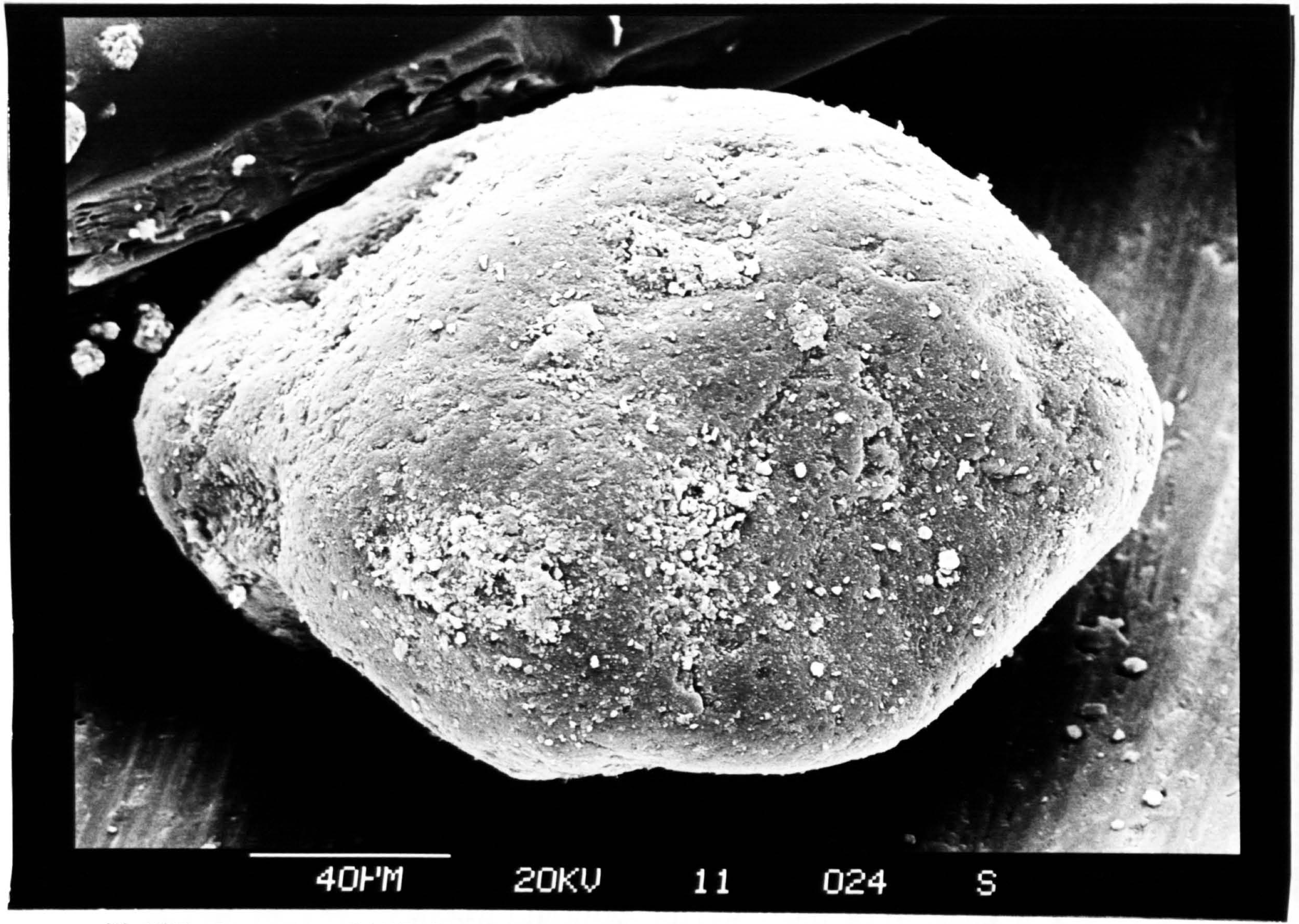


PLATE [7-16] SAND TYPE (C2) PARTICLES SIZE < 0.075MM

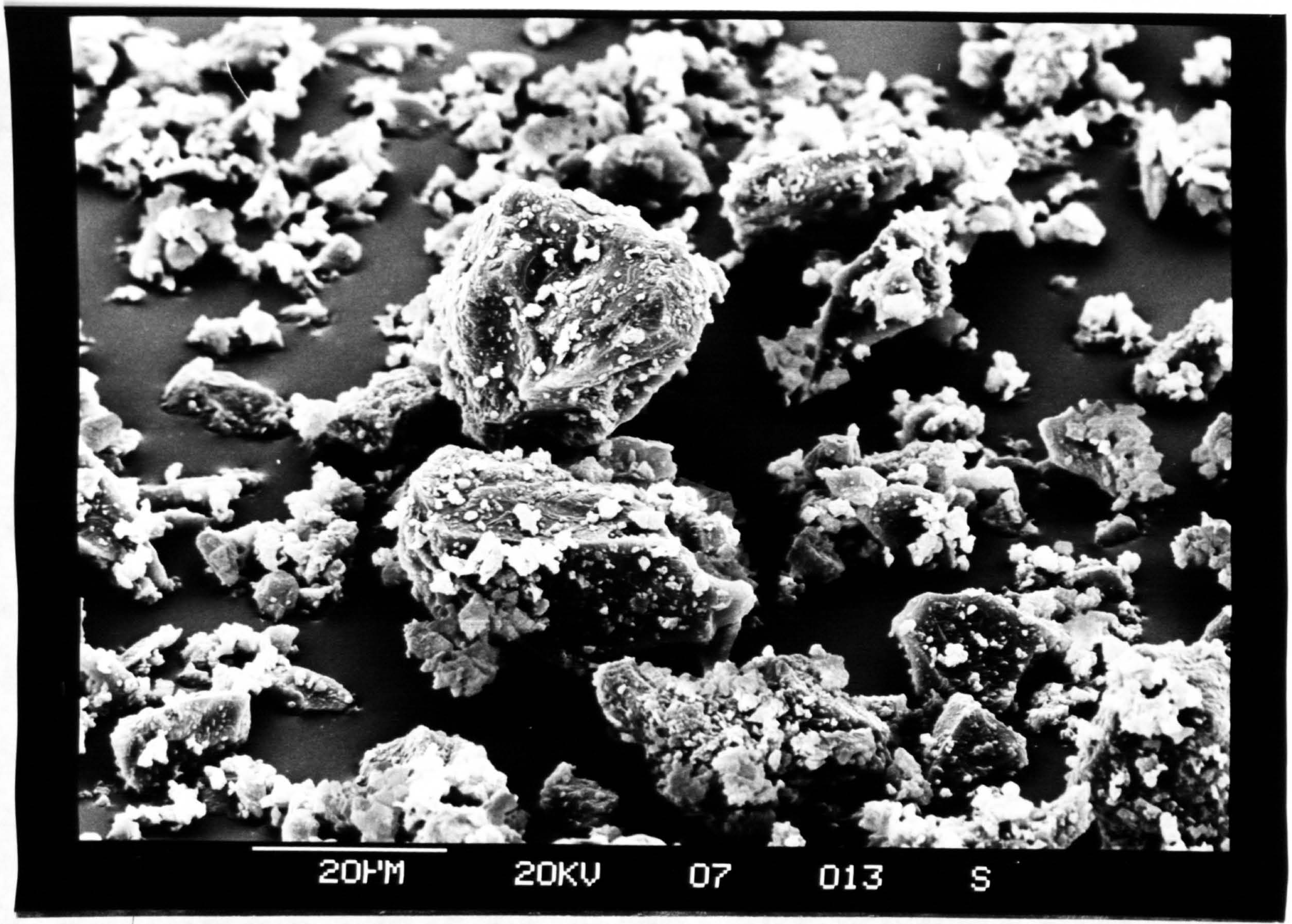


PLATE [7-17] CRUSHED LIMESTONE FILLER USED WITH SAND B & C

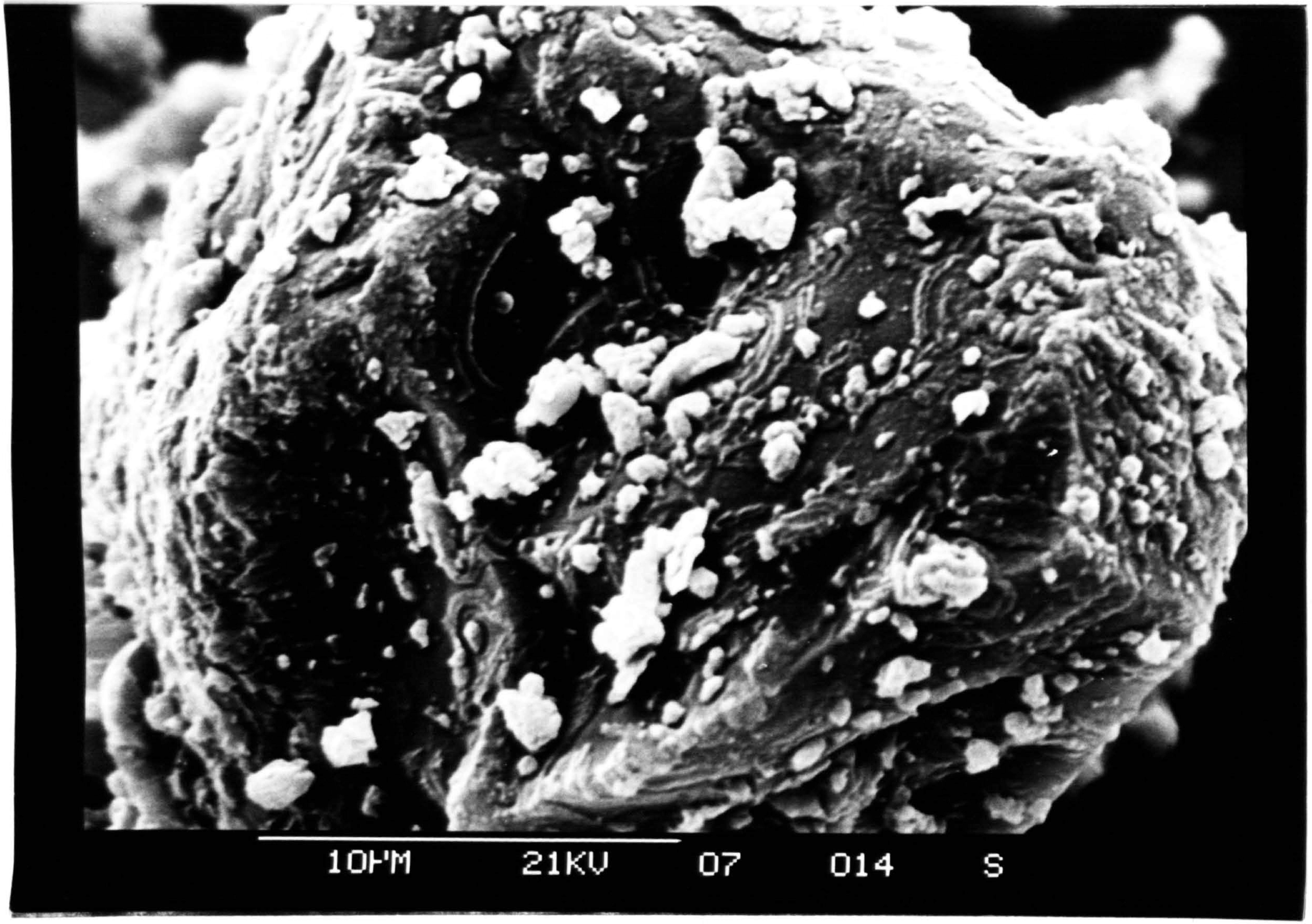


PLATE [7-18] CRUSHED LIMESTONE FILLER USED WITH SAND B & C

8.0 PREDICTION OF INTERNAL RESISTANCE COMPONENTS

8.1 INTRODUCTION

The nature of this study raised the possibility of producing a mathematical model capable of predicting the components of resistance to internal movement, mix viscosity, mix cohesion and angle of internal friction for an asphaltic mix. The data in this study suggest that the components of internal resistance draw a clear picture about the performance of an asphalt mix during the compaction process. The profiles of Percentage Compacting Factor are similar to the profiles of angle of internal friction. The peak in the profile of angle of internal friction for mixes made with 3 percent void content is found to be at a temperature value almost identical to that for the peak in the corresponding Percentage Compacting Factor profile. On the other hand, the values of Percentage Compacting Factor are inversely related to the value of mix cohesion and mix viscosity; mixes exhibiting high mix cohesion and high mix viscosity have a low value of Percentage Compacting Factor,and vice versa. A mathematical model based on the available data will be helpful in highlighting the influence of changing material ingredients in a quantitative manner.

In many studies investigators have tried to find a direct relationship between pair of variables relating to mix performance. This means that the number of expressions is as large as the number of variables. In this study an attempt has been made to establish a direct link between the components of resistance to internal movement and the ingredients on a volumetric basis. This approach, when applied to mix viscosity and mix cohesion models, succeeds in reducing a wide range of equations and variables to one relationship consisting of many factors. The approach with angle of internal friction was however limited to low void content mixes because of the complexity of the variation in angle of internal friction with void content.

The models developed highlight many factors that have an important role in influencing the magnitude of internal resistance for a mix and show how quantitive changes in the material ingredients influence the values of mix cohesion, angle of internal friction and mix viscosity. There is a consistency between the experimental results and the theoretical data obtained from the mathematical model. The mathematical model was based entirely on the declared understanding of the test data in the chapter relating to the physical model.

The mathematical model developed in this chapter is confined to the particular material used in the main programme of this study. The approach with the development of the model is considered generally applicable and able to be used with other materials having similar properties.

8.2 MIX VISCOSITY

The presence of the binder in an asphaltic material results in the material having temperature dependent properties; the binder viscosity is an important factor in defining mix viscosity. The method of defining mix viscosity theoretically was found to be less complex than with the other components of resistance to internal movement. However, the mix viscosity relationships defined in earlier chapters were found to be,

a) directly proportional to the volume of coarse and fine aggregate used in the mix.

b) inversely proportional to the volumes of bitumen, filler and air voids.

c) directly proportional to the filler to bitumen ratio when the volume of filler is kept constant.

d) inversely proportional to mix temperature.

The volume basis was used with the development of the model to overcome the difference in specific densities of material ingredients and the differences between mineral aggregates, fillers and binders.

After a number of trials a method to define mix viscosity was found by adopting the following steps.

Step 1

An equation was established to evaluate a parameter named "D" based on the volume of the ingredients making up an asphalt. When mix viscosity was divided by this parameter a particular number was obtained for each temperature used in the research programme. This number was found to be the same regardless of void content or mix proportions (such as the proportion of filler and mineral aggregate, and, filler to bitumen ratio). The exception to this was bitumen content. The resulting expression was found to be:

$$D = (A/B)^2 . C \qquad (1)$$

where A = the volume of coarse plus fine mineral aggregate (percent)

B = volume of bitumen plus filler plus 1.5 times the voids content (percent)

$$C = 1 + \frac{\text{volume of filler}}{\text{volume of bitumen}}$$

The formation of equation (1) is a product of a lengthy series of calculations by trial and error to find the form capable of accommodating the various mixes. This expression is applicable to a wide range of bitumen contents, mix void contents and film thickness. The parameter 'C' was found to cover the range of filler to bitumen ratios used in the study, from zero to a value as high as 1.56.

The values of parameter 'D' for the complete test series of the main programme are shown in Table 8.1.

The quotients of mix viscosity and the value of 'D' are shown in Table 8.2; the values in this Table represent the average of the four void content values used in the research programme; the values are approximately equal at any voids content. However, the quotient of mix viscosity and value of 'D' from both Test Series 1 and 2 are approximately equal at any bitumen content. For example, mixes with 7 percent content from Test Series 1 are nearly equal to those of mixes with 7 percent bitumen content with Test Series 2.

Step 2

The average of the values of the quotient of mix viscosity and 'D' for mixes with the same bitumen content were calculated as shown in Table 8.3. The control mix was chosen to be the datum, and used by dividing the values of other mixes (mixes with other bitumen content) by the values of the control mix at corresponding temperatures. The product of this operation was found approximately equal to a particular value for each bitumen content regardless of temperature, as shown in Table 8.3. These values were named parameter 'E'. The average of these values of 'E' were taken and plotted against the bitumen content (by volume) and; the relationships between 'E' and volume of bitumen are shown in Figure 8.1. The equation of the relationships is found to be as follows:

$$E = 4.312 - 0.4056\, V_b + 0.01737\, V_b^2 - 0.00027\, V_b^3 \qquad (2)$$

where V_b = bitumen volume in the mix (%)

Step 3

When the quotient of mix viscosity and 'D' was divided by the parameter 'E', the quotient was almost the same for all mixes; the average value was taken for a particular mix temperature and by that the values of all mixes reduced to that of a control mix divided by the produce of parameters (D x E), as shown in Table 8.4.

Step 4

In order to introduce the properties of the bitumen into the model, the values of the expression $\eta_m/(D \times E)$ (where η_m is mix viscosity) were divided by the viscosity of the bitumen, each at a corresponding temperature. The final relationship, which represents all mixes of Test Series 1 and Test Series 2 at different void content and different temperature, was obtained by plotting the expression Log η_m/F versus temperature, where $F = D \times E \times \eta_b$, and where η_b = binder viscosity. The relationship is shown in Figure 8.2 and was found to have the following equation.

$$\text{Log}\ \eta_m/F = 1.12 + 0.0529T + 3.313T^2 \times 10^{-6} - 6.771 \times 10^{-7}\ T^3$$

The same procedure was carried out with mixes made with 68 pen and 99 pen bitumen (Test Series 3); the relationships are plotted on Figure 8.2. These relationships are considered to represent any mixes prepared with the particular aggregate, used in this research programme, any mix proportion and with any grade of bitumen.

Step 5

A random selection of mix viscosity values from Test Series 1 and Test Series 2 were plotted beside the measured values in Figures 8.3 and 8.4. These are found to be in reasonable agreement which supports the suitability of the mathematical model.

The predictive model for mix viscosity can be summarised as follows:

For 46 pen bitumen

$$\text{Log}\ \eta_m/F = 1.12+0.0529T+3.313\text{x}10^{-6}\ T^{2}-6.771\text{x}10^{-7}\ T^{3} \qquad (4a)$$

For 68 pen bitumen

$$\text{Log}\ \eta_m/F = 1.337+0.0606T-1.593\text{x}10^{-4}\ T^{2}+6.3\text{x}10^{-8}\ T^{3} \qquad (4b)$$

For 99 pen bitumen

$$\text{Log}\ \eta_m/F = 2.413+0.03434T+1\text{x}10^{-4}\ T^{2}-8.03\text{x}10^{-7}\ T^{3} \qquad (4c)$$

where $F = D \times E \times \eta_b$

$D = (A/B)^2 \cdot C$

$E = 4.312 - 0.4056\ V_b + 0.01737\ V_b^2 - 0.00027\ V_b^3$

A = volume of coarse plus fine aggregate (%).

B = volume of (binder + filler + 1.5 void content) (%).

C = $1 + \frac{\text{vol. of filler}}{\text{vol. of bitumen}}$.

η_b = binder viscosity (N/m^2 sec).

T = temperature, degrees centigrade.

V_b = volume of the bitumen in the mix (%).

8.3 MIX COHESION

The mathematical model for mix cohesion was found a little more complicated than that for mix viscosity. Mix cohesion is very much influenced by filler content and void content.

Step 1

A new expression to calculate the parameter 'D' was established. The difference between the parameter 'D' for mix viscosity and mix cohesion is the void content term, which is doubled for this case. The expression to calculate 'D' was found to be as follows:

$$D = (A/B)^2 . C$$

A = volume of mineral aggregate (%).

B = volume of (bitumen + filler + 2 x void content) (%).

$C = 1 + \frac{\text{filler volume}}{\text{bitumen volume}}$.

The 'E' values obtained in the mix viscosity determinations were used, and the product of (D x E) is shown in Table 8.5.

Step 2

The mix cohesion value divided by the product (D x E) is found to be approximately equal with different void contents, but, the values generally decrease when the filler to bitumen ratios decrease. However, the average of the terms C/D x E are ranked according to their filler to bitumen ratio as shown in Table 8.6. All the values of the term C/D x E were divided by those values for the control mix.

It is found the new values at 80°C to 100°C, shown in the lower part of Table 8.6, are around unity and those values above or below these temperatures are either more than unity, for mixes with a filler to bitumen ratio higher than that of the control mix, or, less than unity, for mixes with a filler to bitumen ratio less than that of the control mix.

The unity temperature range was taken as the average value for 90°C. Relationships between $(T-90)^2$ and these values were constructed in order to establish a simple relationship capable of unifying all mixes. The relationships approximate to straight lines and can be reasonably said to meet at (T=90°C) with value of one, as shown in Figure 8.5.

Step 3

The slopes of the linear relationships shown in Figure 8.5 when plotted against the cube root of the filler to bitumen ratio by volume are shown in Figure 8.6. The factor 'F', which can be said to unite all mixes was then found to be as follows:

$$F = S\,(T-90)^2 + 1$$

$$S = [-25.16 + 34.12\,(f/B^{1/3})] \times 10^{-5}$$

T = Temperature, degrees centigrade

f/B = filler bitumen ratio (by volume)

Step 4

The calculated 'F' values are listed in Table 8.7. A new value of the term mix cohesion divided by [DxExF] was obtained which made all mixes have the same value, or a very close range of values, as shown in Table 8.7. The average of all mixes was taken and then divided by the square root of the binder viscosity in an attempt to introduce the influence of the type of the binder into the model. However, a relationship was constructed between the expression mix cohesion divided by a term G and temperature for all three types of bitumens used, as shown in Figure 8.7.

The final relationship to define mix cohesion was found to be as follows:

For 46 pen bitumen

$$\frac{\text{mix cohesion}}{G} = 248.4-102.5T+1.374T^{2}-0.00466\,T^{3} \qquad 5a$$

For 68 pen bitumen

$$\frac{\text{mix cohesion}}{G} = -345.8+4.06T+0.1605\,T^{2}-1.2813\times10^{-4}\,T^{3} \qquad 5b$$

For 99 pen bitumen

$$\frac{\text{mix cohesion}}{G} = -2159.81+67.895T-0.5196T^{2}+0.002469\,T^{3} \qquad 5c$$

where $G = D \times E \times F \times \eta_b^{1/2}$

η_b = binder viscosity N/m^2 sec.

F, E and D are as defined earlier

Step 5

Selected mixes were chosen for plotting the measured and calculated values of mix cohesion, as shown in Figures 8.7 and 8.8.

8.4 ANGLE OF INTERNAL FRICTION

The mathematical model for angle of internal friction is limited to mixes containing 3 percent air voids, due to the complexity of the relationships, particularly when void content changed, and, due to the time available for this study. However, as shown in earlier chapters using 3 percent voids content may be accepted as a fair representation of a mix in terms of a measure of its workability.

The following steps highlight the procedure followed to find this model.

Step 1

The angle of internal friction, as with the other components of internal resistance, is related to the proportions of the material ingredients which make up a mix. Angle of internal friction increases when the volume of film thickness decreases and consequently the volume of mineral aggregate increases. Also the value of angle of internal friction increases when the filler to bitumen ratio increases. These were organised in a formula which was found to be of the order $D = A \times C^2/B^2$ where

A = volume of mineral aggregate %

B = volume of film thickness (filler + bitumen) %

$C = 1 + \frac{\text{filler volume}}{\text{bitumen volume}}$

when the value is divided by the term 'D', the result shows a similarity of angle of internal friction between mixes made with equal bitumen content, regardless of the filler and mineral aggregate proportions.

Step 2

The control mix was chosen to be a datum value for calculating by dividing the product of Step 1 at each temperature by the corresponding value of the control mix, as shown in Tables 8.8 and 8.9. It is found that those values vary with temperature, particularly for mixes with high bitumen content. With the mixes of Test Series 1, the variations are small between the temperatures 60°C to 120°C. There is a noticeable reduction in value at 140°C, whilst with mixes of Test Series 2 the value varied gradually with temperature, almost at a constant rate. This led to the definition of two factors to cover this phenomena. The required factors were named 'E' and 'G'.

Step 3

The mathematical approach to evaluate the value of 'E' was defined by first averaging the value of E at 60°C (E60) and then evaluating its rate of change for the temperature range of 60°C to 120°C. The rate was termed 'S'. However, a relationship was found between E60 and the volumetric percentage of the bitumen within the mix as shown in Figure 8.10. The rate of change in the value of E was found to vary with the filler to bitumen ratio. This led to the establishment of a relationship between factor 'S' and the filler to bitumen ratio, as shown in Figure 8.11. The latter relationship represents the slope of the relationship whilst the E60 term represents a point in the wider relationships which cover all mixes. This was found to be as follows:

$E = S(T-60) + E60$

where

$E60 = [(3.172-0.4338.Vb)+(2.194\text{x}10^{-3}.Vb^{2})-(2.798\text{x}10^{-4}.Vb^{3})]$

$S = -0.00285 + 0.01307\ f/B - 0.01362\ (f/B)^{2}$

T = Temperature (°C)

Vb = percentage of the bitumen in the mix

F/B = filler-bitumen ratio (by volume)

The second factor 'G' was found by trial and error, taking the binder viscosity, filler to bitumen ratio, and volume of film thickness into account. The factor was found to be as follows:

$G = (2B - 0.33.f/B - 0.4)/\text{Log}\eta_b - (f/B - 0.4)\ (\text{Log}\,\eta_b - 1)$

where η_b = the binder viscosity (N/m^{2} sec.)

B = volume of film thickness %

Step 4

Final relationship was drawn between $\frac{\phi - G}{F}$ and temperature which represents all mixes in both series, as shown in Figure 8.12. A polynomial expression was defined,

$$\frac{\phi - G}{F} = 1.2208 + 5.3126\text{x}10^{-3}\ T + 1.4288\text{x}10^{-5}\ T^{2} + 1.6396\text{x}10^{-7}\ T^{3}$$

where F = D x E

G, E and D are defined earlier

ϕ = angle of internal friction, degree

The measured and calculated values of predicted angle of internal friction are plotted in Figure 8.13. The relationships are a close approximation to those defined by experiment.

TABLE 8.1 D-values for mix viscosity calculation

Mixes	Bitumen content	Filler-Bitumen ratio	'D' values at different void content			
			3	6	9	12
Series No.1	7	1.19	9.507	6.965	5.234	4.011
	8.2 *	1.0	7.28	5.45	4.166	3.238
	9.4	0.86	5.743	4.376	3.394	2.67
	10.6	0.75	4.623	3.577	2.810	2.234
	11.8	0.67	3.7827	2.966	2.356	1.891
Series No.2	7	1.56	8.382	6.273	4.795	3.727
	8.2 *	1.00	7.28	5.450	4.166	3.238
	9.4	0.59	6.468	4.841	3.701	2.876
	10.6	0.26	5.837	4.368	3.339	2.595
	11.8	0.01	5.334	3.992	3.052	2.372

* The control mix also apply to the mixes of series 3 and 4

Table 8.2 η_m/D-values

Mixes	Bitumen content	Filler-bitumen ratio	(η_m/D) x 10^5 value at different temperature				
			60	80	100	120	140
Series No.2	7.0	1.19	96.58	60.44	47.02	38.33	33.73
	8.2 *	1.00	88.53	54.39	43.97	35.62	29.35
	9.4	0.86	81.29	50.44	39.65	33.55	25.63
	10.6	0.75	74.25	46.82	36.81	30.67	22.86
	11.8	0.67	66.74	40.76	32.97	27.90	20.52
Series No.2	7.0	1.56	96.05	60.74	47.52	39.62	33.37
	8.2 *	1.00	88.53	54.39	43.97	35.62	29.35
	9.4	0.59	82.28	50.04	39.88	33.66	25.73
	10.6	0.26	75.21	45.96	37.43	30.28	20.95
	11.8	0.01	66.28	41.43	32.61	23.46	14.76

* control mix

Table 8.3

η_m/D and E Values

Temperature	Average of η_m/D x 10^5 value at different bitumen content				
	7	8.2	9.4	10.6	11.8
60	96.32	88.53	81.78	74.73	66.51
80	60.59	54.39	50.24	46.39	41.10
100	47.27	43.97	39.77	37.12	32.79
120	38.97	35.62	33.60	30.48	25.68
140	33.55	29.35	25.68	21.91	17.64
E = [(η_m/D) for any mix]/[(η_m/D) for control mix]					
60	1.088	1.0	0.924	0.844	0.751
80	1.114	1.0	0.924	0.853	0.756
100	1.075	1.0	0.904	0.844	0.746
120	1.094	1.0	0.943	0.856	0.721
140	1.143	1.0	0.875	0.747	0.601
Average (E)	1.103	1.0	0.914	0.829	0.715
Calculated (E)	1.104	0.999	0.915	0.828	0.716

Table 8.4

η_m/D.E and η_m/F Values

Temperature	η_m/(D x E) x 10^5 at different bitumen content				
	7.2	8.2	9.4	10.6	11.8
60	87.25	88.62	89.38	90.25	92.89
80	54.88	54.44	54.91	56.03	57.40
100	42.82	44.01	43.46	44.83	45.80
120	35.30	35.66	36.72	36.81	35.87
140	30.39	29.38	28.07	26.46	24.64

Temperature	The average of η_m/(D x E) x 10^5	Log η_m /(D x E xη_b) = η_b /F*
60	89.68	4.1745
80	55.53	5.0096
100	44.18	5.7811
120	36.07	6.329
140	27.79	6.7483

η_b = viscosity of the binder

F = D x E x η_b

Table 8.5 D x E values for cohesion calculation

Mixes	Bitumen content %	Filler/ bitumen ratio	DxE value of different void content			
			3	6	9	12
Series No.1	7.0	1.19	9.47	6.434	4.564	3.342
	8.2	1.00	6.611	4.604	3.328	2.473
	9.4	0.86	4.804	3.419	2.511	1.899
	10.6	0.75	3.519	2.549	1.899	1.445
	11.8	0.67	2.502	1.841	1.388	1.067
Series No.1	7.0	1.56	8.412	5.827	4.235	3.146
	8.2	1.00	6.611	4.604	3.328	2.473
	9.4	0.59	5.380	3.742	2.709	2.012
	10.6	0.265	4.393	3.060	2.212	1.643
	11.8	0.01	8.472	2.418	1.748	1.298

Table 8.6 The average of (cohesion/D x E) x 10 value of all void content

F/B (by wt)	1.56	1.19	1.0	0.86	0.75	0.67	0.59	0.26	0.01
Bitumen Content %	7.0	7.0	8.2	9.4	10.6	11.8	9.4	10.6	11.8
(F/B by vol.)	0.833	0.761	0.718	0.683	0.653	0.628	0.601	0.462	0.155
Temp									
60	10.73	10.4	10.36	10.17	10.11	10.38	9.79	9.16	8.63
80	7.12	7.12	7.15	7.17	7.11	7.42	7.08	7.07	7.22
100	5.14	5.13	5.14	5.2	5.22	5.34	5.15	5.12	5.25
120	3.91	3.82	3.77	3.68	3.68	3.75	3.55	3.43	3.22
140	3.07	2.87	2.74	2.53	2.46	2.44	2.3	2.07	1.50
When the above values divided by those of control mixes the following were obtained									
60	1.036	1.004	1	0.982	0.976	1.002	0.945	0.884	0.833
80	0.996	0.996	1	1.003	0.994	1.038	0.990	0.989	1.010
100	1.000	0.998	1	1.012	1.015	1.039	1.002	0.996	1.021
120	1.031	1.013	1	0.976	0.975	0.995	0.942	0.910	0.854
140	1.120	1.047	1	0.923	0.898	0.890	0.839	0.755	0.547

Table 8.7 Factor F and Cohesion/D x E x F

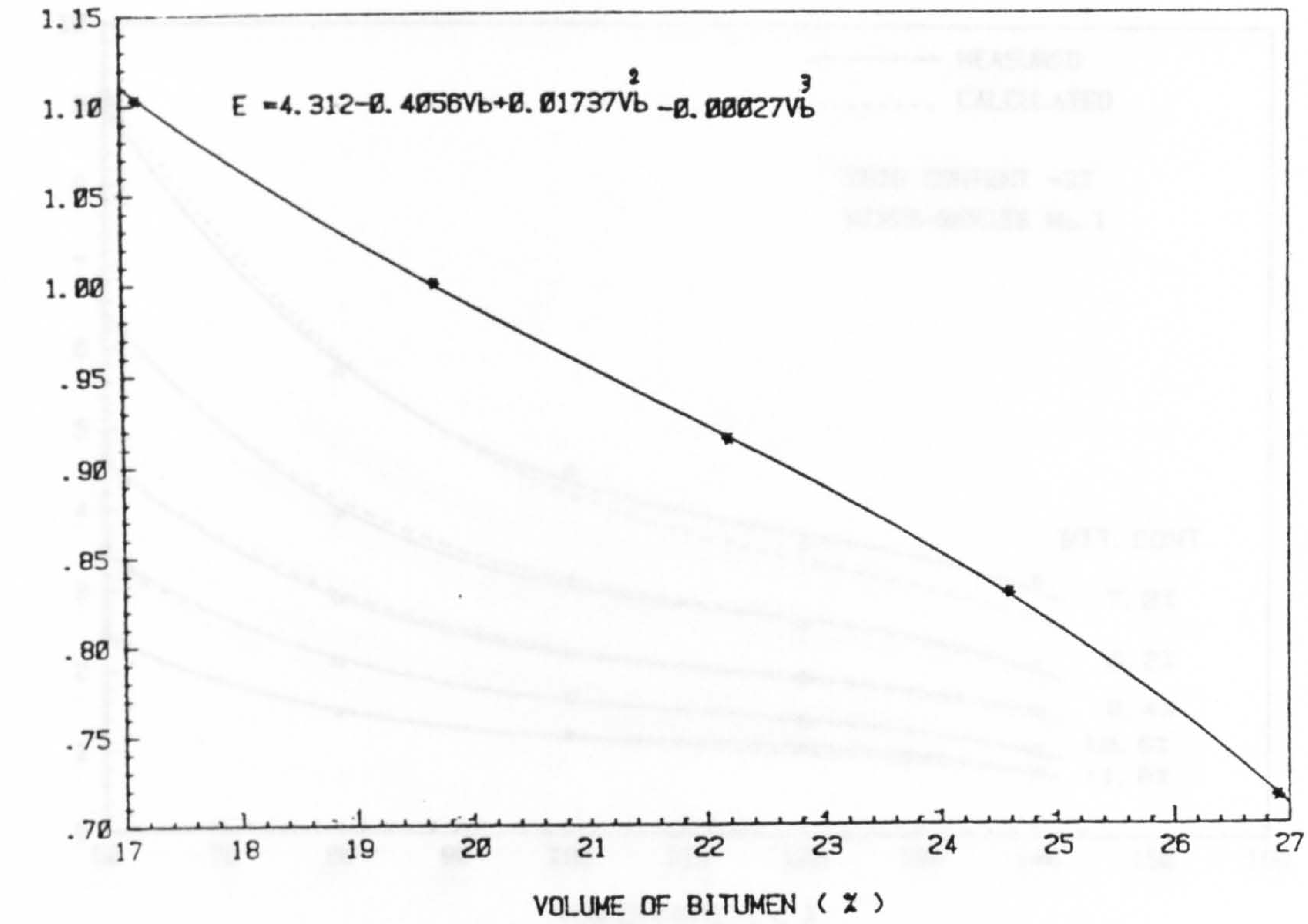
F/B (by ut)	1.56	1.19	1.0	0.86	0.75	0.67	0.59	0.26	.01	
Bitumen content %	7.0	7.0	8.2	9.4	10.6	11.8	9.4	10.6	11.8	
F/b (by vol)	0.833	0.761	0.718	0.683	0.653	0.628	0.601	0.462	0.155	
Temp	F - values (calculated)									
60	1.029	1.007	0.994	0.983	0.974	0.966	0.958	0.915	0.821	
80	1.003	1.00	0.999	0.998	0.997	0.996	0.995	0.991	0.980	
100	1.003	1.00	0.999	0.998	0.997	0.996	0.995	0.991	0.980	
120	1.029	1.007	0.994	0.983	0.974	0.966	0.958	0.915	0.821	
140	1.082	1.02	0.984	0.954	0.928	0.907	.884	0.765	0.503	
When (cohesion/DxE) 10^3 divided by the above F value										average
60	10.43	10.33	10.42	10.35	10.38	10.74	10.22	10.01	10.51	10.38
80	7.10	7.12	7.15	7.18	7.13	7.45	7.11	7.134	7.37	7.19
100	5.12	5.13	5.14	5.21	5.24	5.36	5.17	5.17	5.36	5.21
120	3.80	3.79	3.79	3.74	3.78	3.89	3.71	3.75	3.92	3.8
140	2.84	2.81	2.79	2.65	2.65	2.69	2.6	2.71	2.98	2.75

Table 8.8 Data for Test Series 1

Bitumen content %	7.0	8.2	9.4	10.6	11.8
Filler/ bitumen ratio	1.19	1.0	0.86	0.75	0.67
D values	25.65	18.81	14.37	11.35	9.20
Temperature	Φ/D				
60	1.2514	1.5578	2.0006	2.480	2.9463
80	1.3177	1.6536	2.1293	2.6473	3.1637
100	1.3625	1.7333	2.2268	2.775	3.3431
120	1.3957	1.7811	2.2964	2.8808	3.3975
140	1.4074	1.7971	2.2824	2.775	3.2398
	E values = (Φ/D) / (Φ/D) for control mix				
60	0.803	1	1.284	1.592	1.891
80	0.797	1	1.288	1.601	1.913
100	0.786	1	1.285	1.601	1.929
120	0.784	1	1.289	1.617	1.908
140	0.783	1	1.270	1.544	1.803
E60 (average of the two series	0.773	1	1.292	1.609	1.93
$S \times 10^{-4} = \frac{E_{120}-E_{60}}{60}$	1.96	0.00	-3.35	+1.27	-3.95

Table 8.9 Data for Test Series No.2

Bitumen content %	7.0	8.2	9.4	10.6	11.8
filler/ bitumen	1.56	1.0	0.59	0.26	0.01
'D' value	24.91	18.81	14.84	12.08	10.09
Temperature	Φ/D				
60	1.156	1.5578	2.025	2.533	3.073
80	1.2584	1.6536	2.12	2.595	3.122
100	1.3386	1.7333	2.167	2.632	3.147
120	1.3848	1.7811	2.197	2.657	3.147
140	1.4009	1.7971	2.184	2.624	3.073
Temperature	E = Φ/D) / (Φ/D) for control mix				
60	0.742	1	1.30	1.626	1.973
80	0.761	1	1.283	1.569	1.888
100	0.772	1	1.250	1.519	1.816
120	0.778	1	1.234	1.492	1.767
140	0.780	1	1.215	1.46	1.711
E60 (average of the two series)	0.773	1.00	1.292	1.609	1.93
$S \times 10^{-4} = \frac{E_{120} - E_{60}}{60}$	0.88	0.00	-9.60	-19.65	-27.37



FIG(8-1) FACTOR (E) VRSUS PERCENTAGE OF BITUMEN VOLUME IN THE MIX

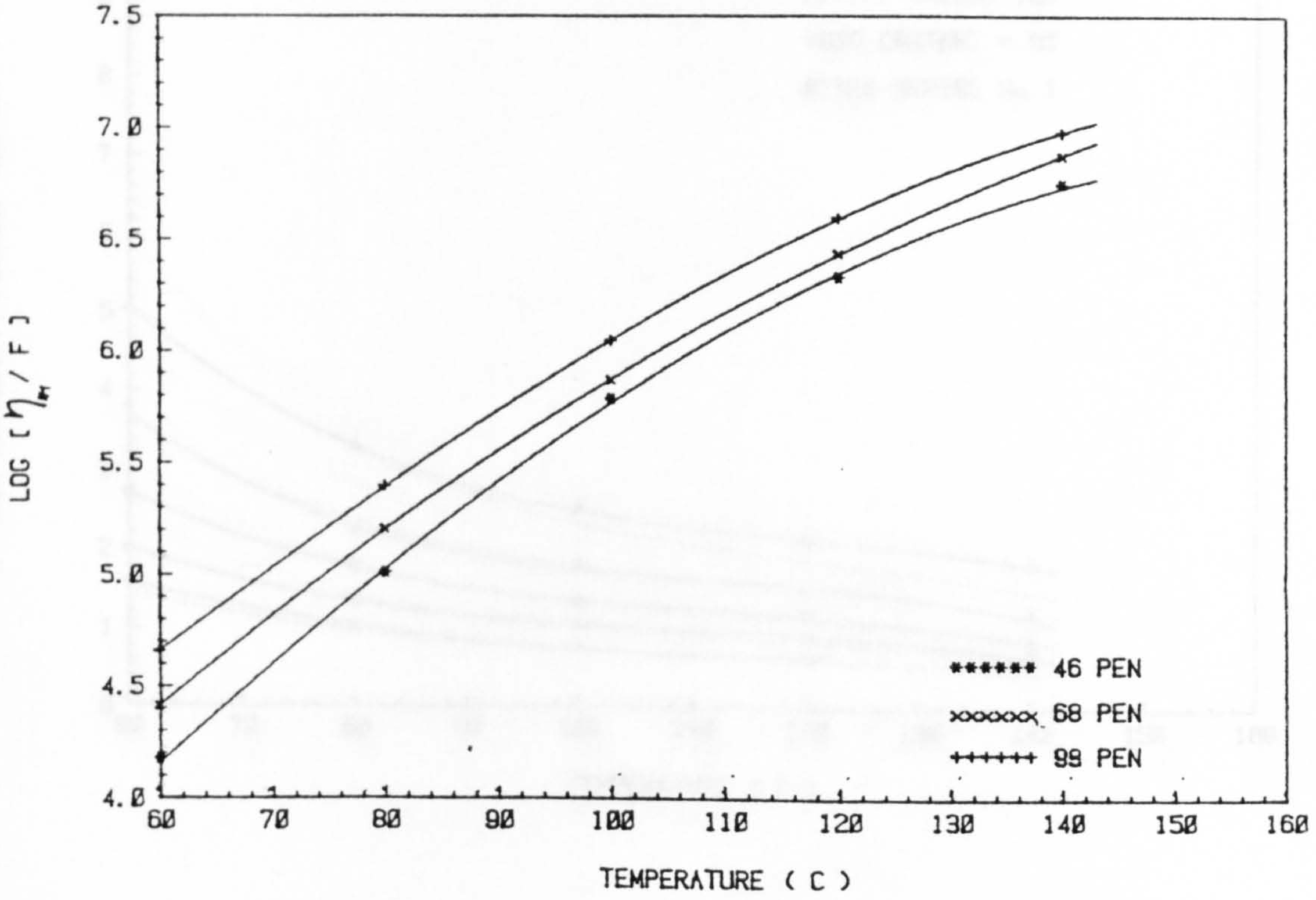
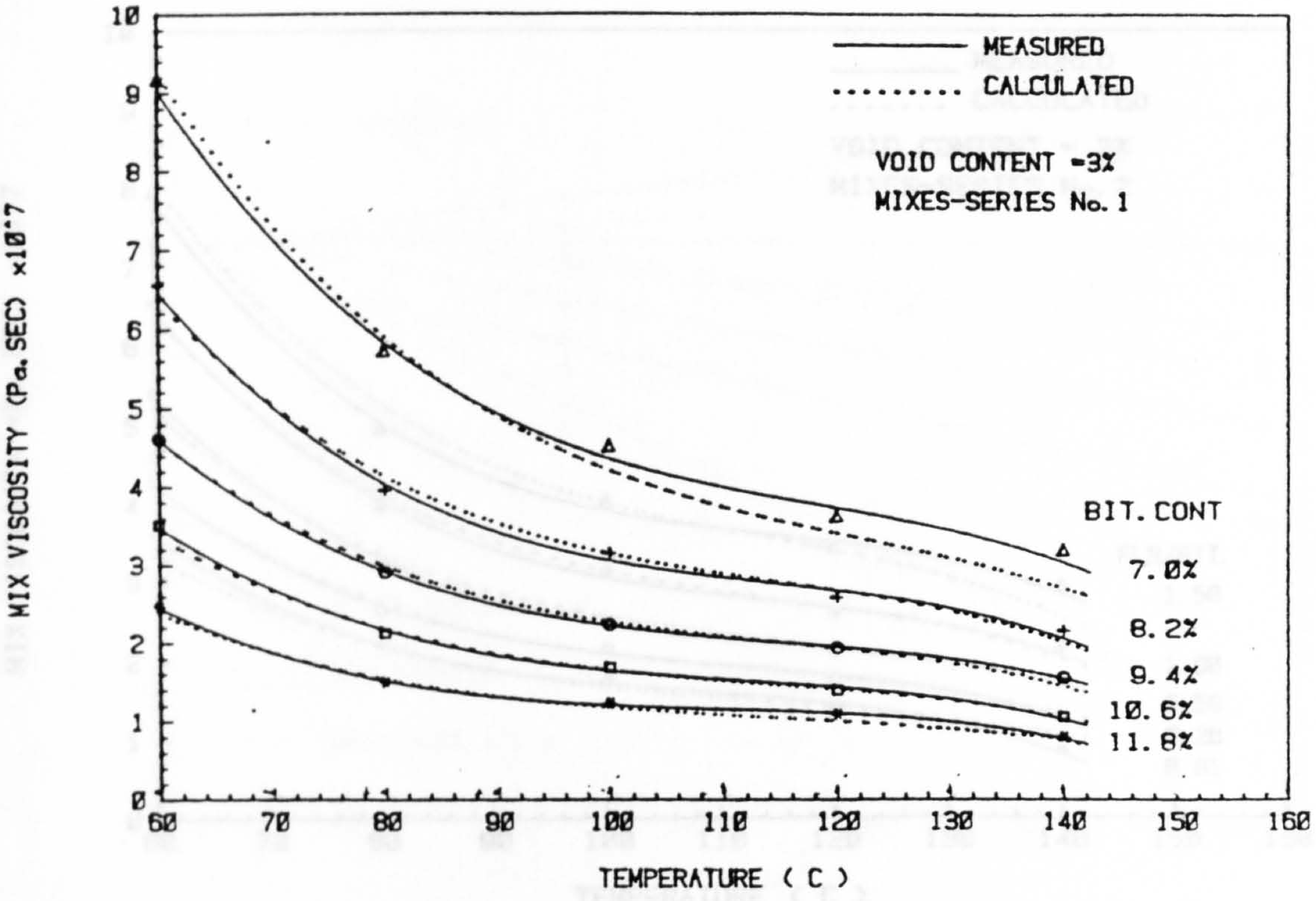


FIG (8-2) $\text{Log}\,\eta_m / F$ VERSUS TEMPERATURE



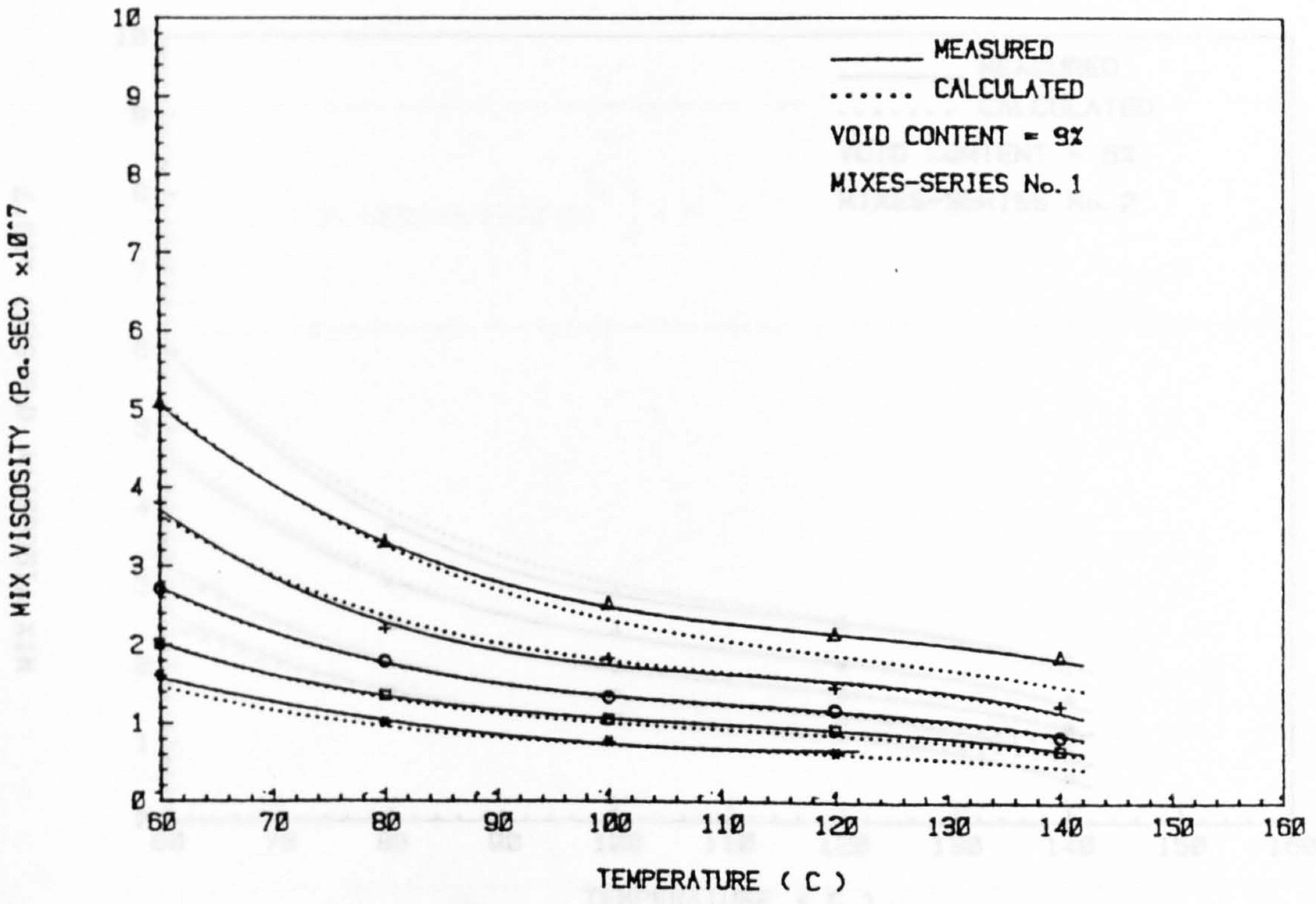
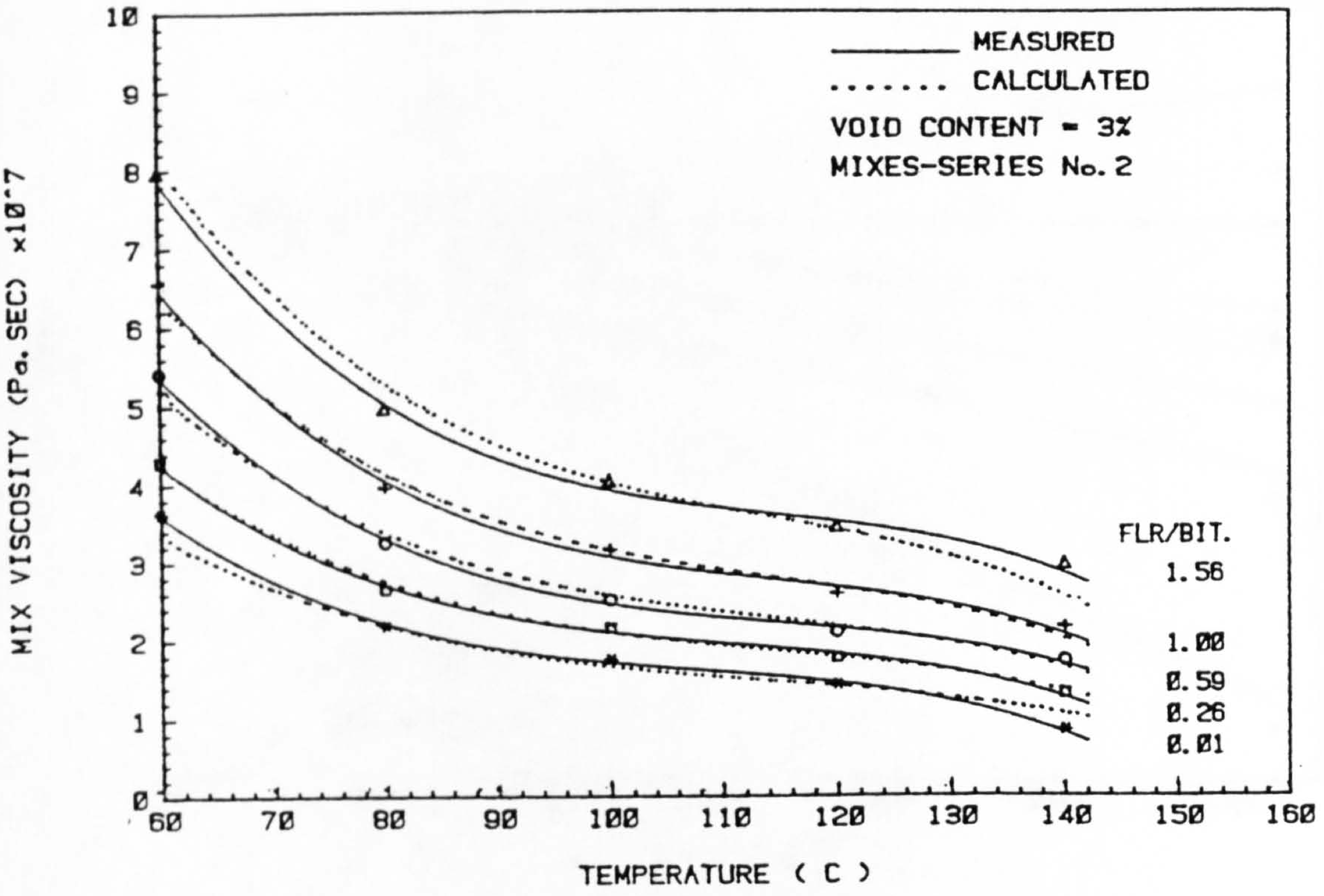


Figure 8.3: Measured and calculated relationships between mix viscosity and temperature for selected cases with Test Series 1.



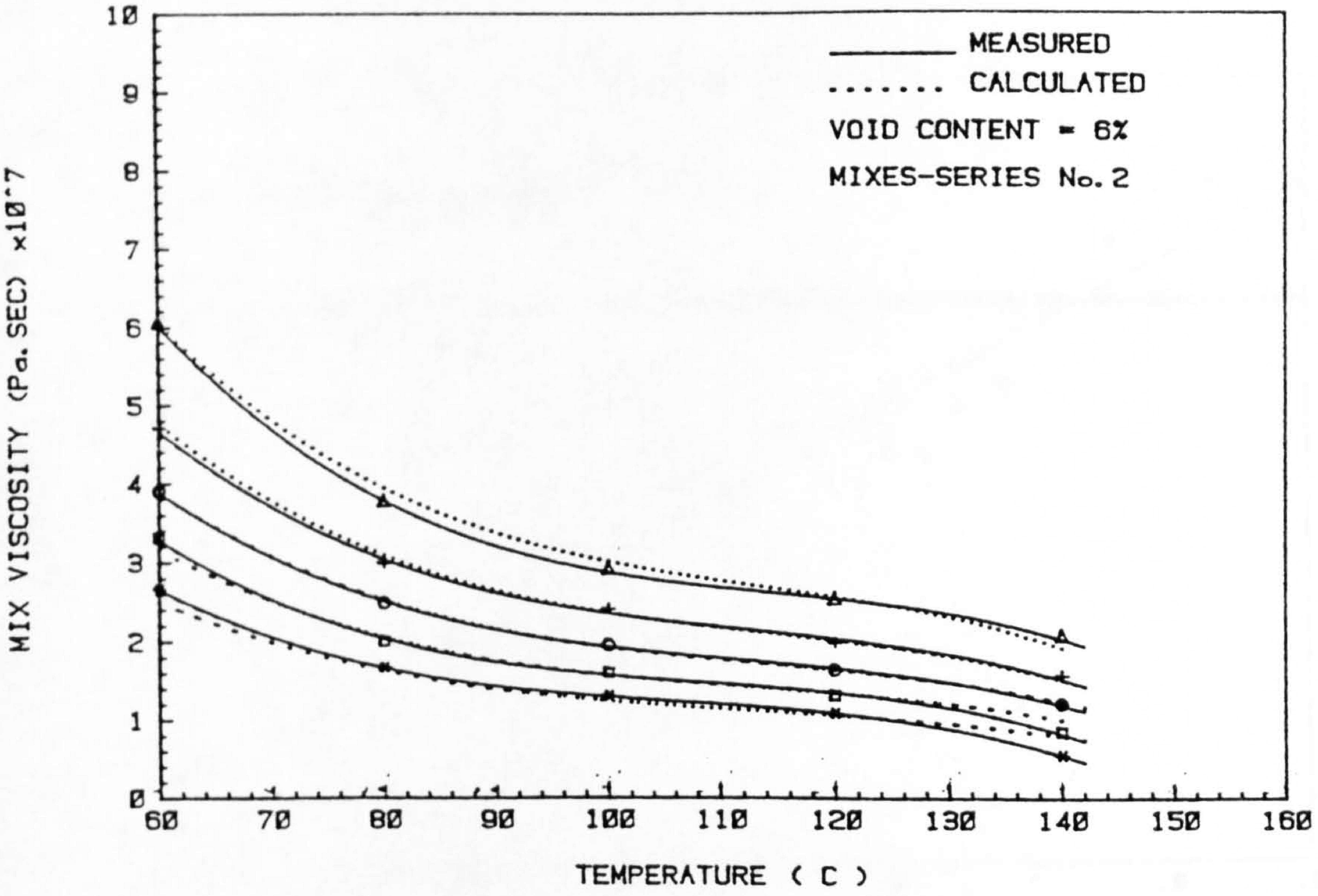
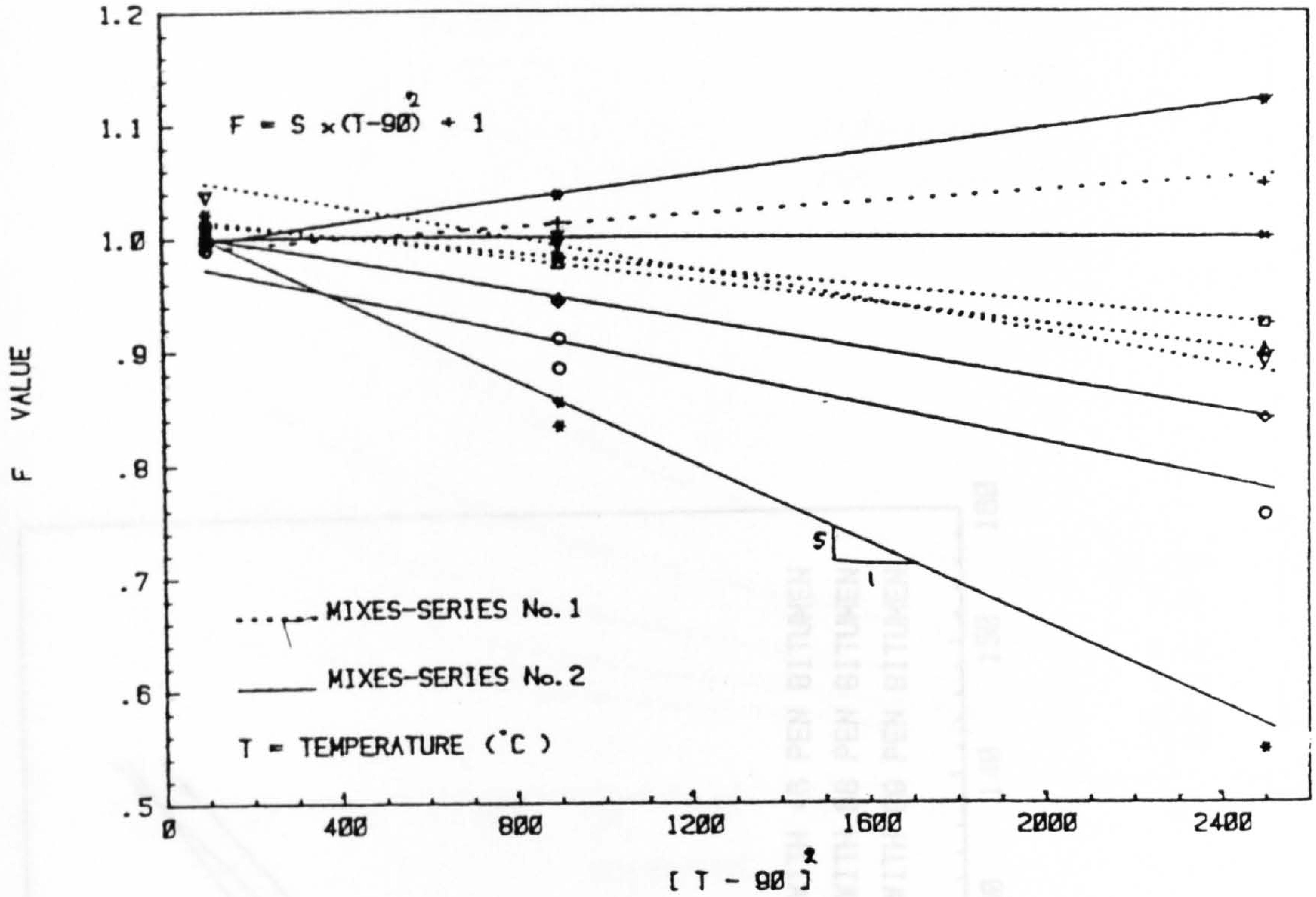
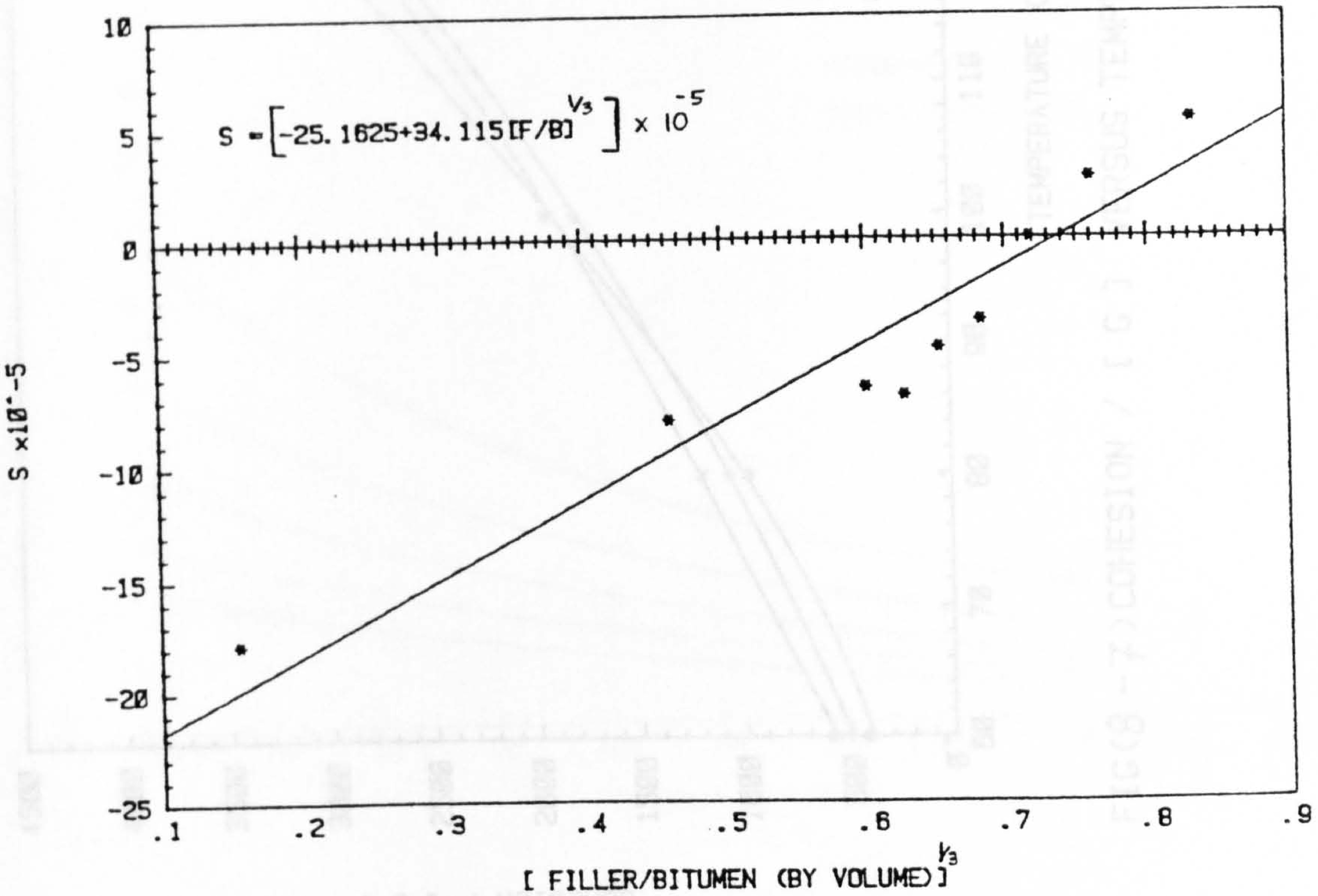


Fig-8.4

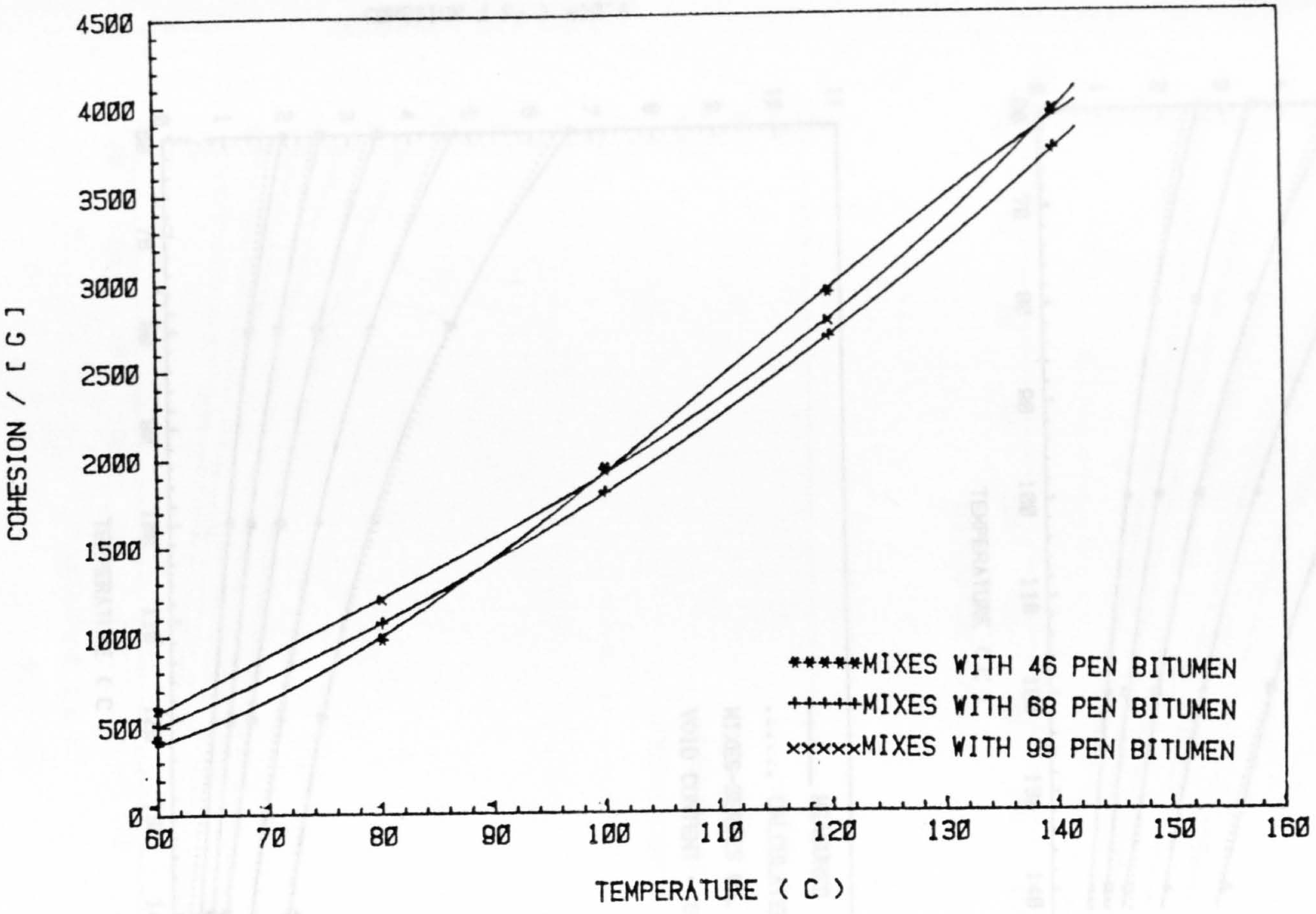
Figure 8.4: Measured and calculated relationships between mix viscosity and temperature for selected cases with Test Series 2.



FIG(8 - 5)F VALUE VERSUS [TEMPERATURE-90°C]



FIG(8 _6)S VALUE VERSUS FILLER-BITUMEN RATIO



FIG(8 -7)COHESION / [G] VERSUS TEMPERATURE

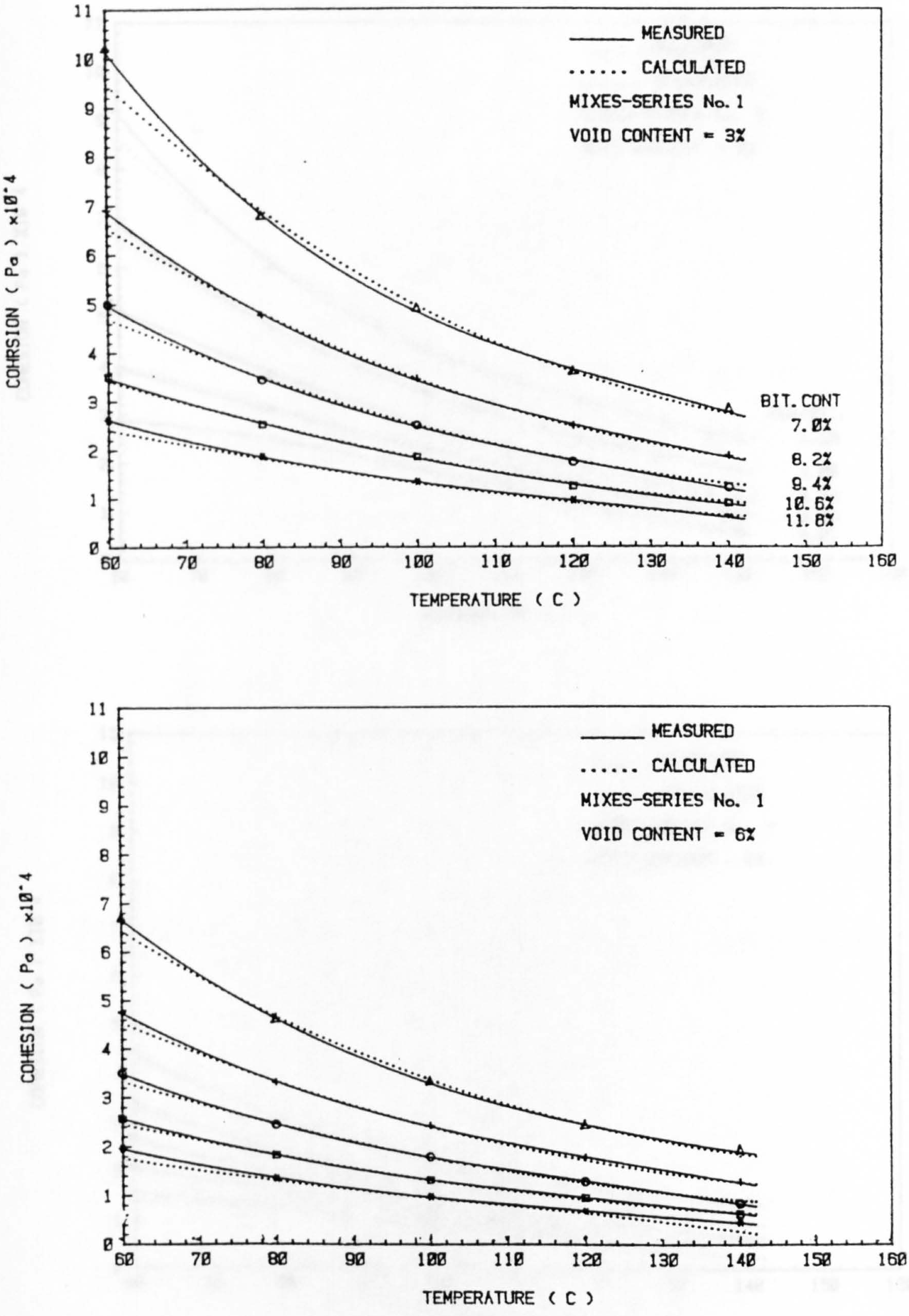
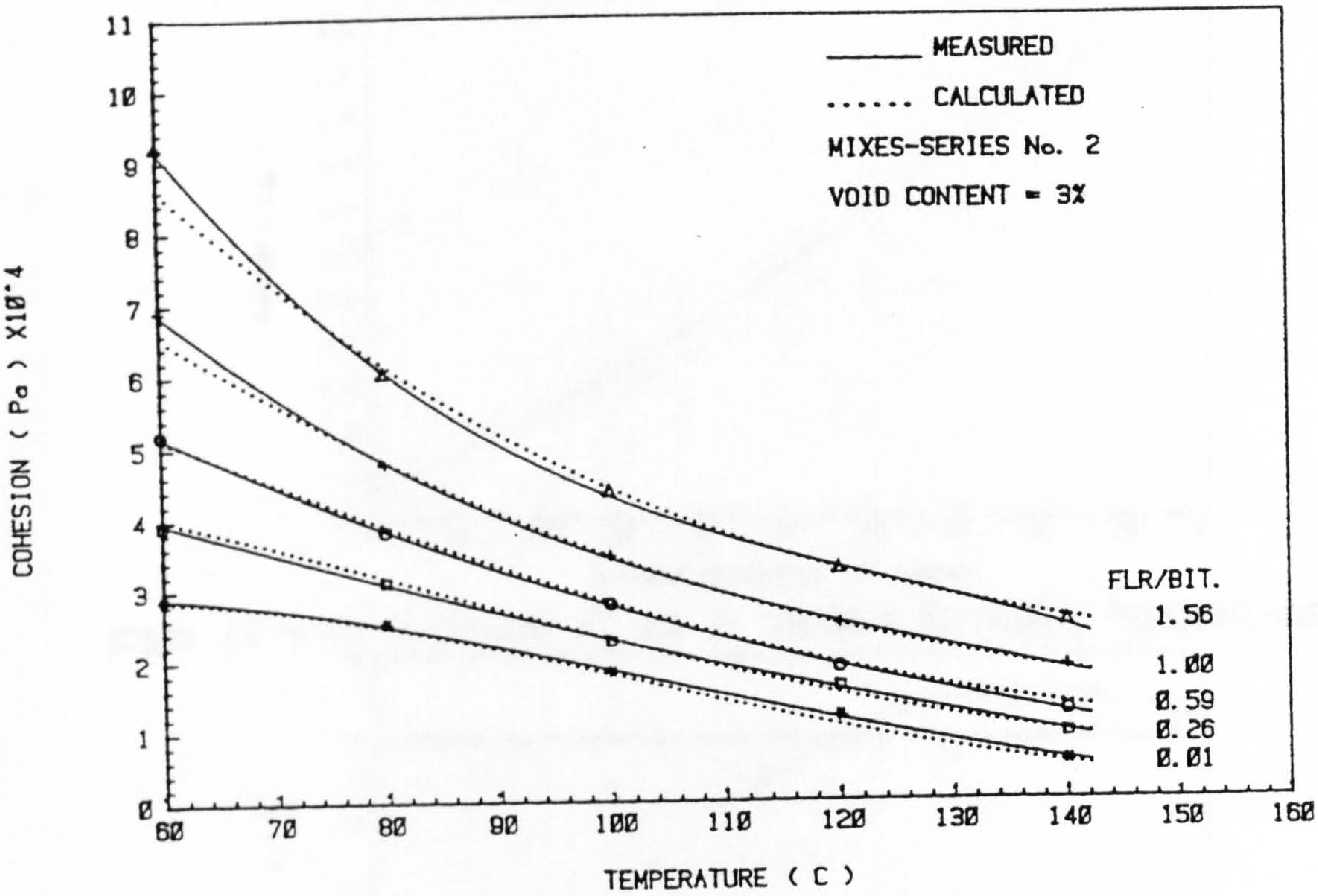


Figure 8.8: Measured and calculated relationships between mix cohesion and temperature for selected cases with Test Series 1.



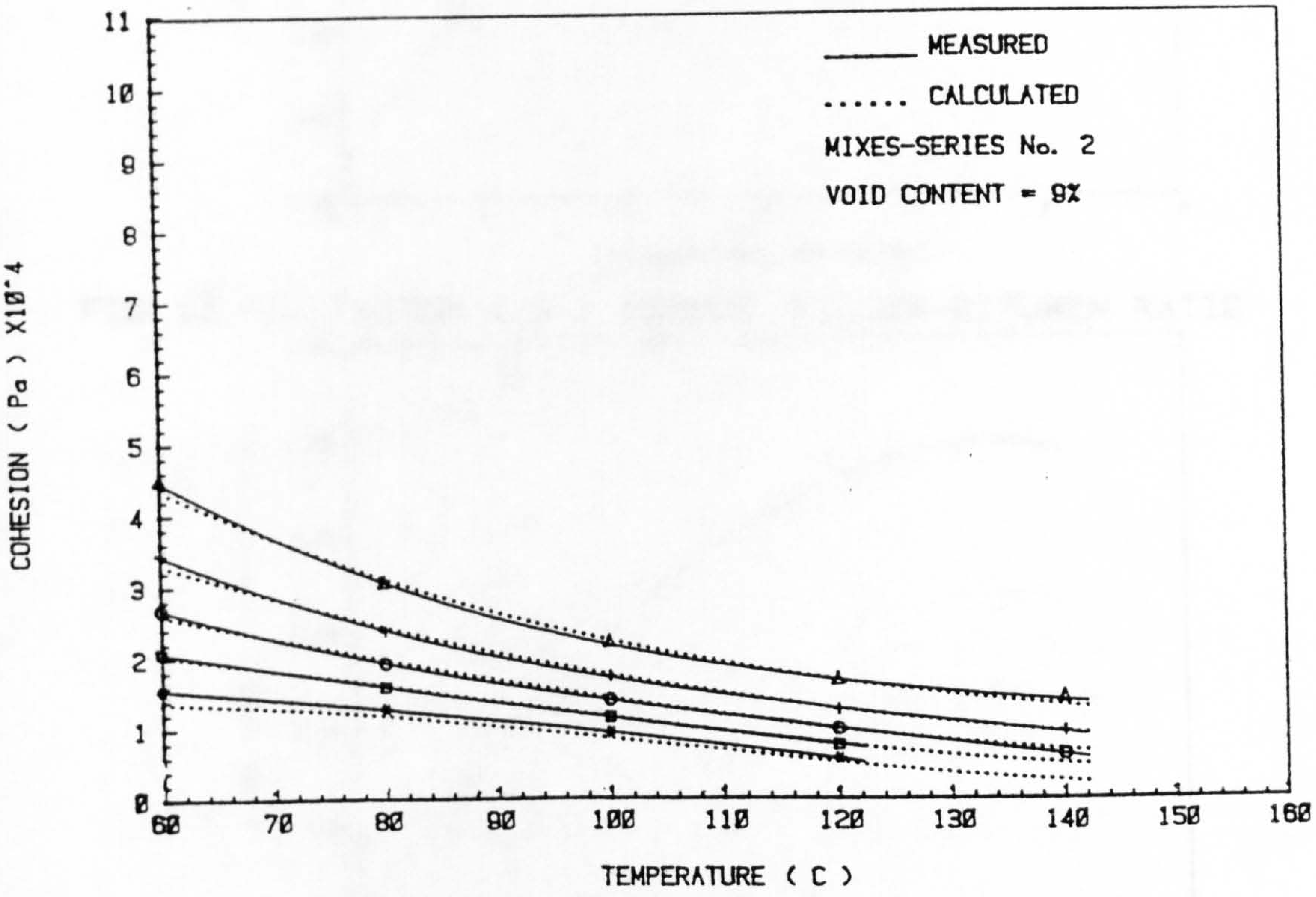


Figure 8.9: Measured and calculated relationships between mix cohesion and temperature for selected cases with Test Series 2.

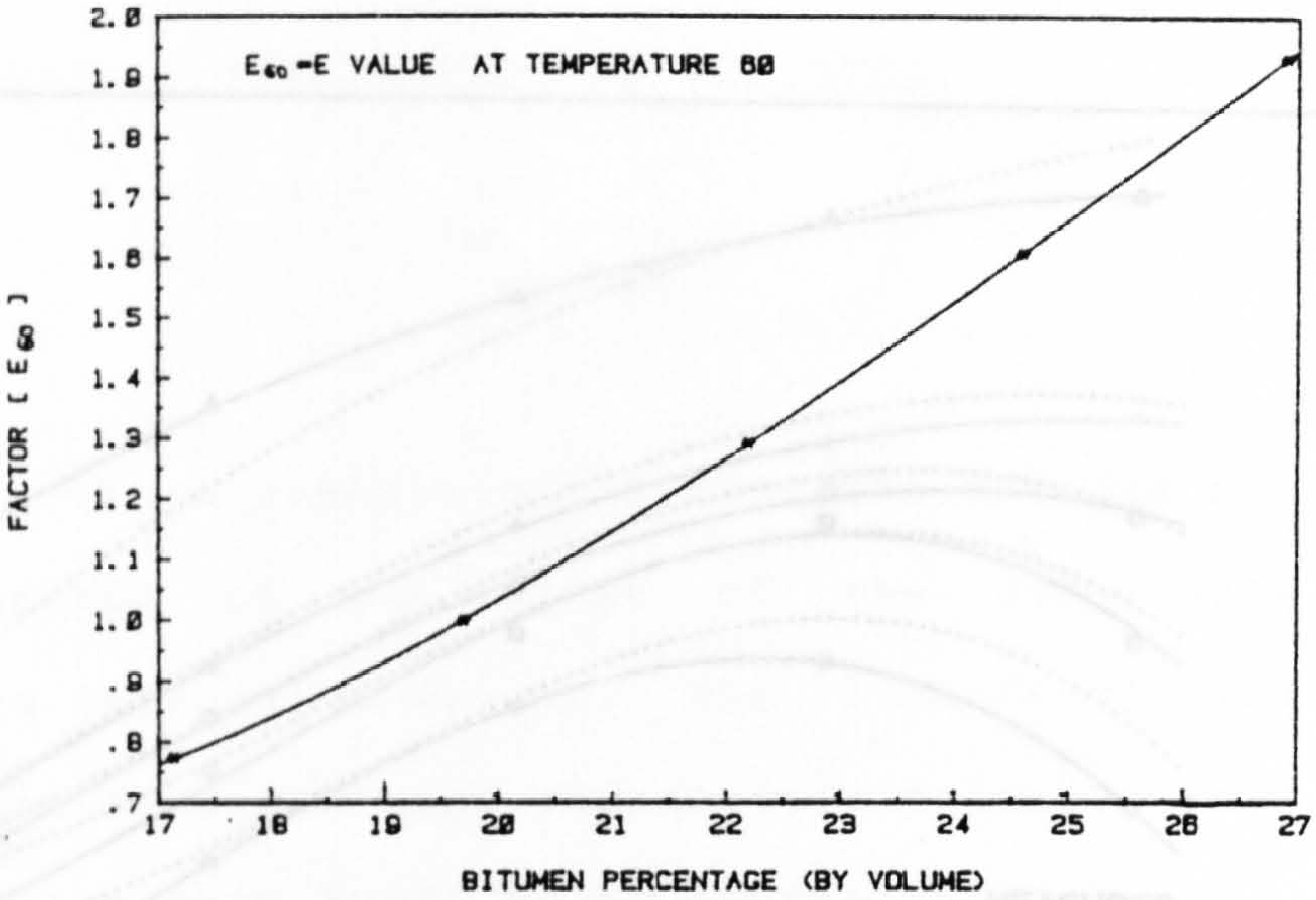


FIG (8 - 10) E VALUE AT 60 C VERSUS BITUMEN PERCENTAGE

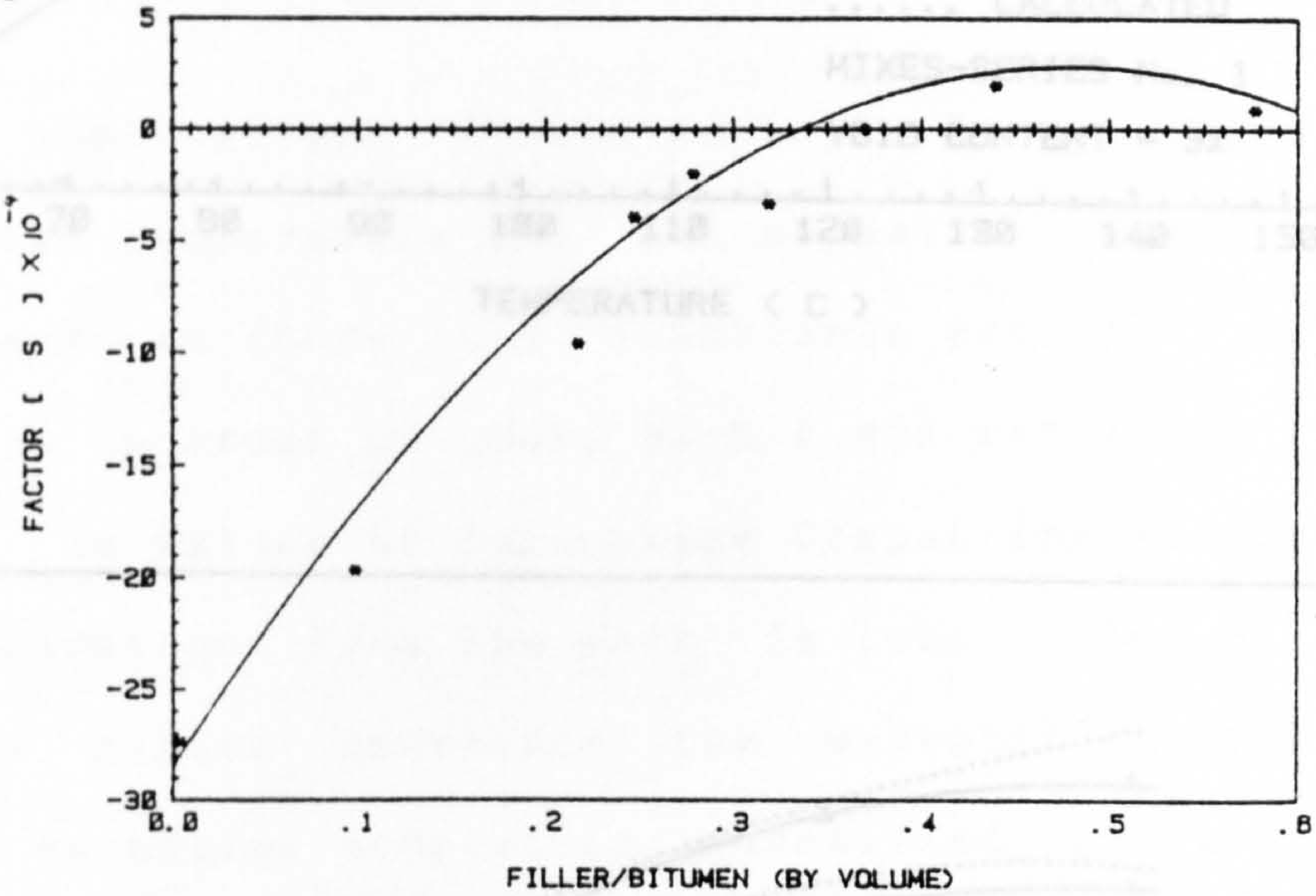


FIG (8 -11)FACTOR (S) VERSUS FILLER-BITUMEN RATIO

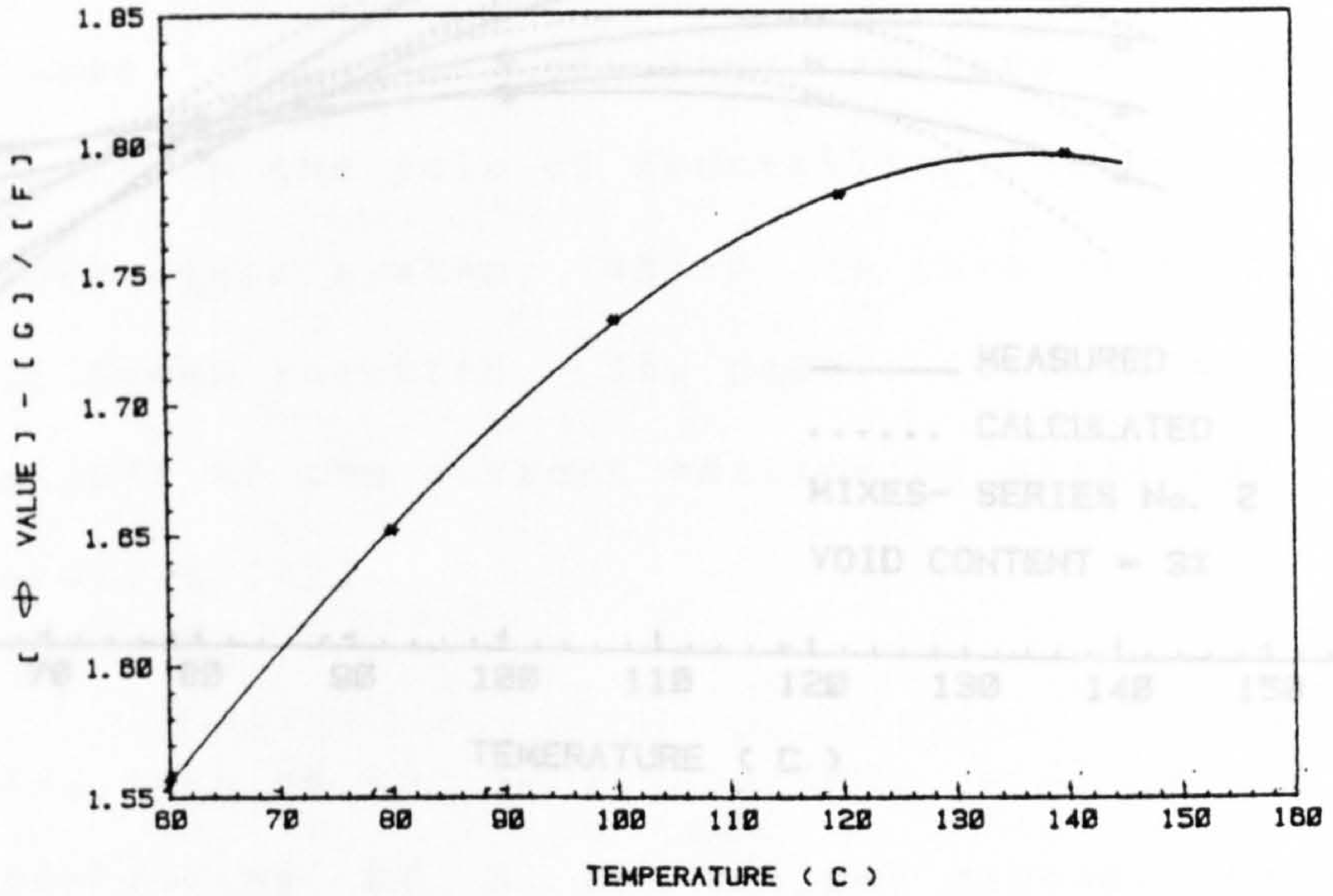
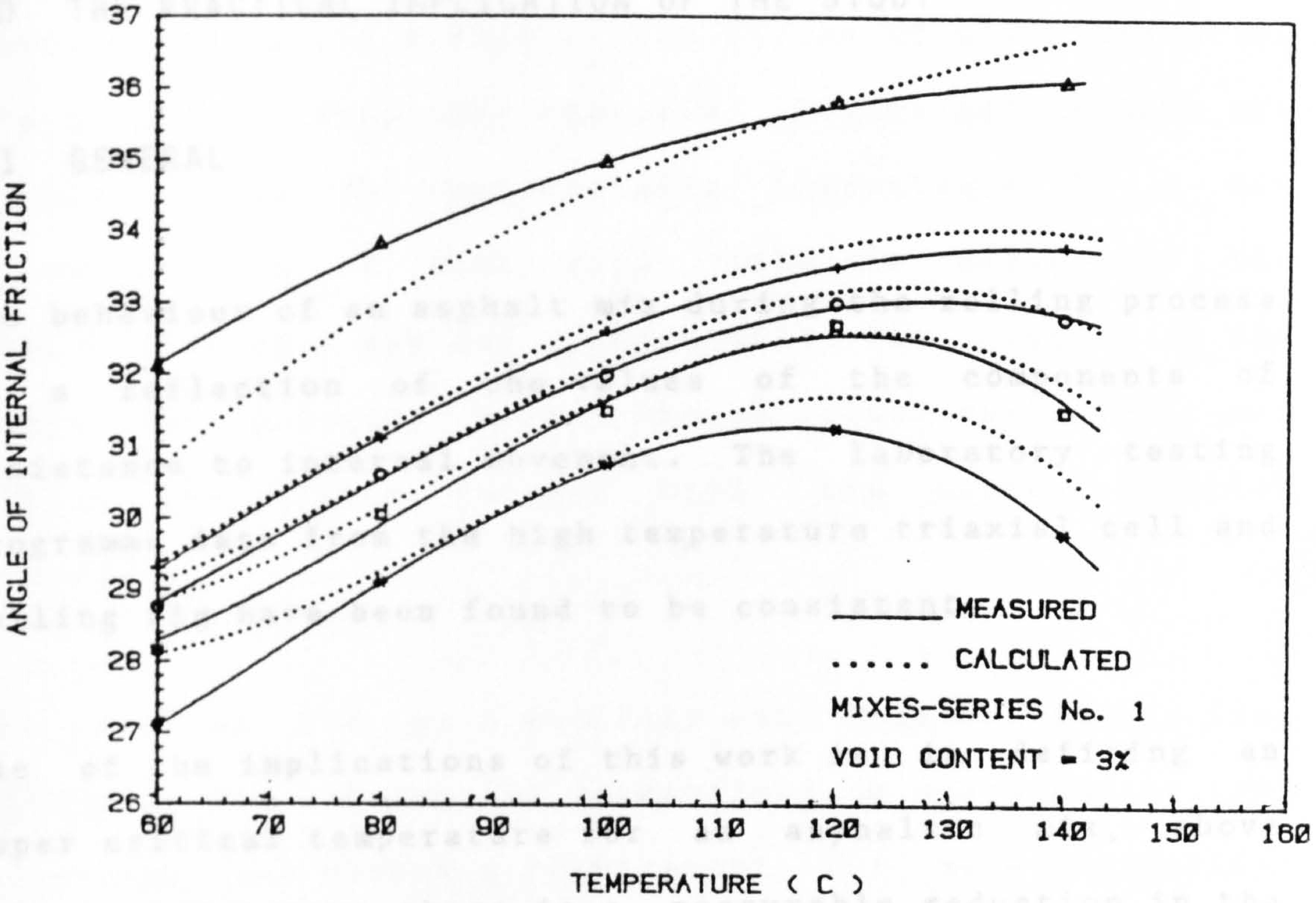


FIG (8 - 12) Φ-F/G VERSUS TEMPERATURE



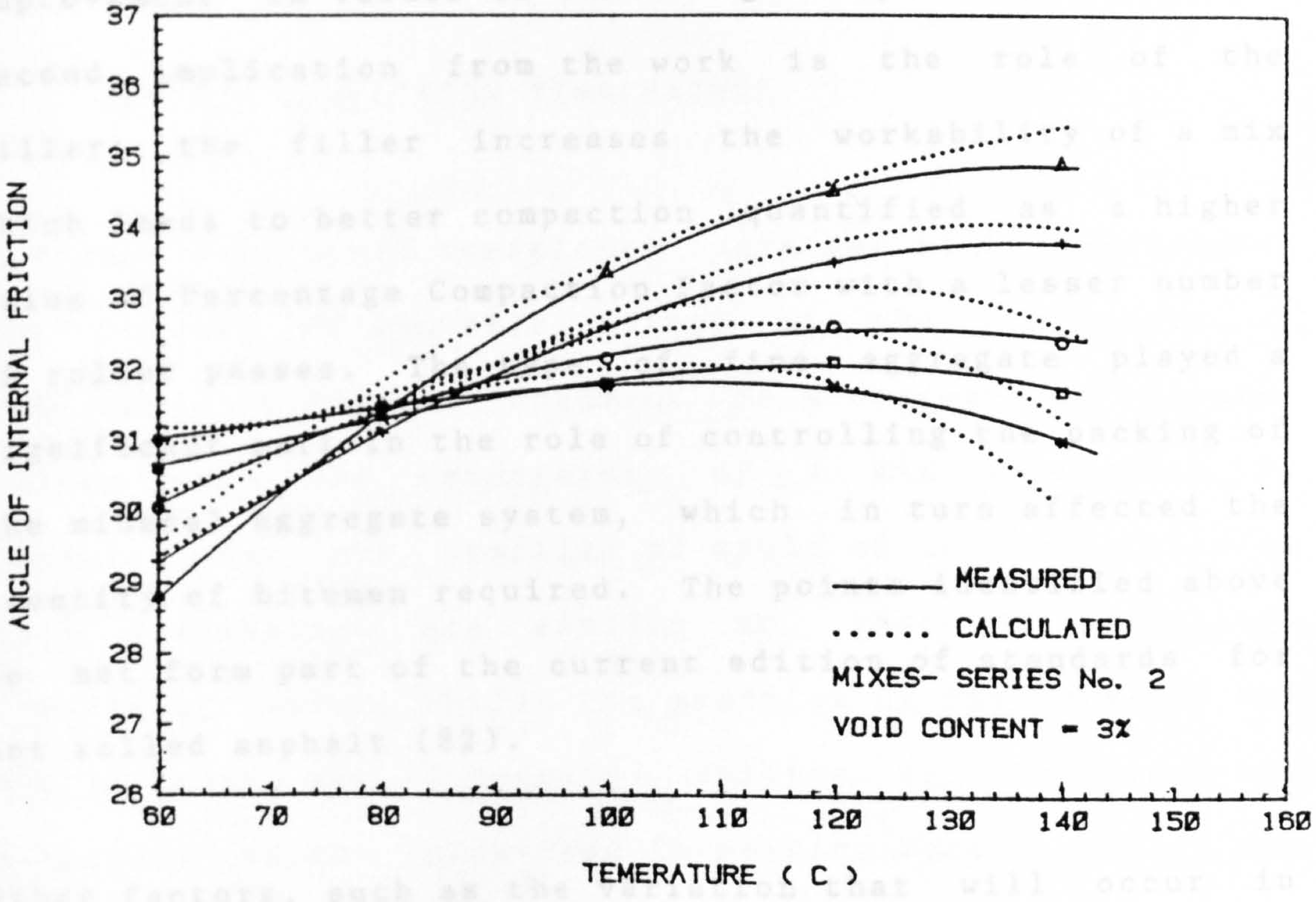


Figure 8.13: Measured and calculated relationships between angle of internal friction and temperature for Test Series 1 and 2.

9.0 THE PRACTICAL IMPLICATION OF THE STUDY

9.1 GENERAL

The behaviour of an asphalt mix during the rolling process is a reflection of the values of the components of resistance to internal movement. The laboratory testing programme data from the high temperature triaxial cell and rolling rig have been found to be consistant.

One of the implications of this work is in defining an upper critical temperature for an asphaltic mix, above such a temperature there is a measurable reduction in the resistance to internal movement with a mix reflected in no improvement in values of Percentage Compacting Factor. A second implication from the work is the role of the filler; the filler increases the workability of a mix which leads to better compaction quantified as a higher value of Percentage Compaction Factor with a lesser number of roller passes. The type of fine aggregate played a significant part in the role of controlling the packing of the mineral aggregate system, which in turn affected the quantity of bitumen required. The points identified above do not form part of the current edition of standards for hot rolled asphalt (82).

Other factors, such as the variation that will occur in the mix proportions of a hot rolled asphalt between batches and is the result of the nature of plant operation are quantified from this research. Filler and bitumen are likely to be the most variable ingredients in a mix operation and as such will influence measurably the workability of a mix and consequently the outcome of the compaction process, even though actual variations are within the limits defined with the current British Standard.

The use of EVA as a modifier with high stability fine aggregate did not improve workability as measured in this programme and showed a requirement for more compaction time (i.e. a high number of roller passes), or a higher bitumen content.

9.2 OPTIMUM COMPACTION TEMPERATURE

Although frictional resistance increases with temperature, the outcome of the total effect of the components of resistance to internal movement is a decrease in measured values when the temperature of a mix increases. It appears that the profiles of angle of internal friction with temperature are similar to that of Percentage Compacting Factor, whilst the profiles of mix cohesion and mix viscosity are (inversely) related to the order and magnitude of the Percentage Compacting Factor. It is not surprising that the profiles of angle of internal friction appear to indicate directly the influence of temperature on the compaction performance of bituminous mixtures. This is a consequence of the influence of the main component of an asphaltic mix, the mineral aggregate, which is a granular material with high value of angle of internal friction. The presence of bitumen and filler reduces the frictional properties of the mineral aggregate, particularly at low mix temperatures. When the temperature of a mix increases the influence of the bitumen on the frictional resistance offered by a mix decreases. The profile of angle of internal friction is it is believed from this study a significant guide to the performance of an asphaltic mix with change in temperature relevant to that of layer compaction.

This is not unrealistic because at high temperature the mineral aggregate will form the principal internal structure of an asphaltic mix, dominating the properties of the bitumen or the mastic materials. When the profile of angle of internal friction peaks at some elevated temperature, a temperature similar to peak point recorded in the Percentage Compacting Factor profile, then beyond this point a drop or tendency toward a drop in value was noted. This behaviour concurs with a drop in values of mix cohesion and mix viscosity and suggests that the magnitude of resistance to internal movement is so low that the material as a layer will not resist the weight of a roll - an 'overstress' condition. The temperature of maximum angle of internal friction and that of Percentage

Compacting Factor are plotted in Figure 9.1 which show good agreement within the laboratory programme. The interpretation of this data is that these temperatures represent the optimum compaction temperature for that particular mix, compacting the material at beyond these temperatures either results in no improvement in degree of compaction which can be achieved or there will be a reduction in state of compaction, in the programme defined as a reduction in Percentage Compacting Factor.

Figure 9.1 exhibits a curvelinear relationship between temperature and bitumen content. As the bitumen content is increased the Optimum Compaction Temperature decreases. Also, the Figure shows a linear relationship between filler to bitumen ratio and Optimum Compacting Temperature a low filler to bitumen ratio reduces the Optimum Compaction Temperature markedly. Further, increasing the penetration grade of the bitumen reduces the Optimum Compaction Temperature. The values of Optimum Compaction Temperature shown in Figure 9.1 with such a high stability fine aggregate (>10kN) is likely to form the Optimum Compaction Temperatures for most fine aggregates used in the U.K.

9.3 THE INFLUENCE OF FILLER ON MIX WORKABILITY

The comparison made between mixes of test series 1 and 2 show that increasing the filler content, but keeping the bitumen content constant, along with the fine and coarse aggregate proportions, increases the degree of compaction achieved with a mix, as indicated by an increase in Percentage Compacting Factor. This is the result of an increase in mix workability; but, the increases in mix workability is accompanied by an increase in the sensitivity of a mix to temperature changes and an increase in the upper critical temperature of a mix. The optimum temperature for layer compaction is increased with increasing filler content. But, mixes with higher filler contents require less number of roller passes to achieve a particular level of compaction compared with those mixes with a lesser filler content but the same bitumen content; this is the result of measured mix workability.

The influence of filler on internal resistance was noticeably different at high temperature compared with low temperature. At high temperature, where the role of bitumen significantly decreases, the filler reduces the frictional resistance and interlocking resistance (mix cohesion and mix viscosity). This is due to the role of the filler in separating the fine aggregate particles and reducing the resistance to rolling and sliding of those particles. At the same time the filler fills the voids in the mineral aggregate more efficiently during mix compaction process.

9.4 THE INFLUENCE OF BITUMEN CONTENT

Increasing the bitumen content generally increases the compaction of a layer as indicated by an increase in Percentage Compacting Factor value. This is due to increased mix workability by reducing the components of resistance to internal movement, which in turn, reduces the Upper Critical Temperature of a mix, and the Optimum Compaction Temperature for a layer of material.

Although this confirms what is known from practice in general, what is available is a quantifiable measure of the change in mix performance, even within the range of mixes allowed in the current edition of BS 594; a 0.6 percent variation in bitumen content has noticeable influence on the workability and possibly durability of a hot rolled asphalt layer. The study shows marked differences in performance of mixes with differences of 1.2 percent in bitumen content (as permitted by BS 594), such as 7 percent and 8.2 percent bitumen content of series 1. Such differences showed a significant difference in value of the components of resistance to internal movement and compaction as indicated by the values of Percentage Compaction Factor.

9.5 THE INFLUENCE OF TYPE OF FINE AGGREGATE

There are no adjustments to the bitumen content as a result of the type of fine aggregate in the current edition of BS 594 (82). It is stated in Appendix A of the current edition of BS 594 that "problem(s) may occur in obtaining reliably durable material of low permeability because of the harshness of the mixtures which make compaction more difficult. These problems may be overcome by increasing the binder content by up to 1% above the design binder value". This study shows that different fine aggregates affect the bitumen content by up to 4 percent. Mixes with high stability fine aggregate used in main programme (those with 10.6 percent bitumen content) were the most suitable to compare with those commercial mixes discussed in Chapter Seven, ie those with 6.5 percent and 7.1 percent bitumen content and made with lower stability fine aggregate. This shows how the type of fine aggregate (shape or surface texture) influences the packability of the material ingredients and its demand for a bitumen based binder.

9.6 INFLUENCE OF EVA AS BITUMEN MODIFIER

The apparent contradiction in the data is the effect of EVA. Commonly a nominal 70 pen bitumen with EVA replacement is taken as a substitute for a 50 pen bitumen binder. In the test series of the main programme the nominal 100 pen bitumen with EVA replacement was found to be a better match for the 50 pen bitumen base binder. In addition, during triaxial tests when the cell valve was opened to bleed the oil from around the sample and create a condition of dynamic equilibrium, a significant delay was observed between opening the valve and movement of the sample. Although an EVA bitumen blend may be more shear susceptible this time delay may be significant if vibrating rollers are used for layer compacton (101).

The use of EVA as a modifier, enhances the stability of hot rolled asphalt markedly. This increase in mix stability could be used in allowing higher bitumen content mixes to be used to enhance mix workability and subsequently mix durability, without sacrificing the stability of the mix when compared with unmodified materials.

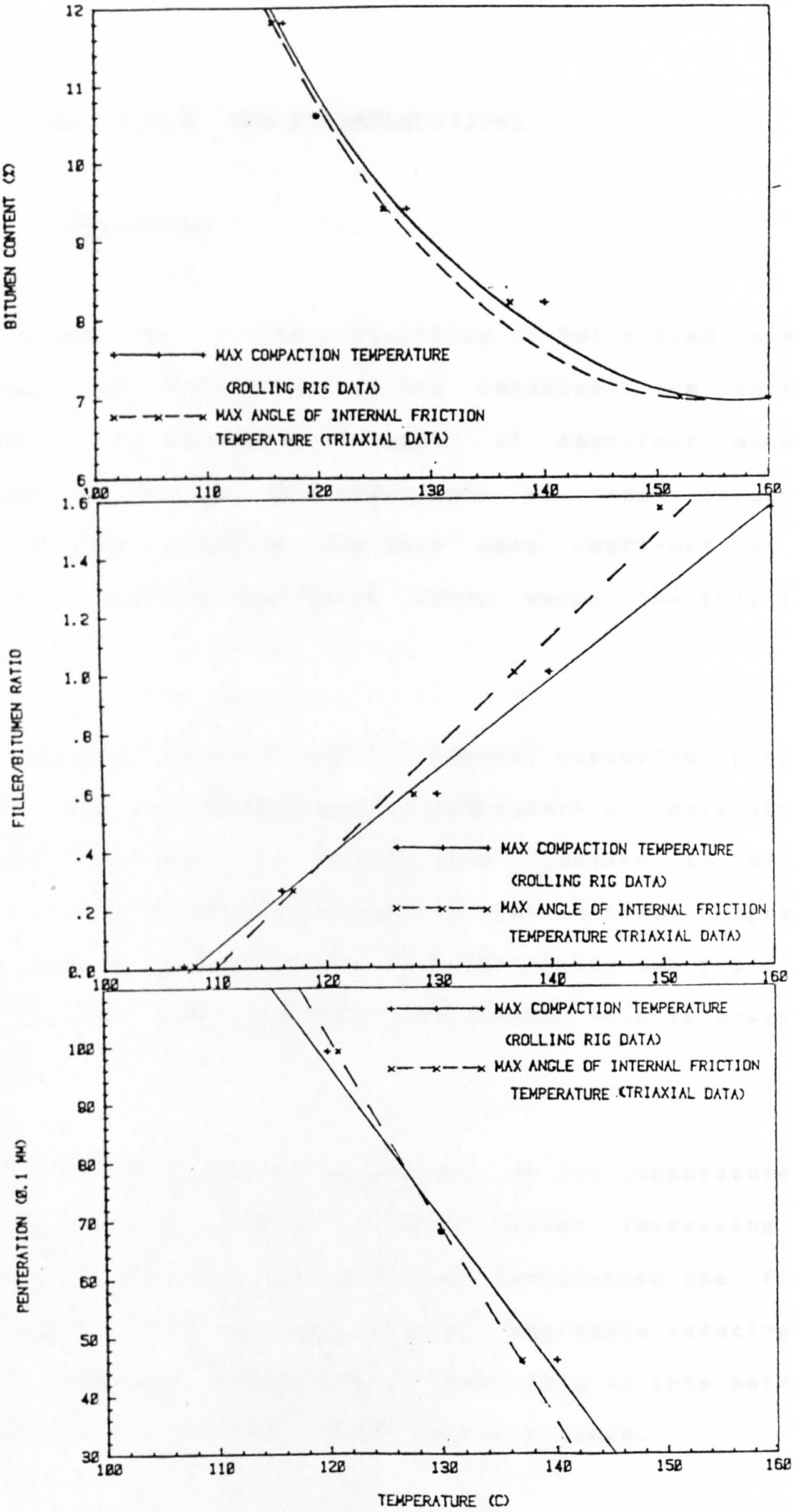


Figure 9.1: The relationship between bitumen content, filler/bitumen ratio, penetration and temperature at upper critical compaction temperature.

10.0 CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

The assessment of the workability of hot rolled asphalt through the evaluation of its resistance to internal movement has identified a number of important material performance issues. The importance of these issues are particularly relevent when they were confirmed by the result of rolling 40mm thick slabs using the full scale roll.

The bitumen showed that its thermal expansion plays a major role in decreasing the components of resistance to internal movement of a mix. The increase in bitumen volume with temperature separates the mineral aggregate particles and thus reduces the interlocking and frictional resistance at the time where the bitumen role is nominally minimal.

The filler role is also important. At low temperature the filler becomes a part of the binder increasing its apparent stiffness, whilst at high temperature the filler becomes a part of the mineral aggregate reducing the frictional and interlocking resistance of this material ingredient in the same manner as the bitumen.

The shape and surface texture of the mineral aggregate, particularly the fine aggregate particles, have great influence on the packability of this mix fraction and in turn the packability of all whole system. However, for the particular materials used in this study the following points can be made.

a) Angle of internal friction increases when temperature increases, making the relationship essentially a concave upward profile. The angle of internal friction profile peaks at a particular elevated temperature; the profile is either asymptotic to this peak value or a drop in value at higher temperatures is observed. The drop becomes more pronounced and takes place at a lower temperature when a mix of higher workability is used. A change in temperature over the range 60°C to 140°C can raise the angle of internal friction value by up to 5 degrees. With voids content the angle of internal friction profile also has a concave upward orientation. The value of angle of internal friction increases with a reduction in voids content, up to a particular limit and then drops when the voids content is reduced further. Mixes with low workability (such as that with low bitumen content), have an angle of internal friction value which peaks at voids content around 9 percent, whilst mixes with a high workability the peak is at a voids content around 6 percent. Important features are

- Angle of internal friction values decrease when the bitumen content and/or filler content increases.

- Angle of internal friction values increase when the filler to bitumen ratio increases provided that the volume of filler and bitumen are constant.

- Angle of internal friction values increase when the bitumen viscosity decreases; mixes with high penetration grade bitumen produce higher values of angle of internal friction than those incorporating a low penetration grade bitumen.

- A low angle of internal friction fine aggregate will produce mixes with low values of angle of internal friction.

b) Cohesion values decrease when mix temperature increases and/or the voids content decreases. Also, cohesion values decrease when: the bitumen content increases, but when keeping the filler and mineral aggregate proportions constant; or, when the filler to bitumen ratio decreases, but when keeping the volume of filler and bitumen constant; or, when the filler content increases, but when keeping the bitumen content constant.

The relationship between mix cohesion and temperature generally exhibits a concave downward profile, but when the filler content is reduced the curvature becomes flatter and the profile becomes concave upward when the filler is almost totally removed.

Increasing the penetration grade of the bitumen reduces the cohesion value of a mix whilst a replacement of 5 percent EVA increases the cohesion value of a mix noticeably. The presence of EVA appears to enhance mix cohesion significantly, particularly when the temperature drops below 120°C. It raises the value of mix cohesion more than 30 percent and that increases further when the mix temperature decreases.

c) Mix viscosity (as with mix cohesion) decreases when mix temperature increases and/or the void content of a mix decreases. Mix viscosity decreases when: the bitumen content of a mix increases, but when keeping the filler and mineral aggregate proportions constant; or, the filler to bitumen ratio decreases, but when keeping the volume of the mastic constant; or, the filler content increases, but when keeping the bitumen content constant; or, the pen grade of the bitumen increases, but when keeping mix proportions constant.

The profile of mix viscosity with temperature may be divided into three parts: rapid reduction in value when the temperature of the mix is raised from 60°C to around 80°C, followed by a flat profile to around 120°C with highly workable mixes, and 140°C or above with low workable mixes, terminated by a noticeable drop in value observed with highly workable mixes and just a tendency to drop with other mixes.

Mix viscosity increases markedly when EVA replace 5 percent of the bitumen. This was more noticeable when the mix temperature drops.

d) Percentage Compacting Factor profile with temperature is a similar profile to that of angle of internal friction with temperature. The value of Percentage Compacting Factor is inversely proportional to the value of mix cohesion and mix viscosity.

The Percentage Compacting Factor peaks at a particular (elevated) temperature, similar to that of angle of internal friction and then drops in value. The Percentage Compacting Factor value increases when the bitumen content increases but when keeping the filler and mineral aggregation proportion constant; or, when the filler to bitumen ratio decreases, but when keeping the volume of the mastic constant; or, when the filler content increases, but when keeping the bitumen content constant.

Increasing the penetration grade of the bitumen increases the value of Percentage Compacting Factor at low temperature and the peak in the Percentage Compacting Factor value takes place at lower temperature.

The use of EVA does not improve the Percentage Compacting Factor value of a mix and it did not show a turning point within the investigated range of temperatures in the test programme.

e) The upper critical temperature that is observed in the profiles of Percentage Compacting Factor and angle of internal friction may be considered as an optimum compaction temperature. Compacting at mix temperatures higher than this will not improve compaction, on the contrary it is likely to decrease the Percentage Compacting Factor value.

For the particular material ingredients used, the optimum compaction temperature was found to decrease in the following manner.

(i) In a curvelinear concave downward profile when bitumen content increased.

(ii) In straight linear profile when the filler to bitumen content decreased. The optimum temperature may drop to below 110°C when the filler to bitumen ratio decreases to around zero.

(iii) In a linear profile when the penetration grade of the bitumen increased. For high stability fine aggregates it was found that the optimum compaction temperature for nominal 50 pen bitumen was around 140°C; nominal 70 pen bitumen was around 130°C, and for nominal 100 pen bitumen was around 120°C.

f) Mixes exhibiting high workability such as those with a high bitumen content (filler and mineral aggregate proportion constant) or low filler to bitumen ratio (the mastic volume constant) show not only high Percentage Compacting Factor values but this is achieved with fewer roller passes.

Also increasing the filler content (keeping the bitumen content constant) yields higher Percentage Compacting Factor values with a noticeably lower number of roller passes.

g) Increasing the bitumen content in a mix leads to a decrease in the components of resistance to internal movement and thus a decrease in workability. But, when the bitumen content is increased by 1.2 percent, accompanied by an inclusion of EVA (5 percent of total bitumen content) this produces a mix with high internal resistance but good compaction. This finding suggests that workability (and durability) of an asphaltic mix can be improved with EVA when the bitumen content is increased.

h) Modified mixes with nominal 100 pen bitumen using a 5 percent EVA replacement are found to be similar in terms of performance profiles to unmodified mixes made with nominal 50 pen bitumen. This finding contradicts with what is presently regarded as compatible mixes, ie a 70 pen + 5 percent EVA replacing a 50 pen bitumen. However 100 pen + 5 percent EVA is found still to show high resistance to internal movement and give a lesser value of Percentage Compacting Factor at low temperatures (60°C to 80°C).

i) Mixes with EVA show continuous increase in Percentage Compacting Factor value when the number of roller passages was increased. According to the delay time in modified asphalt to deform, the time applied to compaction may be crucial to achieve the required compaction. This might lead to a claim that using a vibrating roller is not suitable for mixes modified with EVA.

j) The type of fine aggregate is an important factor in the workability of an asphaltic mix. Noticeable differences in the packability of fine aggregates were found when different source material was used. This led to a 4 percent difference in the required bitumen content to achieve a particular level of workability. This goes beyond the guidance of the current edition of BS 594 which recommends an increase in bitumen content by up to 1% to reduce the higher resistance to internal movement of a 'harsh' mix.

k) Plant variations in material ingredients (such as filler) between batches (even those within the limits defined in the standards) may have a serious implication for mix workability, and in turn the compaction performance of an asphaltic mix. Batches with high workability might lead to the total embedment of coated chipping or with batches exhibiting low workability may lead to chipping loss.

10.2 RECOMMENDATIONS

1. Filler appears to play an important role in defining the workability of a hot rolled asphalt. Studying different types of filler could lead to the definition of guidelines on the influence of fillers on mix workability (and mix durability).

2. The type of fine aggregate used has a significant influence on bitumen content demand and mix workability, far greater than indicated in the current edition of BS 594. Investigating a wide range of fine aggregate would be important in providing information such as exists for different coarse aggregate.

3. A computer control is required to record sample deformation with time in the triaxial cell, not only for getting a more accurate rate of sample vertical deformation but also to record the delay time between the opening of the bleed valve and the start of sample deformation, which takes place with EVA modified mixes.

5. Using different speeds of roller to compact mixes modified with EVA could provide a clearer picture about the response of these mixes to the time of load application.

6. A more detailed theoretical model using the existing data may lead to a suitable relationship for a single definition of mix workability combining the three components of internal resistance to the movement. Such a relationship might predict the amount of compaction which could be achieved given a weight of roller and given a number of roller passages.

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APPENDIX (A)

Marshall Tests were carried out on all mixes usedin this study. The samples were prepared and tested according to British Standard BS 598 Pt 3 (91). The results are tabulated in Table A-1, A-2 and A-3.

Table A-1: Marshall test results of Test Series 1

Bitumen content %	7.0	8.2	9.4	10.6	11.8
Filler/bitumen ratio	1.19	1.00	0.86	0.76	0.67
Stability (kN)	10.63	10.35	9.97	6.24	2.9
Flow (mm)	2.38	3.38	4.64	5.8	10.92
Void content %	8.95	6.55	4.98	4.54	5.51
Mix Density g/mL	2.215	2.232	2.228	2.199	2.139
Compacted aggregate density g/mL	2.060	2.049	2.029	1.966	1.886

Table A-2: Marshall test results of Test Series 2

Bitumen content %	7.0	8.2	9.4	10.6	11.8
Filler/bitumen ratio	1.56	1.00	0.59	0.26	0.01
Stability (kN)	11.03	10.35	9.64	8.6	4.56
Flow (mm)	3.11	3.38	3.64	4.18	9.25
Void content %	8.57	6.55	5.20	3.82	3.55
Mix density g/mL	2.223	2.232	2.224	2.218	2.184
Compacted aggregate density g/mL	2.067	2.049	2.015	1.987	1.926

Table A-3: Marshall test results of Test Series 3 and 4

Type of binder	46 pen	68 pen	99 pen	95% 46 pen + 5% EVA	95% 68 pen + 5% EVA	95% 99 pen + 5% EVA
Stability (kN)	10.35	9.25	8.3	14.13	11.83	10.54
Flow (mm)	3.38	3.63	3.95	3.14	3.32	3.62
Mix void %	6.55	6.04	5.9	6.93	6.15	6.05
Mix density g/mL	2.232	2.244	2.247	2.223	2.242	2.244
Compacted aggregate density g/mL	2.049	2.04	2.063	2.04	2.057	2.06

Binder content for all mixes = 8.2 and
Filler/binder ratio = 1.00

APPENDIX (B)

Marshall tests were carried out on the four commercial mixes, discussed in Chapter Seven. The mixes were tested in accordance with BS 594 (91). The results are shown in the following table.

Mix number	M1	M2	M3	M4
Bitumen content	7.13	6.56	7.06	6.53
Filler/bitumen ratio	1.26	1.3	1.4	1.38
Stability (kN)	7.9	9.0	6.6	9.6
Flow (mm)	2.4	1.5	3.9	2.7
Mix density g/mL	2.315	2.291	2.328	2.332
Void content %	3.37	5.1	3.21	3.72
Density of compacted aggregate g/mL	2.15	2.141	2.164	2.18

PUBLISHED PAPERS

Asphalt workability

by Kadhim Kweir, Derek Fordyce and David Whiteoak

Presently in the UK the only bituminous material which has a specified mix design standard is wearing course hot rolled asphalt. A 'Marshall' design mix procedure optimises the binder content for a particular source of material ingredients — coarse aggregate, fine aggregate and filler. The bitumen content specified is based on the binder contents which maximise compacted mix density, compacted aggregate density and mix stability. The design of asphaltic wearing course mixes relates to the service performance of the material layer, specifically, its resistance to plastic deformation under traffic loading. Currently, categories of traffic loading have stability limits and a maximum specified flow value. The suitability of a particular design mix as a wearing course for a pavement will depend on whether its stability and flow values comply with load category values for the roadway.

Unlike the design of a structural concrete or pavement quality concrete the design of a wearing course hot rolled asphalt takes no account of the ability of the material to be placed and compacted. Structural concrete requires to be workable enough to flow around reinforcement and allow the escape of entrapped air when agitated; allowance is made for this in a mix design. Wearing course hot rolled asphalt requires to be workable enough to be spread evenly on a substrate and allow the controlled embedment of coated stone chippings into the surface of the layer during layer compaction; no allowance is made for this in a mix design.

The compaction process with a chipped hot rolled asphalt wearing course is not the same as other, unchipped, bituminous layers. Where surface texture is required a chipping spread rate of 70% shoulder to shoulder is applied. With such a chipping rate the surface of the roller has little contact with the asphaltic material layer. The compacted voidage achieved within such a material layer depends on the degree of embedment of the stone chippings. The voidage of importance to the durability of the exposed surface is that around the embedded chippings.

The workability of a hot rolled asphalt, as with structural concrete, is a function of the physical properties of the mineral aggregate. But, with hot rolled asphalt, unlike structural concrete, the lubricating medium, to enable the mineral aggregate to pack, is temperature dependent. The resistance to internal movement of an asphaltic mix at any point in time during the compaction process depends on how a mix stiffens with decreasing temperature. The consequence of using a temperature sensitive mix can be the lack of adequate embedment of chippings, or the lack of adequate compaction of the asphalt around the embedded chippings. Chipping loss or fretting of the surface of the wearing course is the likely consequence. Presently no accepted fundamental measure of asphalt workability exists, in particular no accepted measure exists on how the resistance to internal movement of a mix changes with temperature, or, and possibly more importantly, how plant variation of mix ingredients influences the resistance to internal movement of a hot rolled asphalt mix at any particular temperature.

Research on asphalt workability

A paper in Asphalt 88 by Al Nageim and Fordyce (Al Nageim and Fordyce 1988) outlined an initial research programme carried out at Heriot-Watt University to define a fundamental measure of the workability, or resistance to internal movement, of wearing course hot rolled asphalt. Three commercially available hot rolled asphalt mixes were used as candidate materials to develop a high temperature closed-system triaxial cell. The cell allows the measurement of three fundamental components of the resistance to internal movement of an asphaltic mix. The three fundamental components are: angle of internal friction; cohesion; and mix viscosity.

The initial research programme measured the three fundamental components over the temperature range 60 to 120°C, the lower temperature range relevant to layer compaction. Using the particular analysis of the data described in the paper the authors suggested that a critical temperature for a mix could be defined, the temperature at which the components of internal resistance show a significant increase in their rate of gain in value with reducing temperature. This temperature, it was said, related to cessation of compaction, or at least the temperature by which compaction should have been "substantially completed" as it is phrased in BS 594, Part 2, the Specification for the transport, laying and compaction of rolled asphalt (BS 594, Part 2: 1988).

The initial research on asphalt workability has been extended in three ways.

1. The temperature range used with the triaxial cell has been extended to around 150°C, which encompasses the practical compaction temperature range.
2. A parallel programme of laboratory rolling of 300 by 300 by 40mm thick slabs of asphalt has been undertaken. The slabs were rolled using a roller of the same diameter and unit weight per mm width of roll as the rear wheel of a static three point roller. Slabs were compacted using a 50% shoulder to shoulder chipping rate, a 70% shoulder to shoulder chipping rate, and unchipped.

   Profiles of slab voidage with number of roller passages at the discrete compaction temperatures used in the triaxial work were plotted and related to profiles of an empirical relationship between the components of resistance to internal movement.
3. The profiles of the components of internal resistance with temperature have been related to compacted slab voidage data and, more importantly, to mix ingredient variations.

The work relating to the analysis and comparison of triaxial and compacted chipped slab data over the temperature range 60 to 150°C has been described elsewhere (Al Nageim 1989, Al Nageim and Fordyce 1989). It was suggested as a result of this work that,

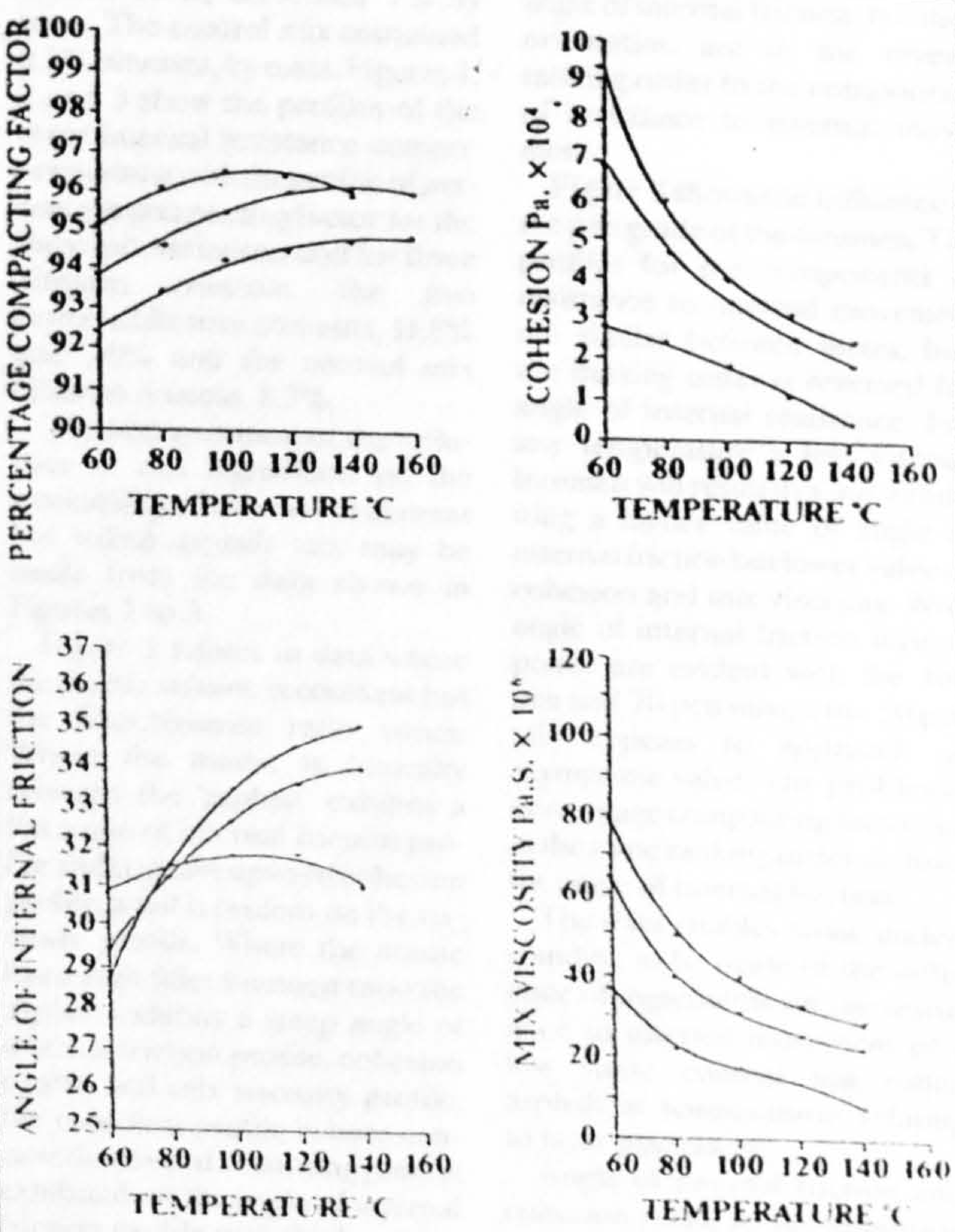

Fig.1 Mastic Volume Constant

× Filler: Bitumen ratio 0.01
+ Filler: Bitumen ratio 1.56

Control Mix

• Filler: Bitumen ratio 1.00

- an upper critical temperature may be able to be defined for mixes which is the temperature at which compacted slab voidage is minimised; above this temperature little resistance to movement exists to generate enough confining pressure to achieve minimum compacted slab voidage.
- the mix temperature which optimises chipping embedment with the compacted voidage of the asphalt surrounding the embedded chippings is believed to be just below the upper critical temperature for a wearing course hot rolled asphalt mix.
- the profile of slab voidage below embedded chippings, with temperature, may be related to a profile of a product of internal resistance components, with temperature; the implication is that triaxial data may be able to indicate the temperature sensitivity of a hot rolled asphalt mix, specifically, how readily, or otherwise, a mix stiffens with decreasing temperature.

Three important physical characteristics of a wearing course hot rolled asphalt mix are potentially available from triaxial data: a lower critical temperature, relating to substantial completion of layer compaction; an upper critical temperature, relating to an optimum compaction temperature for a particular asphalt mix; and, an indication of the potential temperature sensitivity of a particular asphalt mix.

Factors influencing asphalt workability

The most recent phase of the research into asphalt workability has been to identify the influence of selected mix ingredient variations on the components of internal resistance to movement of hot rolled asphalt. The parallel rolling programme in this phase of work used unchipped slabs. One outcome of this work is the definition of the potential variation in performance of a mix as a result of plant variations in metering mix ingredients.

In this phase of the research all mixes were prepared in the laboratory. A laboratory prepared version of one of the commercial mixes used in the first phase of the research programme formed a control mix.

The compacted slab voidage recorded for a rolling temperature is the terminal voidage. Slabs were compacted using 1, 3, 6, 9, 12 and 18 roller passages; a roller passage being taken as one forward and reverse movement of the roller over a slab. The terminal voidage is the lowest recorded voidage, or the voidage at 18 roller passages where this is the lowest value. The compacted slab voidage at any rolling temperature has been expressed as a 'percentage compacting factor', which is (100 – terminal voidage).

The three components of internal resistance to movement of a low stone content hot rolled asphalt are a function of the complex interaction between the bitumen, filler, fine aggregate and coarse aggregate. The three components are also a function of the temperature of the material, through its influence on the viscosity and volume of the bitmuminous binder. Three specific material variants were tested: filler:bitumen ratio, keeping the mastic volume constant; bitumen volume, keeping the total aggregate proportions constant; and bitumen pen grade. The range of mix proportions with the filler:bitumen test series and binder volume test series used the same bitumen contents: 11.8%, 10.6%, 9.4%, 8.2% and 7% by mass. The control mix contained 8.2% bitumen, by mass. Figures 1, 2 and 3 show the profiles of the three internal resistance components along with the profile of percentage compacting factor for the three mix variations and for three bitumen contents, the two extreme bitumen contents, 11.8% and 7.0% and the control mix bitumen content, 8.2%.

The interpretation of the influence of mix ingredients on the workability of a low stone content hot rolled asphalt mix may be made from the data shown in Figures 1 to 3.

Figure 1 relates to data where the mastic volume is constant but the filler:bitumen ratio varies. Where the mastic is basically bitumen the 'asphalt' exhibits a flat angle of internal friction profile and concave upward cohesion profile, a tail is evident on the viscosity profile. Where the mastic has a high filler:bitumen ratio the asphalt exhibits a steep angle of internal friction profile, cohesion profile and mix viscosity profile; the cohesion profile is here concave downward. A turning point is exhibited on the angle of internal friction profile with the low filler content asphalt; no turning point exists on the angle of internal friction profile with the high filler content asphalt, but an asymptotic value is suggested. The percentage compacting factor profiles follow a similar pattern to that for angle of internal friction: a turning point is exhibited with the high bitumen low filler content mix, an asymptotic value is indicated with the low bitumen filler content mix. But, the ranking order of the profiles of percentage compacting factor is reversed to those of the components of internal resistance to movement.

Figure 2 relates to data where the bitumen content varies, but the proportions of filler, fine aggregate, and coarse aggregate are constant. The high bitumen content mix exhibits a distinct concave upward profile with angle of internal friction, a turning point is clearly indicated. A similar degree of curvature of profile of angle of internal friction with the low bitumen content mix and control mix is exhibited, but those profiles appear to approach an asymptotic value. The cohesion profiles are all principally concave downward, the steeper profile relating to the low bitumen content mix. The viscosity profile again shows a tail with the high bitumen content mix. The percentage compacting factor profiles follow a similar pattern to that for angle of internal friction, but their orientation are in the reverse ranking order to the components of resistance to internal movement.

Figure 3 shows the influence of the pen grade of the bitumen. The profiles for the components of resistance to internal movement are similar between mixes, but, the ranking order is reversed for angle of internal resistance. For any temperature a less viscous bitumen will result in a mix exhibiting a higher value of angle of internal friction but lower value of cohesion and mix viscosity. With angle of internal friction turning points are evident with the 100 pen and 70 pen mixes; the 50 pen mix appears to approach an asymptotic value. The profiles of percentage compacting factor are in the same ranking order as those for angle of internal friction.

The data enables some understanding to be made of the influence of ingredients on the resistance to internal movement of a low stone content hot rolled asphalt at temperatures relating to layer placement.

Angle of internal friction and cohesion relate to the condition within a material just prior to internal movement, a limiting static equilibrium condition. From unpublished work on dry

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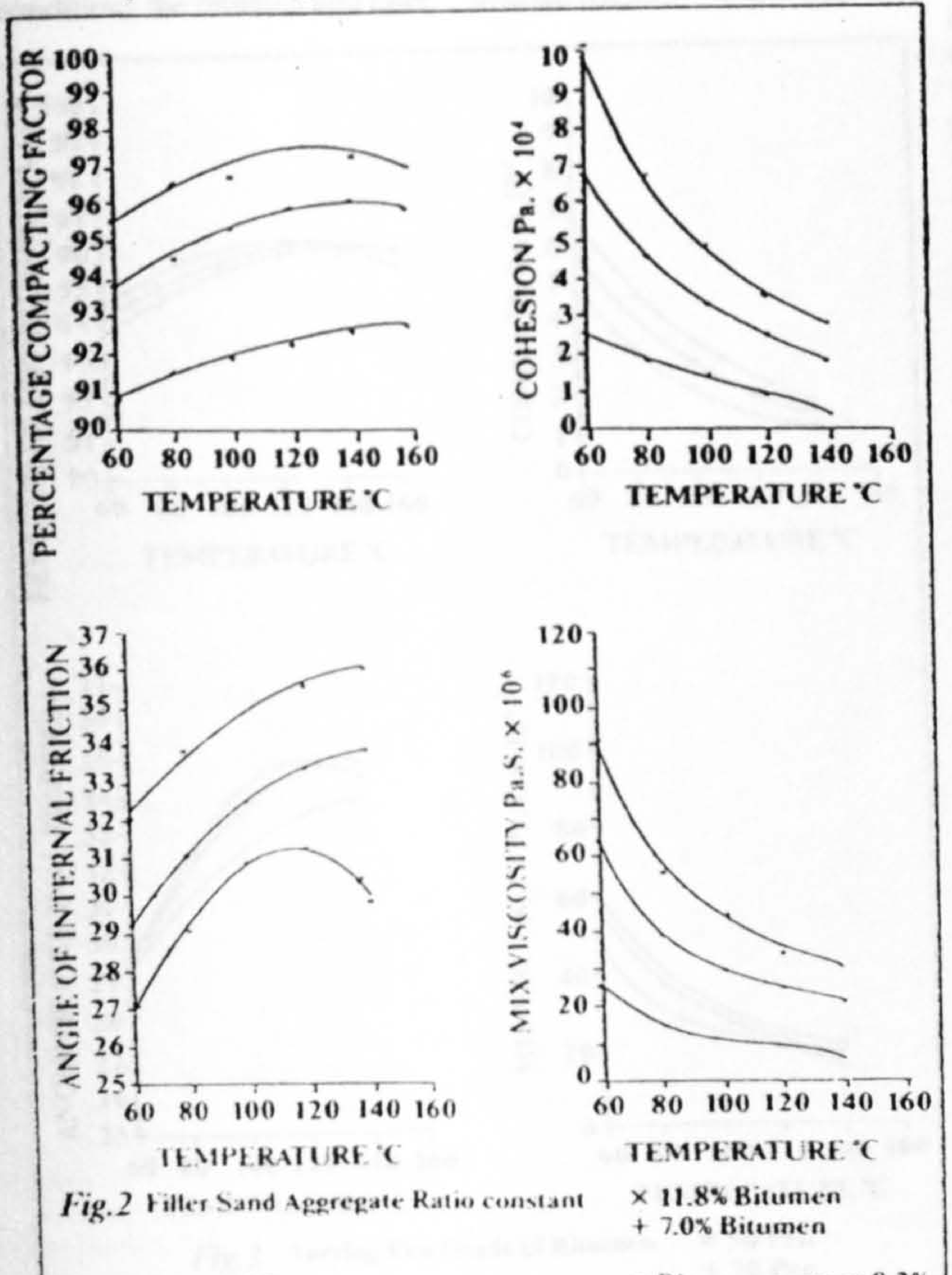

Fig.2 Filler Sand Aggregate Ratio constant

Control Mix

continued from page 17

fine aggregate:filler blends the measured angle of internal friction reduces for a dry fine aggregate:filler blend as the filler content is increased. This is a consequence of filler being trapped betwen the fine aggregate skeleton (Heukelom 1965). The fine aggregate apparently provides the basic frictional characteristics of a fine aggregate:filler blend. A compacted fine aggregate also exhibits cohesion, this results from particle interlock, which is a function of the shape and grading of a fine aggregate and its surface texture.

Fine aggregate forms the bulk of an asphalt. At elevated temperatures the fine aggregate skeleton is likely to be the principal stress distributing system. The mastic will assist in distributing stress between the fine aggregate particles. The filler within the mastic will exist within the voids of the fine aggregate skeleton and between the fine aggregate particles. Although the filler particles may be in point contact, as the temperature of the asphalt reduces the bitumen film around the filler will stiffen restraining the movement of the filler. In such conditions the bitumen and filler will act together in distributing stress, the consequence will be a lower measured angle of internal friction, accompanied by an increased measured cohesion. But, thin bitumen films are less able to restrain particle movement and distribution stress.

Asphalts having thin bitumen films will exhibit higher angles of internal friction and cohesion. High cohesion values are not just as a consequence of the bitumen film, being thin, but also possibly as a result of surface tension around contained discrete air voids.

This viscosity of the bitumen, reflected in its pen grade, influences the magnitude of the angle of internal friction and cohesion. Higher pen grade bitumen will have less stiffness and cohesion, which is reflected in higher angle of internal friction values and lower cohesion values.

As the temperature of an asphalt rises the stiffness of the bitumen film reduces, stress distribution between fine aggregate particles will increasingly be transmitted through the filler network. The consequence is that angle of internal friction will increase, cohesion will reduce. This will be limited for angle of internal friction with low effective filler content asphalt. The fine aggregate voids will not be filled by a skeleton of filler particles. The result will be a much reduced increase in angle of internal friction. Thin bitumen film asphalt will have a more marked change in value of angle of internal friction and cohesion. But, increasing temperature introduces an additional factor in relation to the bitumen, the factor is the thermal expansion of the bitumen with increasing temperature. All the components of an asphalt expand in volume: the volume of the voids within the mineral aggregate will consequently reduce marginally, but, the volume of the bitumen will increase measurably. The actual effect will depend on the relative volume of bitumen to voids within the total aggregate system. A higher bitumen content asphalt will at any temperature have reduced internal resistance component values: angle of internal friction, cohesion, and mixed viscosity. The consequence is the curvalinear nature of components, concave upward for angle of internal friction, and downward for cohesion. The effect is more marked with cohesion when film thicknesses are thin.

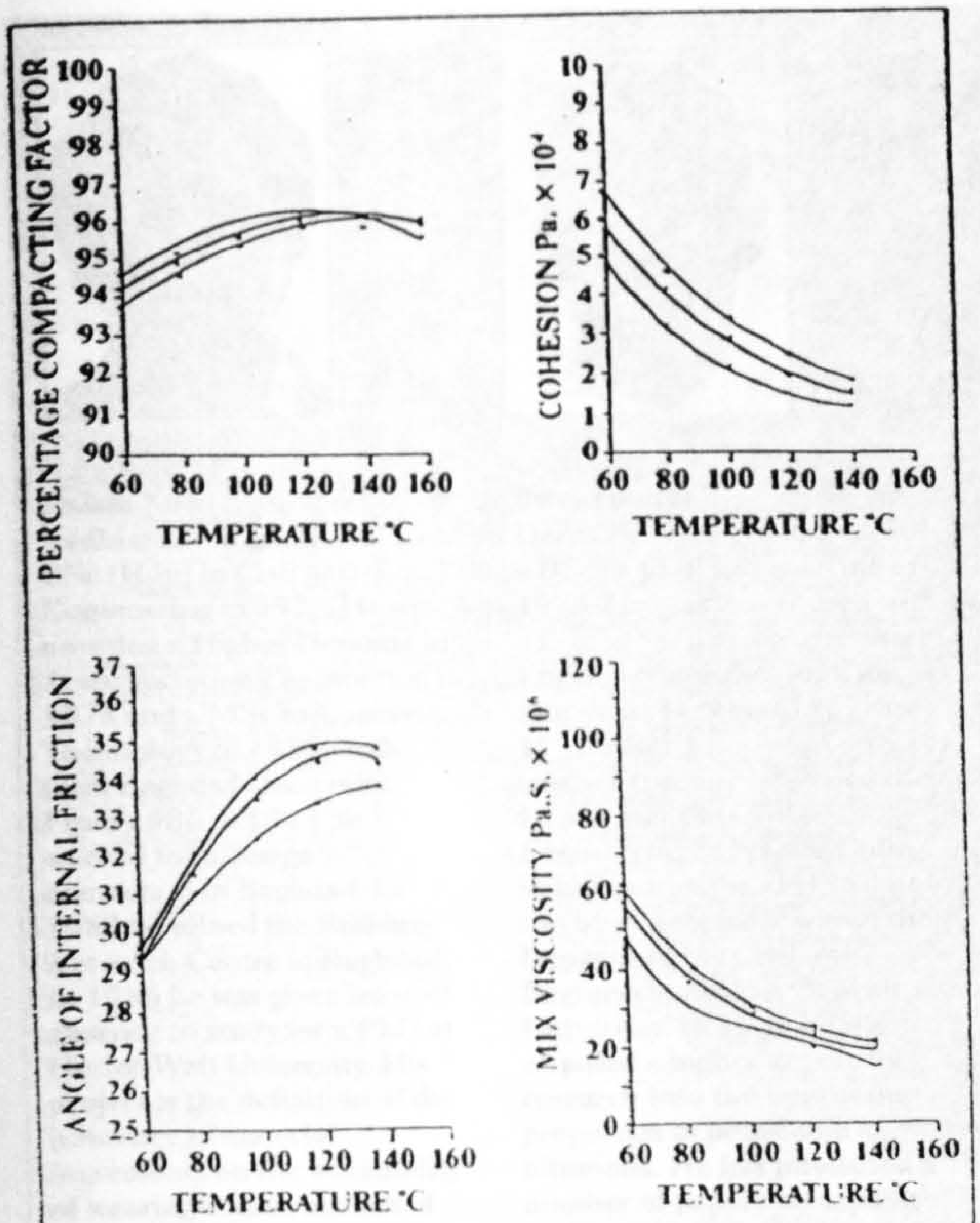

Fig.3 Varying Pen Grade of Bitumen

The turning point with angle of internal friction profiles are a consequence of increasing bitumen volume. There may be an accompanied increase in the rate of loss of cohesion — a tail to the profile at elevated temperatures. This critical temperature, it is believed, is the upper critical temperature for an asphalt mix. Above this temperature resistance to internal movement reduces and limits for an asphalt layer the confinement which is available to compact the material; the material is likely to displace readily ahead of the barrels of a roller. This is evident in the percentage compacting factor data. The turning point temperature on the percentage compacting factor profiles closely relates to the turning point temperature clearly evident in the angle of internal friction profile for an asphalt, where these exist.

The viscosity profiles relate to the condition where movement occurs internally within an asphalt. The profiles relate to the initial movement of an asphalt. Internal friction and cohesion are not lost, viscous resistance is an additional component making up the total resistance to internal movement of a mix. The understanding of the influence of material ingredients on the values of angle of initial friction and cohesion relates to the viscosity of an asphalt; for example, thinner bitumen films and higher filler to bitumen ratios within the mastic lead to higher values of viscous resistance.

Summary of the outcomes from the research programmes

1. Increasing the filler bitumen ratio of an asphaltic mix has the effect of increasing the temperature sensitivity of the mix, the mix stiffens more rapidly with reducing temperature. The upper critical temperature is also increased with increasing filler bitumen ratio. A mix becomes less workable with increasing filler bitumen ratio.
2. Increasing the filler content of a mix *reduces* the components of resistance to internal movement for an asphaltic mix. The mix will become workable as filler is added, but it will also become more temperature sensitive. The upper critical temperature of a mix is increased with increasing filler content.
3. Increasing the bitumen content of a mix reduces the components of resistance to internal movement. The mix will become more workable as bitumen is added, but the temperature sensitivity will only be reduced if the filler content of the mix is reduced. The upper critical temperature is decreased with increasing bitumen content.
4. Increasing the pen grade of the bitumen reduces the components of resistance to internal movement. The mix will become more workable with increasing pen grade. The upper critical temperature is reduced with increasing pen grade. The temperature sensitivity of the mix will depend on its filler content.

Practical implications of plant variations with mix ingredients

Variations will occur in the mix proportions of a hot rolled asphalt between batches. This is the result of the nature of a plant operation. Filler is likely to be the most variable ingredient. For an increase in filler content, where the compensating material is the fine aggregate the workability of a mix will increase, the upper critical temperature, — the optimum compaction temperature, — will reduce, the temperature sensitivity of the mix will change little. Where the compensating material is bitumen (for an increase in the filler content of a mix) the effect will be a reduction in mix worka-

continued on page 20

continued from page 18

bility, the components of resistance to internal movement will increase, there will be an increase in the optimum compaction temperature accompanied by an increase in the temperature sensitivity of the mix. In all respects an increase in filler content accompanied by a reduction in bitumen content will make an asphalt mix more difficult to work. But, both the filler and bitumen contents of a mix may increase, at the expense of the fine aggregate. Here the temperature sensitivity of the mix will change little, but resistance components will decrease in value, the mix becoming more workable, the optimum compaction temperatures will also decrease. The reverse situation will lead to a less workable mix with a higher optimum temperature.

The temperature sensitivity and optimum compaction temperature are important properties of an asphalt mix, particularly in terms of winter working. Where mixes are temperature sensitive, and they have a high optimum compaction temperature they require to arrive on site at higher temperatures. The optimum compaction temperature of stiff mixes may exceed 140°C. The variation in this temperature as a result of mix variations in filler and bitumen content may be more than 10°C. Where the effect of these ingredient variations counterbalance the optimum compaction temperature for example may not change; the difficulty is where the effects do not counterbalance each other. Temperature sensitivity is important in difficult environmental conditions, in particular windy conditions. Although the time taken for a mix to cool to a particular temperature from an initial temperature may be able to be defined (Daines 1985), the effect of this in terms of change in workability will differ between mixes, and more importantly it may change significantly between batches.

Occasionally premature fretting occurs with a hot rolled asphalt surface which cannot be attributed directly to environmental or construction factors, perhaps the implications of the data reported here gives some insight into why this serviceability failure occurs.

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Derek Fordyce graduated with a BSc in Civil Engineering in 1970. He was indentured with a firm of Civil and Structural Engineers in Edinburgh for four years between 1967 and 1971. After a period of teacher training he joined the Department of Civil Engineering at Napier College in Edinburgh. Since 1980 he has been a lecturer within the Department of Civil Engineering at Heriot-Watt University. In 1982 he was awarded a higher degree for research into the weathering properties of petroleum bitumens. He has published a number of papers on asphalt technology.

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Dave Whiteoak has worked in the road construction industry for over 17 years. After graduating from Heriot-Watt University in 1980 with a BSc Honours Degree in Civil Engineering he joined Shell Research working in the bitumen group based at Thornton Research Centre near Chester. Here he was involved in research investigating various aspects of the performance of bitumen and bituminous materials and the development of new products.

In June 1986 he joined Shell Bitumen UK where he is a member of a three man technical department based at their head office in Chertsey.

Introduction

Engineers designing or maintaining roads in the UK tend to use bituminous materials selected from British Standards. On Motorway and Trunk Road Schemes, the DTp Specification for Highway Works[1] is used to describe bituminous road materials, in its 900 Series of clauses. Hot rolled asphalt wearing course (with pre-coated chippings if required for texture), or bituminous macadams are usually specified for new bituminous roads or resurfacing contracts. When these surfaces have received a certain amount of trafficking, remedial action is required to seal the surface and/or restore skid resistance. Traditionally, the method used for this has been surface dressing. In its various forms, about 170 million square metres of surface dressing is carried out each year in the UK. Unfortunately, as a relatively low-cost treatment, it is not always given the attention to design that it should receive, with the result that some (if not most) failures can be attributed to insufficient planning.

Such failures can be dramatic, and the travelling public are not reticent in complaining when they are affected. Indeed it is difficult to think of a more sensitive public-relations exercise than surface dressing roads in otherwise pleasant environments often not a million miles from the homes of members of County Councils.

Other techniques

Surface dressing technology has improved recently, with the use of modified binders, "racked-in processes" etc. It cannot contribute to the structural strength of a road, but can provide an effective seal against moisture ingress, and (as long as the aggregate lasts) restore skid resistance. There is a danger, which has become apparent recently because of the road temperatures recorded during the summer of 1989, of building up layers of surface dressings which can "fat-up" in a prolonged hot spell. Wiltshire County Laboratory has investigated roads with four or five surface dressings which have contributed in excess of 10% by mass of bitumen to the top 20-25mm of surface. This reservoir of soft bitumen (typically 200 pen base binder on application in emulsions) can cause problems which are not always cured by another layer of surface dressing, or by carbonisation.

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ASPHALT PERFORMANCE DURING COMPACTION

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Synopsis

A high-temperature closed-system triaxial cell has been developed for use with wearing course hot rolled asphalts which can define the variation in three fundamental components of resistance to internal movement with temperature. At temperatures relevant to layer compaction the components relate to the workability of a mix. One component, angle of internal friction, presently appears to indicate relative mix temperature sensitivity, which relates to how a mix stiffens on cooling, and an upper critical temperature, which relates directly to the maximum compaction temperature for a matt. Variations in mix workability, and consequently mix compaction, and maximum compaction temperature have been defined for specific material ingredient variations using a single source fine aggregate and filler. Such data can give objective data on which variations in mix design can be made and it can indicate the potential stability of a mix as a result of plant variations in mix ingredients, resulting specifically from filler variation.

Background

Running surfaces on major roadways in the U.K. are today essentially textured stone surfaces, formed by driving stone chippings into a thin layer of hot rolled asphalt. A textured surface maintains the grip between a road surface and the tyres of a vehicle in wet conditions when vehicles are travelling at speed. This is achieved through the continuity of drainage channels provided by the chippings, as shown in Figure 1.

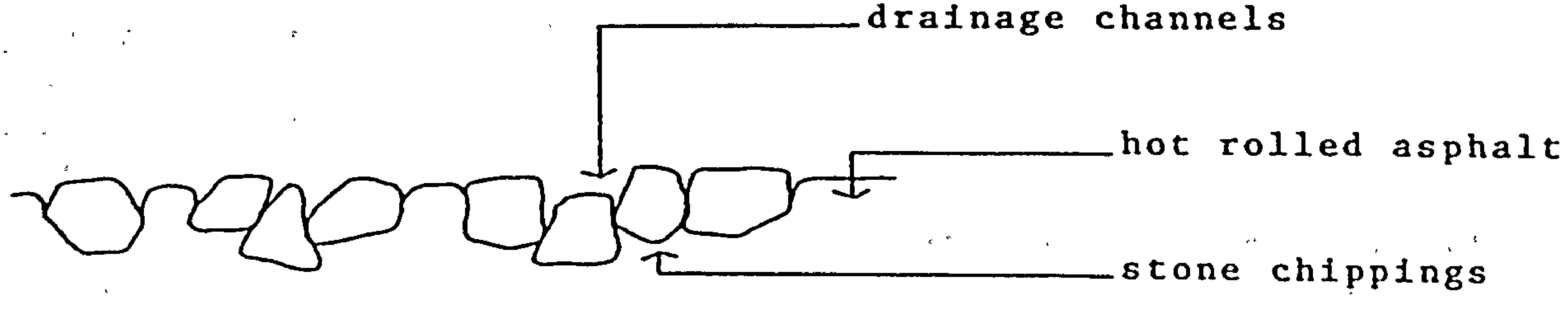

Figure 1: textured running surface

The maintenance of an effective surface texture depends on the quality of stone chippings used, their hardness and soundness, and on the quality of the asphalt; the stiffness of the asphalt at service conditions, which relates to displacement under vertical stressing, and to its state of compaction around the chippings, which relates to the loss of the asphalt matrix

A measure of asphalt workability

A high-temperature closed-system triaxial cell has been developed at Heriot-Watt University which is capable of measuring the three fundamental components of internal resistance to movement with hot rolled asphalts, within the temperature range relevant to layer compaction. The details of the cell, sample preparation and triaxial test procedure have been described in detail elsewhere (4, 5). The three components of internal resistance to movement are: angle of internal friction, mix cohesion and mix viscosity. The three components are measured at two states of equilibrium with asphalt samples; a sample being a cylinder 100mm in diameter and 200mm in length. The two states of equilibrium are, static and dynamic.

The cell, in principle, is an oil filled cylinder, the oil surrounding an asphalt sample being heated indirectly by an outer annulus of oil, as shown in Figure 2. The sample is protected by an easily deformable rubber membrane. The sample is loaded axially causing distortion through vertical deformation, with the subsequent displacement of the surrounding oil; the oil pressure builds up providing a confining pressure to the sample. Static equilibrium exists when, theoretically, sample distortion stops, the axial load on the sample being sustained by the confining pressure on the sample along with the components of internal resistance, angle of internal friction and mix cohesion. Under high axial loading, high material temperature and, or with mixes with low values of angle of internal friction and mix cohesion, true static equilibrium does not occur. Previous workers in this field have defined static equilibrium as the condition when vertical movement of the loading shaft, and therefore vertical deformation of the sample, reaches a particular low value, 25×10^{-3} mm per minute (6, 7). The authors have found in certain circumstances this value of vertical deformation cannot be achieved, but in these circumstances the confining pressure generally stabalises. Static equilibrium has been defined by the authors as any one of the three test conditions. By achieving a series of conditions of static equilibrium, through applying incremental loads to an asphalt sample, a first approximation to values of angle of internal friction and mix cohesion can be defined, for a given condition of sample [sample voidage] and sample temperature.

By bleeding off the oil surrounding an asphalt sample which is at a state of static equilibrium a controlled and uniform rate of vertical sample deformation can be achieved. Under such conditions a sample is in dynamic equilibrium. Achieving the same rate of vertical sample deformation when a sample is subject to different vertical loads enables values for mix cohesion and angle of internal friction to be defined at conditions of dynamic equilibrium. It is found that angle of internal friction is sensibly constant for a sample when it is in static equilibrium and deforming at different uniform rates in dynamic equilibrium. Plotting mix cohesion values at the different uniform rates of vertical deformation produces a

A definition of asphalt workability

Workability has been defined as resistance to internal movement. For an asphalt of particular composition and mix proportions, including air voids, the resistance to internal movement is a function of material temperature. Typical variations in the components of resistance to internal movement are shown in Figures 5, 6 and 7.

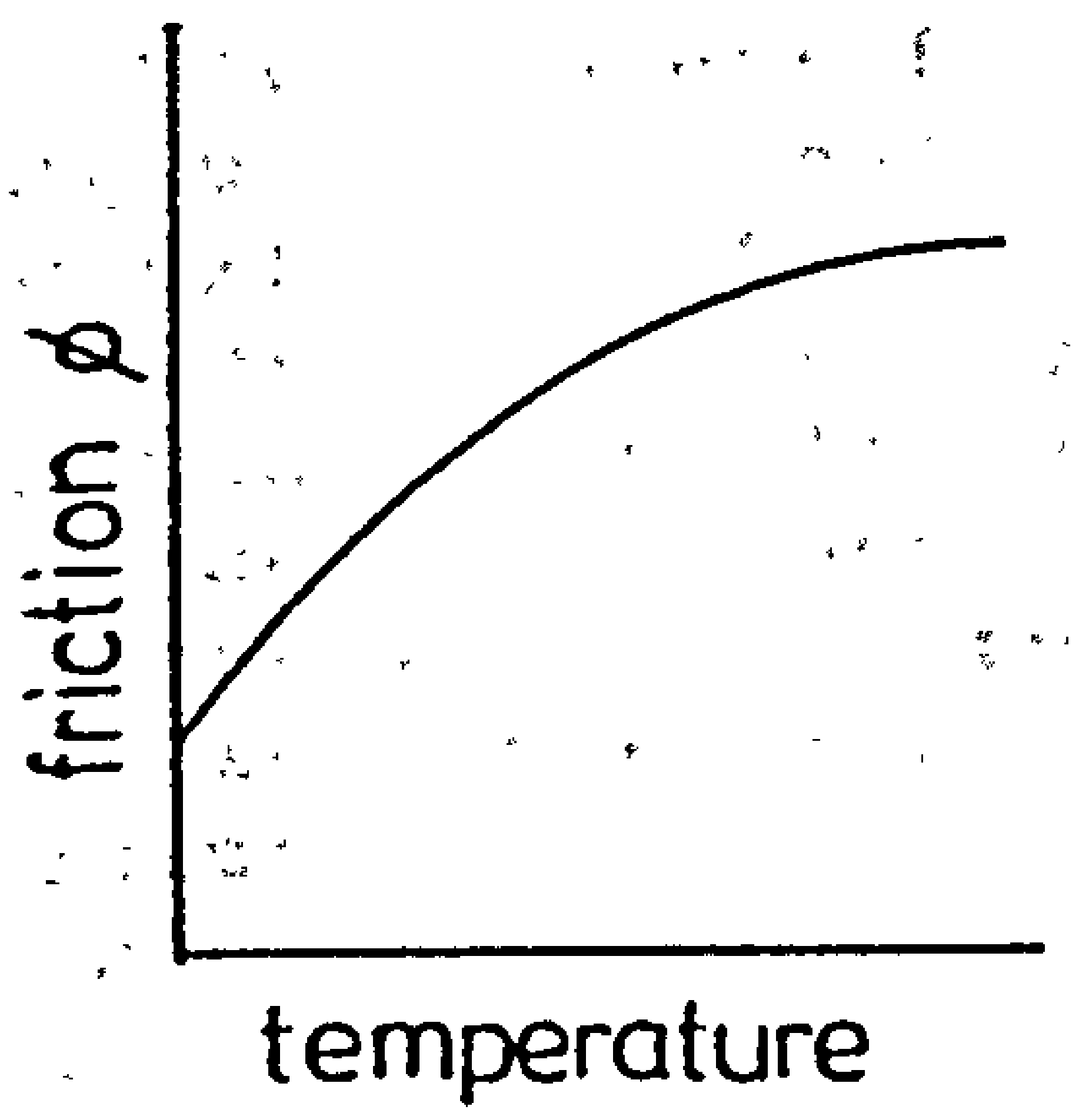

Figure 5: Variation in angle of internal friction with temperature

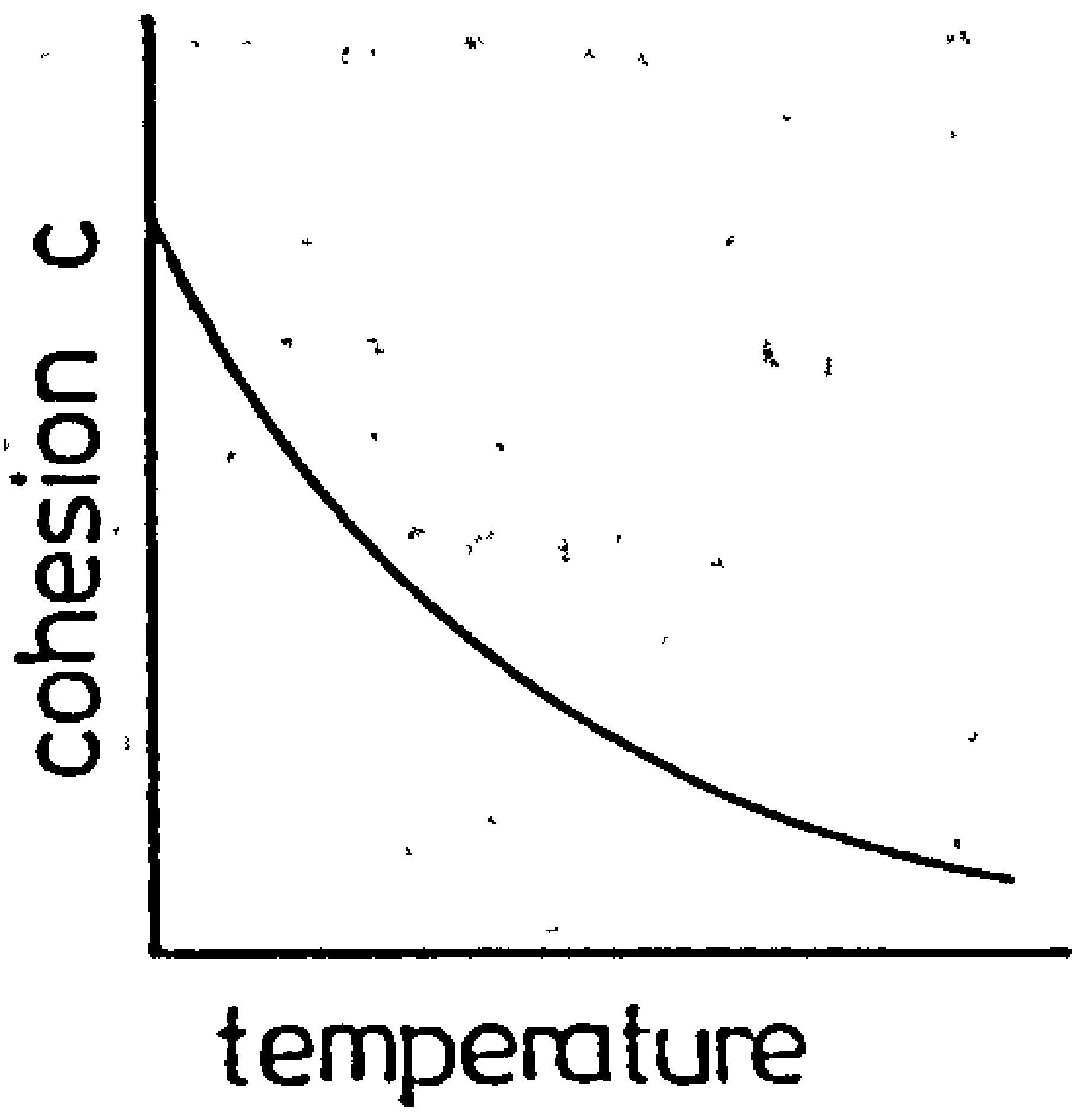

Figure 6: Variation in mix cohesion with temperature

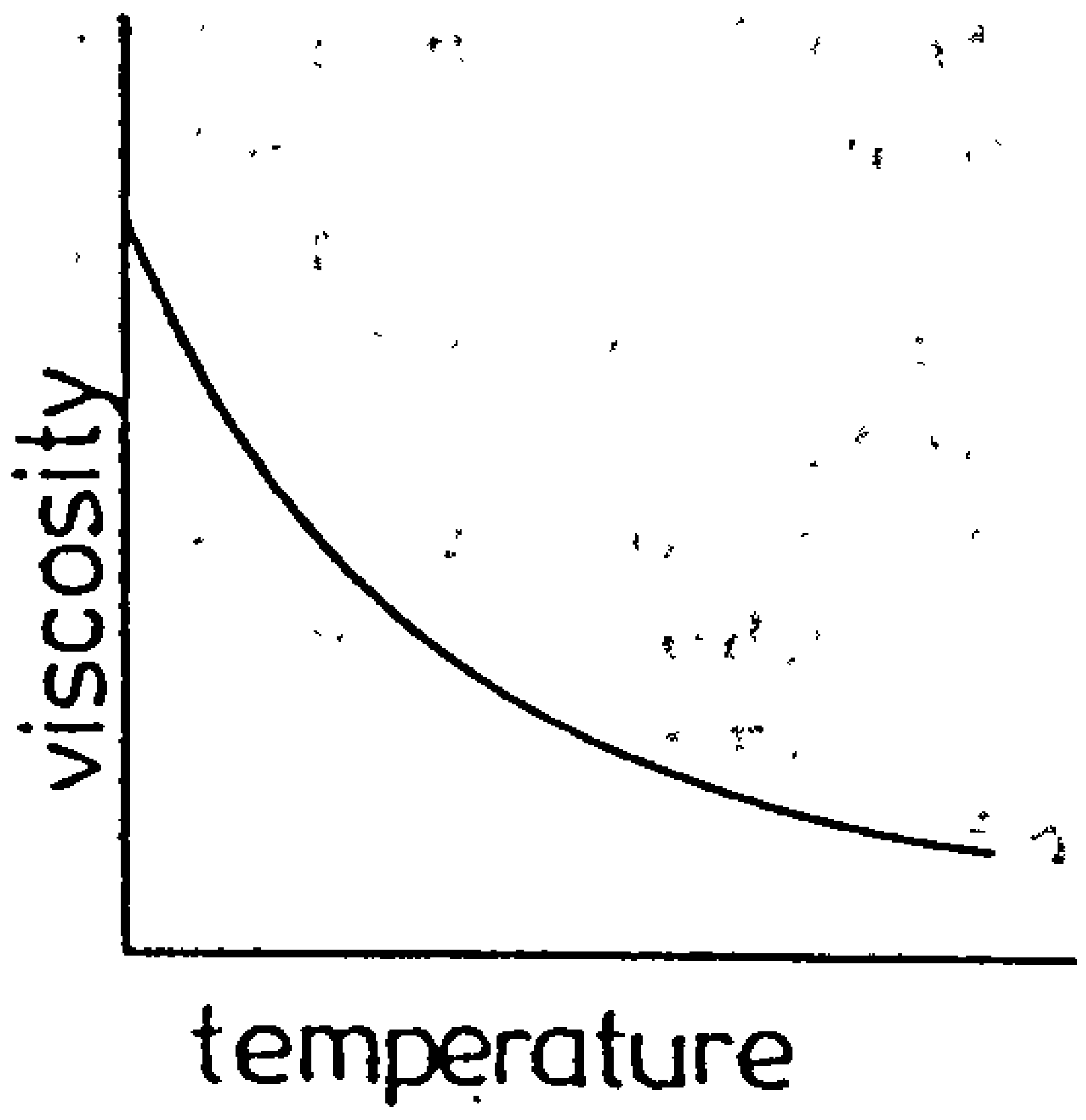

Figure 7: Variation in mix viscosity with temperature

The profile of angle of internal friction is essentially a concave upward profile; the profiles of mix cohesion and mix viscosity are essentially concave downward profiles. The profiles are not unexpected. As a material temperature rises the viscosity of the bitumen binder reduces, the cohesion of the system consequently reduces along with mix viscosity. Angle of internal friction increases as a result of a localised increase in aggregate particle contact. The profiles are consistent in what they infer about the resistance to internal movement of an asphalt.

In terms of the interpretation of the data from the triaxial cell, 40mm thick, 300mm by 300mm slab of asphalt were compacted in the laboratory. One compaction series was performed using two chipping spread rates, 50 percent area coverage and 70 percent area coverage with two commercial asphalts; a second compaction series was performed using unchipped slabs and laboratory prepared asphalts of controlled mix ingredient proportions. Details of slab preparation and data on the first compaction series can be found elsewhere (4).

In summary

- the asphalt below chippings controls chipping embedment, and the voidage of the asphalt surrounding the chippings.

- An upper critical temperature for a mix appears definable from the profile of angle of internal friction and which is replicated with slab compaction data. This is a temperature above which the resistance to internal movement of an asphalt reduces markedly and is likely to be of such a low value that little effective confinement will exist to material below a roll; undue displacement of material ahead of roll is likely to occur.

It would appear from the more recent data that the profile of angle of internal friction is an indicator of the temperature sensitivity of asphalt mixes and can define an upper critical temperature for a mix. Above this upper critical temperature displacement will occur ahead of a roll with little effective compaction; just below this temperature is possibly the most effective temperature to achieve effective chipping embedment and low upper asphalt voidage. More importantly, the more recent research appears to indicate the potential variation in performance in asphalts with variations in mix ingredients.

Influence of mix ingredients on the compaction performance of hot rolled asphalts

A 30 percent stone content hot rolled asphalt has a basic skeleton of fine aggregate; over 50 percent of an asphalt is fine aggregate. Filler both fills the voids within the fine aggregate skeleton and separates the fine aggregate structure (8). A bitumen binder coats the surface of the fine aggregate and filler, and fills the voids in the fine aggregate-filler system. The coarse aggregate bulks the volume of the asphalt mortar.

In the most recent research programme a local Marshall design mix was used as a control mix. The fine aggregate was a crushed rock fines; the filler was a limestone filler; the bitumen was a 50 pen petroleum bitumen. The design mix was replicated in the laboratory and used to prepare triaxial samples, and slabs for laboratory rolling. The stability and flow values of the laboratory replicated design mix were, 10.4 kN and 3.4 mm respectively.

Four mix ingredient variations were assessed using the mineral aggregate and filler.

- Bitumen content, keeping the filler, sand and coarse aggregate proportions constant.
- Filler-bitumen ratio, keeping the mastic volume constant.
- Bitumen penetration grade.
- Binder rheology using a 5 percent bitumen replacement with EVA.

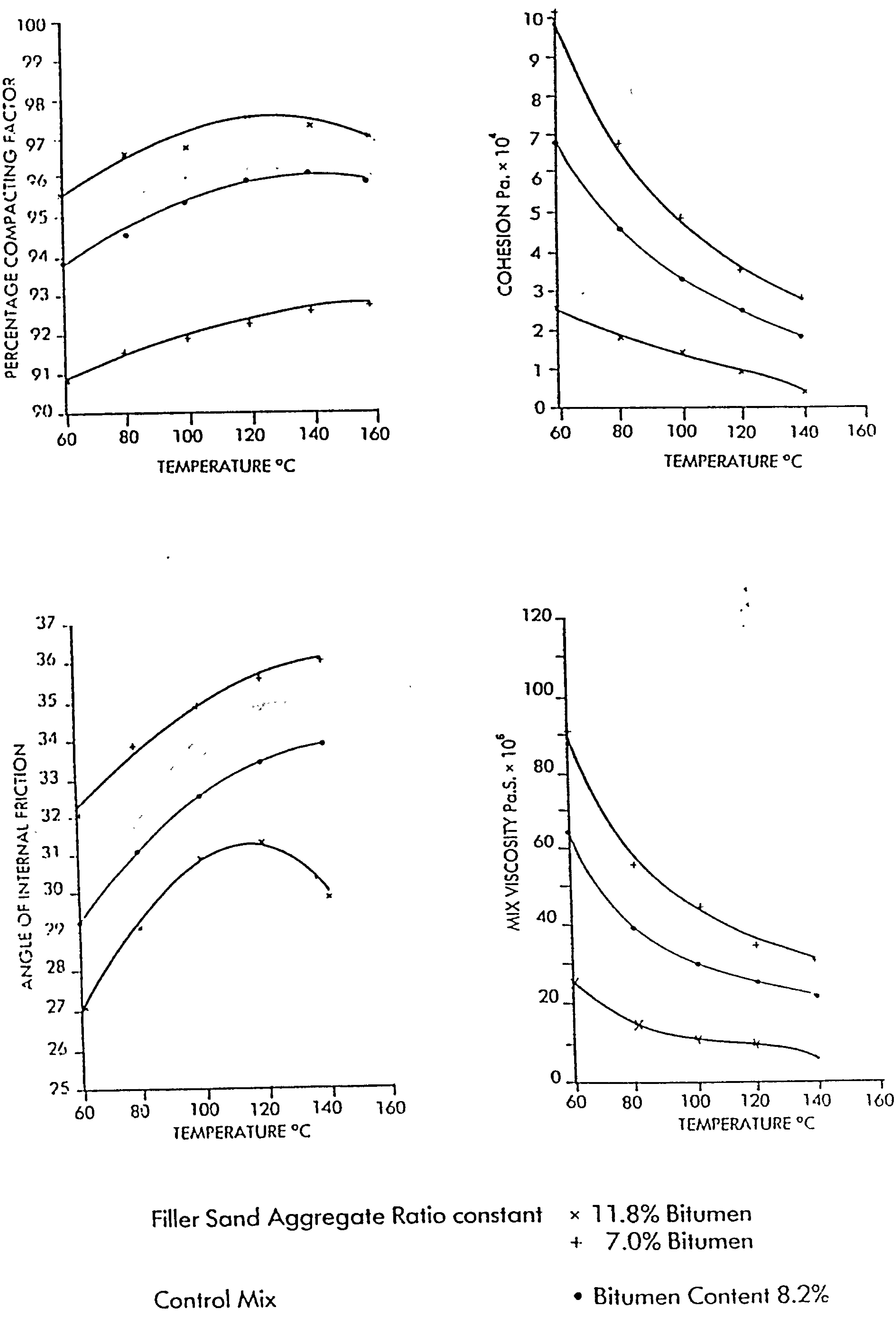

Figure 8: Filler Sand Aggregate Ratio constant.

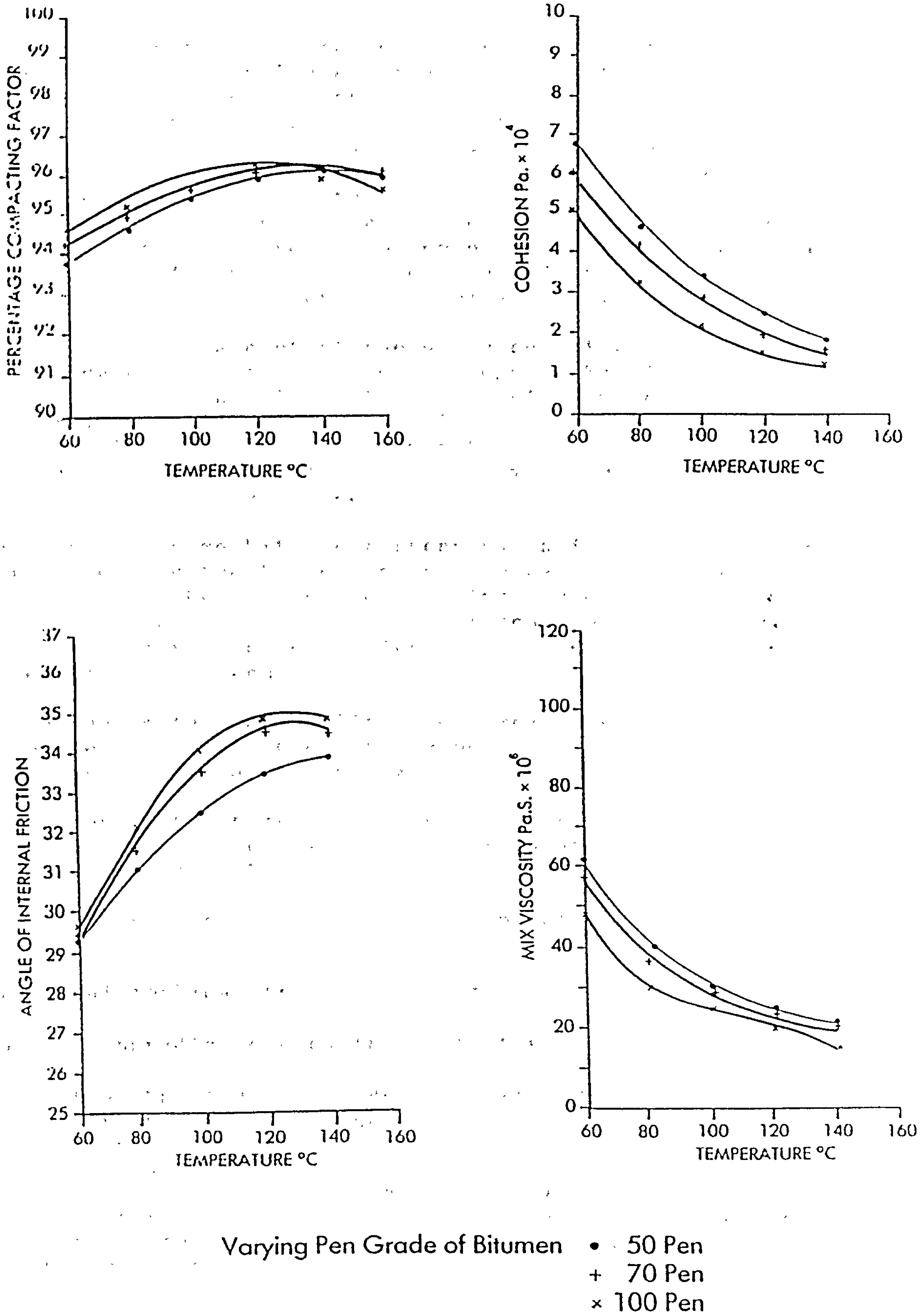

Figure 10: Varying Pen Grade of Bitumen

- Increasing the penetration grade of the bitumen binder reduces the cohesion and mix viscosity but increases the values of angle of internal friction. This is not inconsistent in that a binder with reduced viscosity will displace more readily and allow more intimate fine aggregate particle contact. The changes in values of the profiles is markedly less than with other ingredient changes. The PCF profiles indicate a marginal decrease in voidage with increasing pen grade of bitumen and little or no change in mix sensitivity, but an increase in pen grade leads to a reduction in upper critical temperature.

- Replacing 5 percent of the petroleum bitumen with EVA had the general effect of reducing mix workability indicated by an increase in values of mix cohesion and mix viscosity and a reduction in values of angle of internal friction, this is reflected in reduced compaction by lower values of PCF. Importantly the upper critical temperature for all EVA replacement mixes appears to exceed 160°C.

By using the same bitumen content variations with the test series keeping the filler and coarse aggregate proportions constant and the test series keeping the mastic volume constant, the effect of the filler could be assessed. Figure 12 indicates this effect. Increasing the filler content for a given bitumen content

- increases the workability and compaction of mixes indicated by reducing values of the components of internal resistance to movement and increasing values of PCF.

- increases the temperature sensitivity of mixes, mixes exhibiting an increase in change in angle of internal friction and PCF with temperature.

- increases the upper critical temperature of mixes.

Practical implications of the test data

For the ingredients used in the test programme

- increasing bitumen content, but keeping the filler, fine aggregate and coarse aggregate proportions the same: increases compaction, and therefore durability as indicated by increased PCF values; increases workability by reducing the components of resistance to internal movement; reduces the upper critical temperatures of a mix and the optimum temperature for layer compaction to ensure effective embedment of chippings and upper asphalt compaction.

- increasing the filler content, but keeping the bitumen content the same along with the fine aggregate and coarse aggregate proportions: increases compaction and therefore density as indicated by increased PCF values; increases workability by reducing the components of resistance to internal movement; but, increases mix sensitivity to temperature change; increases the upper critical temperature of a mix and therefore the optimum temperature for layer compaction.

- increasing the pen grade of the bitumen has a marginal effect on workability and compaction but reduces upper critical temperature and therefore the optimum temperature for layer compaction.

- replacing 5 percent of a bitumen with EVA reduces compaction and workability and increases upper critical and therefore optimum temperature; it also reduces the temperature sensitivity of a mix.

Although much of the data confirms what is known from practice, it puts values to fundamental parameters which relate directly to mix workability and which influence directly the compaction of a mix. Presently only the relative effect of ingredient variation can be predicted, but what appears directly definable is an upper critical temperature for mixes and therefore (potentially) optimum compaction temperatures, as they are influenced by three specific parameters: bitumen content, filler-bitumen ratio and penetration grade of the petroleum bitumen. This data is shown in Figure 13; the angle of internal friction data and slab compaction data are plotted together. If, as in the present edition of BS 594, bitumen content is the single ingredient variable then a table of upper critical temperatures, or maximum compaction temperature to avoid "undue displacement of material" would be as shown in Table 1. Compacting just below these temperatures would lead to optimum compaction in terms of chipping embedment and upper asphalt density. It should be noted that these values relate to one fine aggregate source, using a sand rather than crushed rock fines will likely reduce these values.

Penetration grade of bitumen	Maximum compaction temperature
100	120
70	130
50	140

Table 1: Maximum compaction temperatures with one source of crushed rock fines as fine aggregate. (Stability 10.4 kN; flow 3.4 mm)

The apparent contradiction in the data is the effect of EVA. Commonly a 70 pen with EVA replacement is taken as a substitute for a 50 pen pure bitumen binder. In the test series the 100 pen with EVA replacement was found to be a better match with the 50 pen pure bitumen binder. In addition, during triaxial tests when the cell valve was opened to bleed the oil from around the sample, and create a condition of dynamic equilibrium, a significant delay was observed between opening the valve and movement of the sample. Although an EVA bitumen blend may be more shear susceptible this time delay may be significant if vibrating rollers are used for layer compaction.

Practically, the effects of filler and bitumen on the potential performance of a mix may be indicated from the single parameter angle of internal friction. Increasing the filler content of a mix may, for example, increase the workability of a mix but it increases mix temperature sensitivity and the optimum and maximum compaction temperatures. But, in an asphalt plant there are variations in mix ingredients between batches, the filler being the most variable ingredient. Where the bitumen content is low with a mix and this is accompanied by a high filler content the effect is likely to be an increase in mix temperature sensitivity and an increase in maximum compaction temperature resulting from both the lower bitumen content and increased filler-bitumen ratio. The mix is likely to be (markedly) less workable and lead to reduced compaction, particularly with harsh sands. With soft sands and (marginally) high bitumen contents accompanied by low filler-bitumen ratios the converse is likely to be the case; here the mix will be difficult to use because of its high workability. With temperature sensitive mixes which have high upper critical temperature cool asphalt clumps, such as might come through to the augers of a paver having been trapped in the wings of the hopper are likely to result in localised, difficult to compact areas of a chipped matt, leading to localised fretting and possibly chipping loss.

Although values can be defined for the three fundamental components of resistance to internal movement, presently an absolute measure of workability with hot rolled asphalt has not been defined. But, the relative performance of mixes can be predicted using triaxial data, using in particular the profile of angle of internal friction with temperature. What appears to be able to be measured absolutely is an upper critical temperature, or maximum compaction temperature, for a mix. This value is clearly indicated on the angle of internal friction profile. Optimum conditions for chipping embedment appear to exist just below the maximum compaction temperature.

- Guidance on the design of difficult sands is possible presently using the triaxial data, to maximise or minimise mix workability; such data can also indicate the stability of a mix as a consequence of mix variation due to plant operation.

ACKNOWLEDGMENTS

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