AN INVESTIGATION INTO THE FACTORS AFFECTING THE STRENGTH PARAMETERS OF ASPHALTIC CONCRETE

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ABSTRACT

Asphaltic concrete is widely used in America and Europe as a paving material. Although there is general agreement on the type of mineral aggregate and on the type and amount of bituminous binder to be used, investigators are reporting widely different values for the strength parameters of cohesion, angle of internal friction, and elastic modulus of similar mixes. This variation in the reported values of these parameters is a serious obstacle to the adoption of more rational pavement design methods.

The writer believes that these variations in test results are due in larger degree to variations in test methods than to variations in the properties of the mixtures.

The object of this thesis is to determine those factors affecting the values of the strength parameters and to establish, where possible, correlations between the values of the factors and the values of the parameters.

The study of the factors affecting the elastic modulus is based on a laboratory test program carried out by the author because of the extremely limited published data on this subject. The study of the factors affecting the cohesion and angle of internal friction is based on data published by others in order to obtain data sufficiently comprehensive to cover the wide range of test conditions encountered in practice.

An attempt is made to explain the observations made in this study in terms of theoretical principles, to compare them with the observations of others, and to consider the implications to field practice.

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CHAPTER I

SUMMARY STATEMENT OF PROBLEM, METHOD AND SCOPE OF INVESTIGATION

1.1 THE PROBLEM

The design of bituminous paving mixtures and the structural design of flexible pavements at the present time is largely carried out by empirical procedures. While these procedures are useful and satisfactory for use within the range of the practical experience with them, they do not lend themselves well to extrapolation to new design conditions and materials, nor are they capable of suggesting new solutions to old problems (1). This has led to interest in more fundamental design methods, generally involving the shear strength parameters or elastic moduli of materials (2, 3).

Although there is general agreement on the type of mineral aggregate and on the type and amount of bituminous binder to be used in dense graded asphaltic concrete (i.e. asphaltic concrete incorporating a well graded aggregate having a low void ratio in the compacted state), investigators are reporting widely different values for the strength parameters of cohesion, angle of internal friction and elastic modulus of apparently similar mixtures. This lack of agreement as to the values of these parameters for asphaltic concrete has been a serious disadvantage in the application of more fundamental design methods.

1.2 METHOD USED IN THE INVESTIGATION OF THE PROBLEM

This thesis attempts to reconcile, or at least to explain, differences in reported values of strength parameters by attempting

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to determine those factors which affect the value of the strength parameters and to establish, where possible, correlations between the factors and the strength parameters.

Because of the large number of possible factors involved, and the complexity of the relationships, it was desirable to examine as large a mass of data as possible before attempting to observe general relationships with any degree of reliability. For this reason, it was decided to base the study on test data published by others to the extent that this was possible.

Since virtually no data was found which would permit a study of the factors affecting the elastic modulus of asphaltic concrete, it was decided to conduct a laboratory test program to investigate some of the factors affecting the elastic modulus of a typical asphaltic concrete mix.

Sufficient published data was found to permit a study of the factors affecting the shear strength parameters of asphaltic concrete.

1.3 SCOPE OF INVESTIGATION

The scope of the investigation was limited to physical strength properties. That is, factors such as durability were not considered.

Although some reference was made to one size aggregate mixtures and sand asphalts to indicate trends and to supply some information where data on asphaltic concrete was meagre, the study was essentially limited to densely graded asphaltic concrete.

The strength parameters investigated were the elastic modulus and the shear strength parameters of cohesion and angle of internal friction. These parameters are defined in Chapter III, Section 3.1.1.

In the case of the elastic modulus, the study involved the investigation of the effect of the following factors, using one typical mix:

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- Loading modulus versus rebound modulus,
- Stress level,
- Confining pressure,
- Number of repetitions,
- Test temperature.

The study involved the investigation of the effect of the following factors on the strength parameters of cohesion and angle of internal friction:

Method of forming specimen,
- Mixing temperature,
- Compacting temperature,
- Compacting method,
- Degree of compaction,

Method of testing specimen,
- Triaxial cell system,
- Rate of strain,
- Test temperature,
- Conditions of drainage,

Materials,
- Aggregate shape and surface texture,
- Aggregate grading,
- Bitumen penetration grade,
- Bitumen origin,

Volumetric relationships at 5% air voids,
- Volume of bitumen,
- Bitumen-filler ratio,
- Bitumen film thickness.

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CHAPTER II

PREVIOUS WORK ON SUBJECT

Nijboer (4) produced the most notable study analyzing the various components of the shear strength of bituminous mixtures. Nijboer defined the shear strength by three parameters, an angle of internal friction, a static cohesion independent of the rate of deformation, and a viscous cohesion directly proportional to the rate of deformation. Each parameter was further analyzed into components according to the factors contributing to the component of the parameter. The analysis was claimed to be sufficiently extensive to permit the computation of the shear strength parameters of a mix from the composition of a mix. Sufficient experimental data was presented in the published work to validate the analysis for the materials and test methods that were used.

The present author considers that there are two points in Nijboer's study which might be questioned. The first point to be questioned is the division of the cohesion into a static component independent of the rate of strain and a viscous component directly proportional to the rate of strain. While Nijboer's experimental data apparently justified this simple analysis, his range of strain rates was very limited (from approximately 0.01 to 0.1% per minute, or about 1 log cycle). Data compiled in this investigation covering a greater range of strain rates indicates that the effect of strain rate on the cohesion cannot be represented as simply as was done by Nijboer.

Furthermore, it appears that Nijboer's results were greatly influenced by his test method and may not be comparable to results

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obtained by others for similar mixes. Thus his value of approximately 33 degrees for the angle of internal friction of asphaltic concrete is much less than the normal value of 40 to 45° generally reported by others. This leads one to question the applicability of his findings to the mixes and test methods normally used by others.

Neppe (5, 6) has made a comprehensive review of the literature dealing with the strength properties of bituminous mixtures. Unfortunately, his published reviews only treat the influence of various factors on the shear strength parameters in rather general terms, because of the wide scope of his investigations. Furthermore, he used an unconfined compression test to obtain the test results that he has published. Thus the influence of the various factors cannot be resolved into effects on the individual shear strength parameters.

The literature reports many investigations of narrower scope concerned with the effects of a small number of factors. These investigations are too numerous to mention here. Reference is made to them in the discussion of the individual factors in Chapter IV.

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CHAPTER III

METHODS AND PROCEDURES USED IN INVESTIGATION OF PROBLEM

3.1 SELECTION OF STRENGTH PARAMETERS FOR INVESTIGATION

3.1.1 Definition of Parameters

The strength parameters which were selected for study were defined as follows:

cohesion - That part of the shear strength of a mixture which is independent of the normal pressure on the shear plane. The graphical interpretation of this parameter on a conventional Mohr-Coulomb diagram is shown on figure 1.

angle of internal friction -

The angle whose tangent is equal to the ratio between that part of the shear strength along a given plane which is a function of the normal pressure on that plane and the normal pressure on that plane. The graphical interpretation of this parameter on a conventional Mohr-Coulomb diagram is shown on figure 1.

elastic modulus -

The ratio between the deviator stress applied to a sample in a triaxial cell test and the corresponding axial strain. Unless otherwise stated, the elastic modulus has been determined from a rebound test. Details of the test method are given in Section 3.3.1.

3.1.2. Reasons For the Selection of the Parameters.

The elastic modulus was selected as a strength parameter in view of its effect on the deflection of a pavement under load.

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The deflection of a pavement under load is widely used as a measure of pavement strength (7, 8).

The shear strength of a bituminous mixture can be resolved into two components, one independent of normal stresses and one dependent on normal stresses. Most rational bearing capacity analysis involve the use of these two components of shear strength. For this reason, the cohesion and angle of internal friction were selected as two parameters.

Initially it was hoped to resolve the cohesion parameter into two components, one independent of the rate of strain and the other a function of the rate of strain, after the manner of Nijboer (4). However, further study of experimental data showed that the relationship between the cohesion and the rate of strain was not as simple as postulated by Nijboer. Moreover there was not a sufficient amount of experimental data available to justify the development of a more complex relationship between rate of strain and cohesion. Hence, the cohesion was not resolved into components.

3.2 SELECTION OF FACTORS TO BE INVESTIGATED FOR THEIR POSSIBLE AFFECT ON THE STRENGTH PARAMETERS

3.2.1 Criteria for Selection of Factors to be Investigated for their Possible Effect on the Strength Parameters.

The following criteria were used in selecting factors which were to be investigated for their effect on the strength parameters.

a. There should be some reason to believe that the factor might affect one or more of the strength parameters. Typical evidence would be the specifying of limits for a factor in standard test methods or specifications, or references in published literature to the significance of a factor.

b. The factor should be capable of definition and measurement to such a degree of clarity and precision that data from various sources might be compared.

c. The factor should be capable of being controlled in normal engineering practise. For example, the effect of the penetration grade of the bitumen was considered, but the effect of changes in the chemical composition or molecular structure of the bitumen was not considered.

d. There should be sufficient experimental data to provide at least some indication of the effect of a factor.

e. In the case of the elastic modulus only the factors considered most significant were evaluated. Additionally, the factors were selected so as to achieve the maximum value from a limited test program.

3.2.2 Selection of Factors to be Investigated for their Possible Effect on the Elastic Modulus.

Since a bituminous mixture is a visco-elastic material which may undergo strains at constant stress, the deformation under any load consists of a plastic component which is time dependent, and an elastic component which is independent of time. For this reason, the deformation under the application of a load over a period of time is likely to differ from the rebound experienced under the relatively instantaneous release of a load. Since both methods are widely used to measure deflections (7, 8) it was considered to be of interest to compare the elastic moduli as determined by the two methods.

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The ideal elastic modulus is independent of the stress level as expressed in terms of the ultimate stress. Since bituminous mixtures are complex materials, it was considered useful to study the effect of stress level on the elastic modulus. This is of some practical importance since flexible pavements are stressed to various levels in terms of the ultimate load, because of varying vehicle weights and varying ultimate strengths of the asphaltic concrete portion of the pavement as a result of temperature changes.

Since the elastic moduli of various solids are commonly related in a general way with the corresponding strengths of the materials, it was considered probable that the confining pressure and test temperature, which affect the strength of a bituminous mixture, would also affect the elastic modulus. Hence, the effect of these two factors was evaluated.

Repetitive loading was chosen primarily to improve the accuracy of the test data by obtaining more measurements, and to reveal the difference between strains due to the application of a load and strains due to the release of a load.

3.2.3 Selection of Factors to be Investigated for Their Possible Effect on the Shear Strength Parameters.

Factors falling into four general categories were considered:

a) Methods of forming specimens,

b) Methods of testing specimens,

c) Materials,

d) Volumetric relationships of test specimens.

The effects of mixing, compacting and testing temperature were selected for study because the physical properties of the

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bitumen binder are highly temperature susceptible, and because these factors are generally specified in standard test methods (9).

The compacting method, as distinguished on the basis of the degree of sample strain and contact pressure, has previously been shown to have a significant effect on the strength of a bituminous mixture and was, therefore, selected for study (10, 11).

The degree of compaction is invariably controlled by one means or another in asphalt paving specifications. Hence, it was also selected for study.

The triaxial cell systems commonly used are of two general types: the open cell system and the closed cell system. The systems are distinguished on the basis of the manner in which the lateral pressure is applied to the test specimen. In the open cell system the lateral pressure is applied by a fluid which surrounds the sides (and sometimes the top) of the specimen, and which is placed under pressure before any shear stresses are applied to the sample. The cell pressure is maintained constant for the duration of the test. The load may be applied in several ways, incremental loading, constant rate of strain, or constant rate of stress. Normally several test specimens, each tested at a different lateral pressure, are required to determine the cohesion and angle of internal friction of a mix. The open cell test has been described by McLeod (12). In the case of the closed cell system an incompressible fluid surrounds the sides of the specimen. The loading plunger passing through the top of the cell is of the same diameter as the specimen. The fluid is

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held in a closed chamber with a rigid exterior wall. Initially, only a small (2 psi) pressure is applied to the cell fluid. As the test specimen is loaded axially, it also strains laterally causing a pressure to build up in the incompressible cell fluid in the closed chamber. Thus, the lateral pressure develops as a result of the lateral strain of the sample due to the vertical load. Incremental static loading is used. Each load is held constant until the axial strain reaches some small limiting value (.001 inches per minute for an 8 inch high specimen). At this point the developed lateral pressure corresponding to the applied vertical pressure is observed. Several load increments are applied to the specimen, each load providing a vertical and a lateral pressure. Thus, a plot of vertical versus lateral pressure can be developed from a single test specimen. The cohesion and angle of internal friction of the mix can thus be determined from a single test specimen. The values of these parameters apply to near zero rates of strain. The closed cell system test, also commonly known as the "Smith Cell", has been described in detail by Smith (13).

The rate of strain was selected for study since previous investigations have shown it to have a significant effect on the strength of bituminous mixtures (13, 14, 15, 16).

The conditions of drainage were selected for study basically for the information to be gained relative to the development of pore pressures in test specimens.

Specifications for asphaltic concrete generally include some provision for a minimum percentage of crushed aggregate particles.

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Hence, this factor was selected for study. Because of the difficulty of distinguishing between the effect of particle shape and of surface texture, these factors were considered together.

The aggregate grading was selected for study since this is one of the characteristics used most widely to control aggregates.

The bitumen penetration grade was selected for study since this is widely used to identify bitumens, and since several different grades are normally used. It would be of interest to determine whether the bitumen grade used would have any influence on the strength of a mix.

The bitumen origin was also selected as a factor for study since it might indicate the effects of differences in composition.

Bituminous mixtures also vary as to their proportion, by volume, of air, bitumen and mineral aggregate. It seemed reasonable to assume that the relative composition of a mix might have some effect on the strength parameters. The fundamental difficulty in a study of the effects of the volumetric relationships lies in establishing the basis on which different mixes might be compared. First of all, for any comparisons to be valid, the mixes to be compared should be at the same degree of compactness, however the degree of compactness is expressed, since the strength properties of any mix depends on its degree of compactness. The most reasonable basis would seem to be constant compactive effort. Secondly, for any comparison to be valid, the mixes to be compared should also be at the same relative bitumen content, however the bitumen content is expressed, since the

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strength properties of any mix vary with the bitumen content. Possible ways of expressing the bitumen content might be in terms of a constant bitumen film thickness or a constant bitumen to filler ratio. If one is to rely on data published by a number of other investigators, one would likely have to ignore the requirement for a constant degree of compactness, since various compactive efforts and methods are likely to have been used. However, one can normally calculate the bitumen film thickness (17) or bitumen to filler ratio from the available data and so make a comparison at a constant relative bitumen content, however one chooses to express this. The foregoing has discussed the problem of the basis of a comparison simply in terms of the effect of the degree of compactness and relative bitumen content on the strength parameters. In field practice, however, the bitumen content is determined as much or more by durability considerations as by strength considerations. Hence, it may be argued that mixes should also be compared on the basis of the same or some satisfactory level of durability. In the face of these very formidable difficulties, it was decided to study the effect of the volumetric relationships on the strength parameters at a common basis of 5% air voids. This percentage of air voids was chosen as being representative of the range of air voids generally permitted in densely graded asphaltic concrete binder and wearing courses. For each mix the volumetric relationships and strength parameters were plotted as functions of bitumen content. The volumetric relationships and strength parameters at 5% air voids could then be read from the graph.

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3.3 METHOD OF OBTAINING DATA

3.3.1 Method of Obtaining Data for the Study of Factors Affecting the Elastic Modulus.

Because of the lack of published data on this subject, a laboratory programme was carried out to provide the necessary data.

An asphaltic concrete mix was designed by the Marshall Method (9) to meet the Department of Transport standard specification C.4-9, "Hot Mix Asphaltic Concrete for Airfields". This specification is representative of current engineering practice. The details of the mix design are given in Appendix I. The specimens prepared for triaxial testing were of the same composition as the optimum mix as determined by the Marshall Method. The density of the triaxial specimens averaged 98.5% of the corresponding Marshall density. This is representative of field densities currently required by specifications. Specimens were prepared by double plunger static compaction. A sufficient amount of the hot bituminous mixture to give the required density in a 5 inch high and $2\frac{1}{2}$ inch diameter compacted specimen was placed in a previously heated steel mould and then compressed to the required volume in a concrete cylinder testing machine. Samples were allowed to cure at least 24 hours before testing.

The triaxial specimens were tested by the open cell system using water as a cell fluid. The total cell was immersed in a waterbath for temperature control. The temperature was controlled by circulating hot or cold water through the water bath. The specimen and assembled cell were left in the bath for a time

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(1 hour or more) sufficient to permit the specimen to reach the desired test temperature.

The specimens were subjected to incremental static loading by means of a modified consolidation testing device. The assembled triaxial cell installed in the loading device is shown in the photographs on figure 2. The wooden box serving as a waterbath has been removed to reveal the cell.

Specimens were tested at temperatures of 75°F and 120°F. Confining pressures of 0, 15, 30, 45 and 60 psi were used for various trials. The maximum cell pressure was determined by the structural strength of the cell. Also at a temperature of 75°F specimens could not be failed at cell pressures higher than 30 psi because of limitations imposed by the strength of the cell and the capacity of the loading device.

Initially, the cohesion and angle of internal friction of the mix were determined at 75°F and 120°F by testing specimens to failure. Equal load increments, each estimated to be about 20% of the yield load for the specimen, were applied by means of dead weights at 5 minute intervals. Strain readings were taken at 1 minute intervals. Loading was continued until the yield point of the specimen was reached. Typical time - strain relationships for the load increments are shown on figure 3. The yield point was obtained from a plot of stress versus rate of strain as shown on figure 4. The yield points were well defined by this method. In certain cases loading was stopped after the first load increment which gave a rapid increase in strain rate, the load was removed, the

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cell pressure altered and the sample retested at the new confining pressure. The shear strength test results are shown on figures 5 and 6.

The elastic modulus of the samples was obtained with the same equipment that was used to determine the shear strength. The required load was gently placed on the hanger of the loading device, left acting for 3 minutes and then removed for 3 minutes. This procedure was repeated 10 times for each load. An attempt was made to use loads equal to 30%, 60% and 90% of the yield load of the specimen under the testing conditions. Experience with the strength tests had previously indicated that the strain rate had become stabilized at about 3 minutes. Moreover, longer loading and rebound times would have required excessively long test times. The tests as conducted required about 3 hours of loading and unloading exclusive of installation and dismantling time. Figure 7 shows a typical plot of sample strain versus load application number. Figure 8 shows a typical plot of cumulative strain versus load application number.

3.3.2 Method of Obtaining Data for the Study of Factors Affecting the Shear Strength Parameters

As pointed out earlier, a library search for experimental data published by others was employed in the study of the factors affecting the shear strength parameters.

3.4 METHOD OF PRESENTING DATA

An attempt has been made to consider, insofar as the data permitted and the author was able, the following aspects for each

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combination of strength parameter and factor influencing the parameter:

a) The influence which might be expected from theoretical considerations or experience with other similar materials,

b) The influence reported by others,

c) The strength or validity of the conclusions reached from this study.

The data has been presented in graphical form to the greatest extent possible in order to present the large mass of data in a concise form.

The source of the test data shown on the graphs has been identified by a number shown opposite the point representing the test data on the graph. These numbers have been related to the references on the pages immediately following the list of references. The numbers assigned to the data are the author's, and do not correspond to any numbers in the reference from which they were taken. In the case of the data for the elastic modulus study, the small numbers on the graph refer to sample numbers used by the author.

CHAPTER IV

DETAILED ANALYSIS OF DATA

4.1 FACTORS AFFECTING THE ELASTIC MODULUS

4.1.1 Loading Versus Rebound Elastic Modulus

The deformation under load of elastic-plastic materials such as bituminous mixtures consists of an elastic component which is independent of time and a plastic component which is a function of time. Hence, the deformation which occurs upon the application of a load over a period of time will, in general, be greater than the deformation which will occur as a result of the relatively instanteous removal of a load. Thus, the elastic modulus value determined from the application of a load may be expected to be lower than the elastic modulus value determined from the removal of a load. Moreover, this difference may be expected to become greater as the yield strength of the material is reached and plastic strains increase much more rapidly than the load.

The Canadian Good Roads Association noted this phenomena early in their investigation of the Benkelman Beam as a measure of pavement strength. They found that the rebound strains were more significant than loading strains. As a result they modified the Benkelman Beam procedure to measure rebounds rather than deflections under the application of a load.

The experimental results of this investigation indicating the relationship between the load elastic modulus and the rebound elastic modulus are shown on Figure 9. As would be expected, the two values are equal at low load levels (approximately 25% or less of the yield strength) where plastic strains are insignificant.

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At higher load levels the load elastic modulus becomes progressively smaller than the rebound elastic modulus, dropping to about 75% of the rebound elastic modulus at the yield stress. This ratio is, of course, a function of the test procedure since the strain under load depends on the duration of loading.

4.1.2 Effect of Stress Level on Elastic Modulus.

The effect of the stress level on the elastic modulus is shown on Figures 10, 11 and 12. The elastic modulus appears to increase with stress level up to a stress level of about 50% of the yield stress and then to decrease. The magnitude of this variation appears to be roughly $\pm$ 20% of the mean value. This variation is of the same order as the accuracy of the test results and cannot, therefore, be considered to be a major effect.

4.1.3 Effect of Confining Pressure on the Elastic Modulus

For granular materials, the elastic modulus is roughly proportional to the confining pressure. Since bituminous mixtures are granular-cohesive in nature, an increase in the confining pressure would be expected to increase the elastic modulus.

The experimental data indicating the effect of the confining pressure on the elastic modulus are shown in Figures 13, 14, 15, 16, 17 and 18, and are summarized on Figure 19. In all cases the elastic modulus increases with confining pressure. The differences in the results at the various stress levels at any given temperature may be largely experimental error.

The observed affect of confining pressure on the elastic modulus suggests that the elastic modulus may be related to the deviator

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yield stress of the specimen under the particular test conditions. To check this suggestion, the ratio of the elastic modulus to the deviator yield stress at the particular test conditions has been plotted as a function of confining pressure on Figure 20. It is observed that this ratio is independent of the confining pressure. The ratio is the same for 75°F as for 120°F and is approximately equal to 200. This data has been plotted in the form of rebound elastic modulus versus deviator yield stress on Figure 21. This again shows the elastic modulus to be proportional to the deviator yield stress.

4.1.4 Effect of Number of Repetitions of Load on the Elastic Modulus.

It was found that the rebound elastic modulus was independent of the number of repetitions within the range investigated. Typical successive strain measurements for one sample are shown on Figures 7 and 8. It is seen that the variation in successive measurements is random. Hence the variation in the elastic modulus would be random also. This is typical of the other tests not reported here.

4.1.5 Effect of Temperature on the Elastic Modulus.

It would be expected that the elastic modulus would depend on the hardness of the bitumen which depends on the test temperature. Hence, the elastic modulus, insofar as it is a function of the hardness of the bitumen, would be expected to decrease with an increase in temperature. However, the elastic modulus, insofar as it is a function of the frictional or arching stability of the granular particles, would not be expected to be affected by temperature. The net effect would be that the elastic modulus would be

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most susceptible to temperature at low confining pressures where the strength is predominantly due to the cohesion, and that the elastic modulus would be least susceptible to temperature at high confining pressures where the frictional resistance predominates.

The experimental results indicating the effect of test temperature on the elastic modulus are shown on Figure 22. The broken lines are average lines drawn through the plotted points. The solid lines are derived from the yield strengths determined previously and from the relationship:

$$\frac{\text{elastic modulus}}{\text{deviator yield strength}} = 200$$

which was also deduced previously. It is evident that there is considerable scatter in the results, which is believed to be due to variations in test specimens. Nevertheless, the data indicate that an increase in test temperature has the effect of causing a constant absolute decrease in the elastic modulus, which is independent of the confining pressure. Thus the percentage decrease in elastic modulus, due to a given increase in temperature, is much greater for low confining pressures than for high confining pressures. For example, an increase in test temperature from 75°F to 120°F will decrease the elastic modulus by approximately 60%, 30% and 20% respectively for confining pressures of 0, 30 and 60 psi.

4.2 FACTORS AFFECTING THE ANGLE OF INTERNAL FRICTION (ø)

4.2.1 Method of Forming Specimens

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4.2.1.1 Mixing Temperature

Mixing temperature is here considered apart from compacting or testing temperature. No reports were found of attempts to evaluate this variable. However, several indirect indications of its possible significance may be cited.

Rice (18) has pointed out that the mixing temperature (which in the field is generally near the aggregate drying temperature) affects the quantity of bitumen that is absorbed into the pores of the aggregate, and hence affects the quantity of free or unabsorbed bitumen in the mix. This is because the absorption of bitumen depends on the viscosity of the bitumen, which in turn depends on its temperature. Furthermore, the degree to which absorved water is removed from the aggregate pores and permitted to be replaced by bitumen also depends on the temperatures. Thus, an increase in mixing temperature might have the effect of a small decrease in bitumen content. Since the angle of internal friction is not affected significantly by small changes in bitumen content near the optimum bitumen content, it would not be affected by the mixing temperature on this account.

The rate of hardening of a bitumen due to oxidation and loss of volatiles increases with temperature. Thus, an increase in mixing temperature would have the same effect as using a harder (lower penetration) bitumen. It will be shown later (section 4.2.3.2.) that the angle of internal friction is not significantly affected by the hardness of the bitumen. Hence, the angle of internal friction would not be affected by the mixing temperature on this account either.

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On the basis of the available evidence, it is presumed that within the normal range of mixing temperatures, the mixing temperature does not have a significant affect on the angle of internal friction. This assumes that the mixing temperature is sufficiently high to permit proper dispersion of the bitumen and proper coating of the aggregate particles.

4.2.1.2 Compacting Temperature

Compacting temperature is here considered apart from mixing temperature.

The effect of the compacting temperature of a specimen would be manifested indirectly through the corresponding effect on the viscosity of the bitumen. An increase in temperature would decrease the viscosity of the bitumen, thus reducing the resistance to densification of the sample. Hence an increase in compacting temperature would be equivalent to an increase in density up to the point where the viscosity of the bitumen has a negligible effect in resisting densification. It will be shown later (section 4.2.1.4) that the degree of compaction has only a slight effect on the angle of internal friction. Hence the compacting temperature, within normal ranges of compacting temperatures, may be expected to have a negligible effect on the angle of internal friction.

No reports were found of attempts to evaluate this variable.

On the basis of the available evidence, it is presumed that within the normal range of compacting temperatures, the compacting temperature does not have a significant effect on the angle of internal friction.

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4.2.1.3 Compacting Method

Compacting methods are here distinguished on the basis of the amount of shear strain imparted to the specimen as a result of compacting the specimen to a constant density.

Large shear strains during the compaction process tend to produce a non-random particle orientation in those materials where a systematic particle orientation is possible. For example, flat particles might be arranged systematically with their longest dimension parallel while no such arrangement would be possible in the case of spherical particles. Thus, one would expect that the compaction method would have its greatest influence in the case of crushed angular particles.

Endersby (19), in reviewing some test data compiled by the Triaxial Institute states, "We believe that substantial indications have been given to show that (a) results differ radically in some cases with method of compaction regardless of density achieved, (b) that an over-all correlation cannot be obtained because the same relationship does not hold good for all aggregates, and (c) that only kneading or rolling methods are likely to reproduce road conditions". He reports that specimens produced by kneading compactors are generally more sensitive to bitumen content at higher bitumen contents.

Vallerga (10), also commenting on Triaxial Institute data, makes the additional significant observation that the compaction method appears to be of greater significance if the sample is tested in the closed system cell than when tested in the open system cell.

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The data illustrating the effect of the compacting method on the angle of internal friction which was compiled in this investigation is shown on figure 23. The following test series are shown:

TEST SYSTEM	AGGREGATE	COMPACTION METHOD		TEST NO.
Closed	Watsonville granite (rough surfaced)	Kneading	500 psi	88
		Kneading	350 psi	89
		Static	3000 psi	90
	Cache Creek gravel (smooth surfaced)	Kneading	500 psi	91
		Kneading	350 psi	92
		Static	3000 psi	93
Open	Watsonville granite	Kneading	500 psi	94
		Static	3000 psi	95
	Cache Creek gravel	Kneading	500 psi	96
		Static	3000 psi	97
Closed	Crushed gravel	Static	1500 psi	131
		Kneading	250 psi	132

It is readily seen that for samples prepared by kneading compaction and tested in the closed system cell, the angle of internal friction drops off sharply with increasing bitumen content, a phenomenon not observed in the case of static compaction and the closed system test. In the case of samples tested by the open system test, the effect of the compaction method is not pronounced.

A possible explanation for these observations is suggested by stress-strain curves for bituminous mixes published by Monismith and Vallerga (11). They report that the following data is typical of that obtained from their open system tests at a lateral pressure of 30 psi:

COMPACTION METHOD	PERCENT BITUMEN	MAXIMUM STRESS	% STRAIN AT MAXIMUM STRESS
Kneading	4	260 psi	2
Static	4	230 "	2
Kneading	8	200 "	11
Static	8	210 "	2

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It is noted that at the higher bitumen contents, the sample prepared by kneading compaction required a much higher strain to develop the maximum stress, although this was approximately equal to the maximum stress developed by the sample prepared by static compaction. From the details of the closed system test, it can be calculated that the maximum strain for a confining pressure of 100 psi is relatively small. It is possible then that the closed system does not permit the development of the maximum resistance of samples which require large strains to develop the maximum stress. No such restriction is imposed by the open system test.

The maximum angle of internal friction values obtained by the two methods of compaction are approximately the same. The slight differences may be due to differences in densities.

Figure 24 indicates additional data on the effect of the compaction method on the angle of internal friction. The following tests are comparable: 131 and 132, 135 and 136, 137 and 138, 139 and 140, 145 and 146. These tests also indicate a decrease in the angle of internal friction at higher bitumen contents for samples compacted by kneading compaction and tested by the closed system, an effect which is not apparent in the case of comparable samples prepared by static compaction and tested by the closed system. There are, however, certain test specimens (1, 2, 3, 44 and 45), which were prepared by static compaction which indicate a sharp reduction in the angle of internal friction with increasing bitumen content. No possible explanation for this phenomena was found.

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On the basis of the available evidence, it is concluded that a kneading type compaction method produces an effect in samples (probably particle orientation) which requires larger strains to develop the maximum stress at higher bitumen contents. Thus, when samples prepared by kneading compaction at higher bitumen contents are tested in a device permitting little strain, the calculated angle of internal friction value will be lower than for similar samples prepared by static compaction. There are, however, exceptions to this general observation.

4.2.1.4 Degree of Compaction

In the case of granular materials without a cohesive binding material, the angle of internal friction increases with density. Hence, one might expect the same phenomenon in the case of bituminous mixtures, at least up to the point where pore pressures begin to develop in the bitumen.

Monismith and Vallerga (11) found that for samples prepared by kneading compaction and tested at a single confining pressure, the vertical stress increased with density until a density equal to 94% of the maximum theoretical density was obtained. Increases in density beyond this point caused the vertical stress to decrease. This was observed for bitumen contents of 5, 6 and 7%. In the case of the lower bitumen contents, where a relative density of 94% was not attainable, the vertical stress continued to increase over the range of densities investigated.

The data compiled in this investigation which indicate the effect of the degree of compaction on the angle of internal friction are shown in figures 25 and 26.

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The details of the tests are summarized below:

TEST SERIES	AGGREGATE	COMPACTION METHOD	TEST METHOD
28	crushed, coarse, natural fine	static	open
29	"	"	"
88	rough surfaced	400 tamps at 500 psi	closed
89	"	228 tamps at 300 psi	"
91	smooth surfaced	400 tamps at 500 psi	"
92	"	228 tamps at 300 psi	"
98	crushed coarse, natural fine	300 tamps at 150 psi	open
99	" "	" " at 250 psi	"
100	" "	" " at 400 psi	"
101	" "	" " at 500 psi	"

Test series 28-29 and 98-99-100-101 indicate the unexpected result that while the density increased with compactive effort, the angle of internal friction was virtually unaffected by these increases. Test series 88-89 indicates no significant increase in density with compactive effort, and indicates also that the angle of internal friction did not increase with compactive effort, although the angle of internal friction vs bitumen content curve was displaced to the left by about 1% bitumen content as a result of the higher compactive effort. Test series 91-92 indicates a large increase in density and in the angle of internal friction at lower bitumen contents with an increase in compactive effort. This is believed due to the very low density of test series 92. It is also possible that the low density specimens would require large strains to mobilize the angle of internal friction, and that these strains would not be developed in the closed system test as indicated earlier (section 4.2.1.3.).

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On the basis of the available evidence, it is concluded that the degree of compaction has only a very slight effect on the angle of internal friction. Although this conclusion is contrary to expectations, the evidence for it is quite strong.

4.2.2 Method of Testing Specimens

4.2.2.1 Triaxial Cell Systems

Two general methods of triaxial testing are in general use - the open cell system and the closed cell system. These have been described previously (see section 3.2.3).

If each test measures fundamental and distinct properties of a specimen, it would be expected that both test methods would yield substantially the same results. The degree to which the results from the two test methods differ would be an indication of the degree to which the test results are influenced by the method of test.

Smith (13) notes that "At low lateral pressures the measured compressive strengths of specimens tested by the two methods are in poor agreement, but at higher lateral pressures, where the closed-system data assume straight line characteristics (on a plot of vertical stress versus confining pressure), the two methods of test give closely comparable results".

The data compiled in this investigation which indicates the effort of the test method on the test results are test series 88-97 which are referred to in section 4.2.1.3 and illustrated on figure 23.

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The following test series are directly comparable in that the samples were prepared from the same materials and by the same compaction method. Only the test method differed.

CLOSED CELL TEST		OPEN CELL TEST
88	compare to	94
90	" "	95
91	" "	96
93	" "	97

It is readily seen that the maximum angle of internal friction values, which occur at the lower bitumen content, are approximately the same for each pair. However, in the case of kneading compaction and the closed cell system test, the angle of internal friction decreases rapidly with increasing bitumen content. This is not apparent for identical samples tested in the open cell system, nor in samples prepared by static compaction and tested by either system.

From these observations it is concluded that an effect (probably particle orientation) is produced in the sample by kneading compaction, but that this effect is only revealed by the closed system test. The closed cell test then differs from the open cell test in that it reveals this effect. A hypothesis advanced by the author to explain this phenomena is in section 4.2.1.3.

4.2.2.2 Rate of Strain

Since the coefficient of friction between solid bodies is normally inedpendent of the rate of movement, it would be expected that the angle of internal friction would be independent of the rate of strain.

Nijboer (4) found that the angle of internal friction at equilibrium was about 3° less than at a non-zero rate of strain.

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He also observed this in the case of dry aggregate, and concluded that this was a property of the aggregate. This is in contradiction to the observations of Smith, quoted in section 4.2.2.1, that the closed cell test (at substantially zero rate of strain) gives results comparable to those from the open cell test (at non-zero rates of strain).

The data compiled in this investigation which indicates the effect of the rate of strain on the angle of internal friction is shown on figure 27. At low rates of strain (less than about 1% per minute) the angle of internal friction appears to be independent of the rate of strain. At higher rates of strain the angle of internal friction may decrease with increasing rate of strain, the decrease being greater for lower test temperatures. It might be noted that samples 30, 31 and 32 were sand asphalts, and that the angle of internal friction values for sample 148 were considerably below those for normal asphaltic concrete mixes, whereas sample 1c was an asphaltic concrete with a representative angle of internal friction value. Thus, it could be argued that all samples showing a decrease in the angle of internal friction with increasing rates of strain were not normal asphaltic concrete mixes, and that normal asphaltic concrete mixes do not show a decrease in the angle of internal friction with increasing rates of strain.

On the basis of the available evidence, it appears that in the case of normal asphaltic concrete mixes tested at normal test temperatures, the angle of internal friction is independent of the rate of strain, at least within the range rates of strain of about .01% to 30% per minute.

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4.2.2.3 Test Temperature

The only possible effect of the test temperature on the angle of internal friction would appear to be an indirect one through the effect of the temperature on the bitumen. Increasing the test temperature would decrease the viscosity and surface tension of the binder, allowing binder films to be displaced and punctured more rapidly. This might be expected to increase the angle of internal friction.

Nijboer (4) notes that the angle of internal friction will always be at its highest value at the maximum test temperature.

The data compiled in this investigation which shows the effect of test temperature on the angle of internal friction is shown in figure 28. It is apparent that the angle of internal friction is virtually independent of the test temperature. The one exception is a sand asphalt tested at a high (5% per minute) rate of strain. There appears to be a slight reduction in the angle of internal friction at temperatures below about 60°F. However, at temperatures where the strength of an asphalt surfacing is likely to be critical, (above about 80°F) the angle of internal friction is independent of temperature.

On the basis of the available evidence, it is concluded that the angle of internal friction is independent of the test temperature within the range of normal test temperatures.

4.2.2.4 Conditions of Drainage

Since asphalt mixes are not saturated with bitumen, and since the bitumen is firmly held by the aggregate, one would not expect

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significant pore pressures to develop in the air or bitumen, or expect that the bitumen would be drained from the specimen to relieve such pore pressures. The only effect of blocking drainage would derive from the effect the volume change of the sample would have on the gas pressure of the air within the sample voids. Since densely graded and well compacted samples do not undergo large volume changes, such effects should be small. Moreover, since dense samples generally dilate at failure, the internal gas pressure would be reduced from atmospheric pressure. Thus the maximum theoretical effect would be the development of a negative pore pressure of one atmosphere. In reality, only a fraction of this maximum effect would be realized.

Goetz and Chen (15) in a rather comprehensive test series involving 122 tests and 3 different mixtures investigated the effect of applying the lateral pressure by means of applying a vacuum to the porous end caps of the sample. The effect of surrounding the sample with a layer of filter paper was also investigated.

The four variations in the technique of applying the confining pressure produced no significant differences in the angle of internal friction or cohesion values obtained for comparable samples, with one exception. A densely graded sand asphalt type mixture developed a lower angle of internal friction value and a higher cohesion when the lateral pressure was applied by means of a vacuum and no filter papers were used, indicating that in this case the vacuum was not fully effective. Hence, it may be presumed that

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normal type asphaltic concrete mixes are sufficiently permeable to prevent the development of internal gas pressures or vacuums, provided that the samples are not sealed at their surfaces.

Schaub and Goetz (20) investigated the effect of the drainage conditions in a triaxial test. Three types of drainage were investigated:

a) no drainage from specimen,

b) sample consolidated under cell pressure for one hour before testing and then tested without drainage,

c) sample tested with free drainage.

No significant systematic difference in results was observed as a result of the difference in drainage conditions. Volume change measurements during testing indicated in all cases that the volume of the samples first decreased slightly (generally less than $\frac{1}{2}\%$ and then increased with increasing strain. It was also noticed that air rushed into the sample when a drainage valve was opened upon completion of an undrained test. This would, of course, be expected as a result of the volume increase of the sample.

From the foregoing it is concluded that drainage conditions do effect the internal gas pressures in a sample, but that these effects are small, and are consequently masked by the normally high strength of bituminous mixtures.

4.2.3 Materials

4.2.3.1 Aggregate

Aggregate Shape and Surface Texture

Because of the difficulty of separating the effects of these two factors, they will be combined.

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Since the angle of internal friction includes a component dependent upon the interlocking effect of aggregate particles and a frictional component, it would be expected that particles of angular or cubical shape and having rough surfaces would develop a higher angle of internal friction than rounded polished particles. On the other hand, the latter type of particle offers less resistance to densification and may thus achieve a greater degree of compaction for a constant compactive effort. Thus these particles might develop higher angle of internal friction values insofar as angle of internal friction values are dependent upon the degree of compaction.

Specifications for high stability bituminous mixes generally specify a minimum percentage of crushed particles. Empirical tests such as the Marshall Stability test indicate greater stabilities for crushed particles than for uncrushed particles. While this is evidence that crushed particles increase the strength of bituminous mixes, this does not indicate whether the strength increase is reflected in increased angle of internal friction values or in increased cohesion values.

The data compiled in this investigation which indicate the effect of the particle shape and surface texture on the angle of internal friction is shown in figures 29 and 30. Each point on the graphs of figure 29 represents two test results obtained from samples which were identical as to gradation, bitumen content, compaction method, test method, etc., but differed as to aggregate shape or surface texture.

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Figure 29 indicates that aggregate shape or surface texture has no marked or consistent effect on the angle of internal friction for the range of 30° to 50°F for the angle of internal friction. It is of interest to examine a number of test series in greater detail. Test series 13, 14 and 15 which differed only in aggregate gradation, show an increase of 6-10° in the angle of internal friction as a result of crushed aggregate.

In Test series 61-70 a constant angle of internal friction value was obtained for all possible combinations of crushed and uncrushed, fine and coarse aggregate. This is shown very clearly on figure 30A. A combination of crushed stone and crushed fine aggregate actually caused a significant decrease in the angle of internal friction.

In test series 71-80, which was a very open graded aggregate, the angle of internal friction was independent of the percentage of crushed gravel particles in the coarse aggregate, but decreased when crushed fine aggregate or crushed stone coarse aggregate was used. This is seen very clearly from figure 30B.

Test series 88-97 were conducted at various bitumen contents. The effect of the particle shape and surface texture on the angle of internal friction appears to depend on the bitumen content. However, in each case there is a bitumen content at which the angle of internal friction is unaffected.

Test series 149-153 indicate that crushed fine aggregate will increase the angle of internal friction by about 5°, but that the particle shape of the coarse aggregate has very little, if any, effect on the angle of internal friction.

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Test series 44 indicates a very large increase in the angle of internal friction due to the particle shape and surface texture. No apparent explanation for this phenomena could be found.

Figures 30C and 30D show that the particle shape had a significant effect on the angle of internal friction, probably due to the greater interlocking effect.

In conclusion it appears that the effect of particle shape and surface texture depends on the aggregate grading and bitumen content. For densely graded mixtures at normal bitumen contents an increase in the angle of internal friction ranging from 0-5% could be expected as a result of using crushed fine aggregate instead of natural rounded sand. The effect of the particle shape of the coarse aggregate on the angle of internal friction appears to be slight.

Aggregate Grading

Well graded aggregates are generally specified for high quality bases and paving mixtures. This would indicate that the grading of aggregates affects the values of the shear strength parameters, with well graded aggregates being more stable than poorly graded aggregates. However, it is not possible to ascertain on the basis of such experience whether the increased stability would be reflected in the angle of internal friction or in an interlocking effect which might be manifested in the cohesion parameter. This can only be determined by experiment.

Since the values of the shear strength parameters of a bituminous mixture vary with the bitumen content, and since the

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optimum bitumen content, according to any criteria of a mix depends on the aggregate grading, there is some question as to the basis on which the shear strengths of different mixtures can be compared. Thus the three mixtures in figure 31A develop approximately the same range of angle of internal friction values, but each does so over a different range of bitumen contents. In field practice the bitumen content chosen is normally that giving the highest strength while maintaining an acceptable air voids volume, say 3-5% in surface layers or 3-8% in base course layers. It would thus seem reasonable to compare the shear strength of different mixtures on this basis also.

The data compiled in this investigation which shows the effect of the aggregate grading on the angle of internal friction is shown on figure 31. The data on any one graph are comparable (except as noted) with the exception that the gradation differs. The figure in brackets opposite each test series number is the surface area of the aggregate in square feet per pound, and is an indication of the fineness of the aggregate.

Figure 31A indicates that the aggregate gradation did not have a significant influence on the angle of internal friction, since the maximum angle of internal friction values within normal ranges of bitumen content are approximately equal for all three gradations.

Figure 31B indicates a higher angle of internal friction value for a one size mixture than for an open graded mixture. Since tests were only conducted at one bitumen content, it may be that these values are not directly comparable.

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Figure 31C indicates that the less densely graded mixture had a higher angle of internal friction value although the question of comparable bitumen contents again arises.

Figure 31D indicates rather unexpectedly that identical angles of internal friction vs bitumen content curves were obtained for considerably different gradings.

Figure 31E indicates that the grading did not have a significant effect on the angle of internal friction in the case of a mix containing crushed fine aggregate, but had a significant effect in the case of a mix containing natural sand.

Figure 31F indicates the results of tests on a one size stone to which various amounts of sand asphalt were added. The sand asphalt portion had a constant percentage of bitumen so that the test results are approximately comparable. It appears that the aggregate grading had no significant effect on the angle of internal friction.

It is thus concluded that the angle of internal friction of a bituminous mixture is not greatly affected by changes in grading, provided that comparisons are made at comparable bitumen contents. It is noted that the range of gradings which were compared in the data presented is much greater than the range normally encountered in asphaltic concrete mixtures.

4.2.3.2. Bitumen

Penetration (or Viscosity) of Bitumen

Until recently paving grades of bitumens were classified chiefly on the basis of their penetration (ASTM D-5). However, good correlations can be obtained between the penetration of a bitumen and its

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viscosity at any temperature. Hence the two tests may be considered to reflect the same property of the bitumen.

Since the viscosity of a bitumen is a function of temperature, the effect of changes in the viscosity (or penetration) of a bitumen at a given temperature may be expected to be similar to changes in temperature for bitumens of constant viscosity at a given temperature.

Earlier (section 4.2.2.3) it was shown that the test temperature had little effect on the angle of internal friction value obtained. Hence it might be expected that the penetration of the bitumen would also have little effect on the angle of internal friction.

The data compiled in this investigation which indicates the effect of the penetration of the bitumen on the angle of internal friction is shown on figure 32. As expected, the effect is slight, being only 1^{o} to 2^{o} over the normal range of bitumen penetrations (100-200) commonly used in Canada.

It is concluded that the penetration grade of a bitumen has no significant effect on the angle of internal friction of a bituminous mixture.

Origin of Bitumen

Nijboer (4) notes that the angle of internal friction is not affected by the origin of the bitumen. No other data was found on this subject. In view of the very small effect that the test temperature and bitumen penetration have on the angle of internal

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friction, it is of course reasonable to expect that the origin of the bitumen also would have little effect.

4.2.4 Volumetric Relationships at 5% Air Voids

4.2.4.1 Volume of Bitumen

The data compiled in this investigation which indicate the effect of the volume of bitumen on the angle of internal friction (at 5% air voids) are shown on figure 33. Each point represents one mix. The mixes were compacted and tested by various methods. Although there is considerable scatter in the results, there appears to be a slight decrease in the angle of internal friction with increasing bitumen content. The decrease appears to be about 2^{o} - 5^{o} for an increase in the volume of bitumen from 10 to 20%.

The sum of the volume of bitumen and volume of air voids is equal to the volume of voids in the compacted mineral aggregate. Hence for a constant volume of air voids, the volume of bitumen is a measure of the voids in the compacted mineral aggregate. This is a function of the degree of compaction and the aggregate grading. Previously it was shown (section 4.2.1.4 and 4.2.3.1) that neither of these factors had a significant effect on the angle of internal friction. Hence it follows that the volume of bitumen at 5% air voids should have little effect on the angle of internal friction.

On the basis of the available evidence, it is concluded that the volume of bitumen at 5% air voids has little effect on the angle of internal friction.

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4.2.4.2 Bitumen-Filler Ratio (by volume)

The data compiled in this investigation which indicate the effect of the bitumen-filler ratio on the angle of internal friction at 5% air voids are shown on figure 34. The angle of internal friction appears to be independent of this variable.

It is concluded that the bitumen-filler ratio at 5% air voids has no significant effect on the angle of internal friction of a bituminous mixture.

4.2.4.3 Bitumen Film Thickness

The data compiled in this investigation which indicate the effect of the bitumen film thickness on the angle of internal friction at 5% air voids are shown on figure 35. The angle of internal friction appears to be independent of this variable.

It is thus concluded that at 5% air voids the angle of internal friction is not significantly affected by the bitumen film thickness.

4.3 FACTORS AFFECTING THE COHESION

4.3.1 Method of Forming Specimens

4.3.1.1 Mixing Temperature

See also section 4.2.1.1

Since the cohesion of a bituminous mixture is not significantly affected by slight changes in bitumen content at bitumen contents near optimum, any effect that the mixing temperature may have on the absorption will have a negligible affect on the cohesion.

It will be shown later (section 4.3.3.2) that the cohesion of a bituminous mixture decreases about 40% as the penetration of the

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bitumen is increased from 100 to 200 units. Fink and Lettier (21) found that the penetration after testing of samples was about 85% of the original penetration. Assuming an initial penetration of 150 and a lost of 15% in penetration, the increase in cohesion due to the hardining of the bitumen would be about 9% (0.15 x 150 x 40/100). The differences in penetration losses due to different mixing temperatures would only affect the cohesion to the extent of a fraction of this amount and are not considered significant.

4.3.1.2 Compacting Temperature

See also section 4.2.1.2

Since no data was found indicating the effect of the compacting temperature on the cohesion as measured in triaxial tests, reference is made to the effect of the compacting temperature on the Marshall stability. Since it is unlikely that the compaction temperature affects the angle of internal friction significantly, the variation in Marshall stability may be considered to reflect a variation in the cohesion. Figure 36 indicates the variation in stability with compacting temperature. All samples were taken from a commercial asphalt plant mixing at a constant temperature and reheated before compaction to the required temperature. The cohesion increases with increasing compacting temperature up to about 260°F and then levels off. It is of interest to note that the viscosity of the bitumen used was about 80 S.S.F. at 260°F, which is approximately the mixing viscosity specified for the

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Marshall Test. The temperature effect is significant, and points out the necessity of standardized test methods. The cohesion may be roughly doubled within the range of normal field compacting temperatures.

From the available data it is concluded that the compacting temperature has a significant effect on the cohesion.

4.3.1.3. Compacting Method

See also section 4.2.1.3

The data compiled in this investigation which indicates the effect of the compaction method on the cohesion are shown on figures 37 and 38. The following tests are comparable:

88, 89	compare	with	90
91, 92	"	"	93
94	"	"	95
96	"	"	97
132	"	"	131
135	"	"	136
137	"	"	138
139	"	"	140
145	"	"	146

In general the cohesion increases with bitumen content up to a maximum and then decreases. It appears that the peak of the cohesion curve occurs at a lower (about 1% less) bitumen content in the case of kneading compaction than in the case of static compaction, but that the maximum cohesion values obtained are approximately the same. This observation is also supported by the results of tests at only one bitumen content, such as tests 135-140 and 145-146. At the lower bitumen contents comparable values of cohesion are obtained (145-146), whereas at higher bitumen contents the samples prepared by kneading compaction (135, 137, 139) give lower cohesion values than the samples prepared by

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static compaction (136, 138, 140).

On the basis of the available evidence it is concluded that the compacting method does not greatly affect the maximum cohesion value obtained, but that this maximum is obtained at a bitumen content of 1% less in the case of kneading compaction than in the case of static compaction.

4.3.1.4 Degree of Compaction

See also section 4.2.1.4

The data compiled in this investigation which indicates the effect of the degree of compaction on the cohesion is shown on figures 25 and 26. In all cases an increase in compactive effort caused a significant increase in cohesion.

On the basis of the available data it is concluded that the cohesion increases with density, and that an increase in cohesion of about 50% might be achieved by increasing the degree of compaction from a low value to a high value.

4.3.2 Method of Testing Specimens

4.3.2.1 Triaxial Cell Systems

See also section 4.2.2.1

The data compiled in this investigation which indicate the effect of the testing system on the cohesion are the following pairs of tests which are illustrated on figure 37: 88 and 94, 90 and 95, 91 and 96, and 93 and 97.

It should be noted that the closed system tests were conducted at room temperatures and at virtually a zero rate of strain. This latter characteristic is alleged (13) to eliminate viscosity effects

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due to rates of strain and temperatures. The open system tests were conducted at a temperature of 140°F and a rate of strain of 5% per minute. Variation in either test temperature or rate of strain would have caused variations in the cohesion determined by the open test system. Thus a comparison of the absolute values of cohesion determined by the open cell system and the closed cell system cannot be made. However, relative comparisons between one pair and another appear to be justified.

Examination of the test data indicates that specimens tested by the open cell system can tolerate higher bitumen contents without a reduction in cohesion than samples tested by the closed system test. It should be noted that the specimens were identical as to composition and method of preparation.

4.3.2.2 Rate of Strain

Since bitumen is a visco-elastic material, it might be expected that the cohesion observed at non-zero rates of strain would contain a component dependent upon the viscosity of the bitumen and on the rate of strain. The cohesion would thus be expected to increase with the rate of strain.

Nijboer (4) has presented data for asphaltic concrete and sand asphalt (series 112 and 129) indicating that the cohesion can be separated into two components, one independent of the rate of strain and the other directly proportional to the rate of strain. These tests covered rates of strain between 0.025 and 0.1% per minute.

The data compiled in this investigation which indicate the influence of the rate of strain on the cohesion are shown in

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figure 39. In all cases the cohesion increases with rate of strain as expected, although the magnitude of the increase varies. The data (except Nijboer's tests 112 and 129) does not support Nijboer's findings that the cohesion can be divided into two components, one independent of the rate of strain and the other proportional to the rate of strain. The relationship appears to be more complex.

On the basis of the available evidence it is concluded that the relationship between the cohesion and the rate of strain is complex. The cohesion increases with increasing rates of strain. Within the range of normal rates of strain the cohesion is roughly doubled for an increase in the rate of strain of one log cycle.

4.3.2.3 Test Temperature

The cohesion of a bitumen mix would be expected to decrease with increasing test temperature for two reasons. The cohesion of the bitumen at zero rate of strain would be lower at elevated temperatures. Additionally the decrease in the viscosity of the bitumen would decrease that component of the cohesion which is a function of the rate of strain.

The data compiled in this investigation which indicates the effect of the test temperature on the cohesion is shown in figure 40. As expected, the cohesion decreases rapidly with increasing temperature.

It is of interest to compare the change in cohesion with the change in the viscosity of the bitumen as a result of the change

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in temperature. This data is shown in figure 41. Samples 30-32 and 114-128 are for sand asphalt mixtures. In order to obtain more points on the graph certain data for tests at a constant temperature but using bitumen of different penetration (or viscosity) were added. (4-11, 137-139, 138-140). All other curves are for bitumens of constant penetration tested at various temperatures.

For a range of bitumen viscosity of about one log cycle, which corresponds roughly to a 20°F change of temperature within the range of normal testing temperatures, the cohesion increases as the log of the bitumen viscosity. For larger ranges of viscosity the cohesion increases more rapidly than the log of viscosity, but much less rapidly than the viscosity.

Certain curves show a tendency for the cohesion to become constant and independent of temperatures below a viscosity of 10^6 - 10^7 poises. It may be of significance that the test series exhibiting this property were tested by the closed system or by a variation of the closed system (Nijboer tests) and are for a near zero rate of strain. Samples tested by the open system showed a greater sensitivity to changes in viscosity. This would appear to indicate that the component of cohesion which is a function of the rate of strain is more sensitive to the viscosity of the bitumen than the component which is independent of the rate of strain.

From the available data, it is concluded that the relationship between cohesion and test temperature or viscosity is complex. The increase in cohesion corresponding to a decrease in temperature of 20°F or an increase in viscosity of one log cycle may range from 0 to 100%.

4.3.2.4 Conditions of Drainage

See section 4.2.2.4.

4.3.3. Materials

4.3.3.1 Aggregate

Aggregate Shape and Surface Texture

There does not appear to be any basis for expecting that the particle shape and surface texture should have a significant effect on the cohesion of a bituminous mixture. The effect, if any, could only be evaluated by experiment.

The data compiled in this investigation which indicate the effect of the particle shape and surface texture on the cohesion are shown on figures 42 and 43.

The data indicates that the use of crushed fine aggregate in place of natural fine aggregate will increase the cohesion by 50 to 100%. The effect of the particle shape of the coarse aggregate on the cohesion is much less pronounced, although a change from crushed gravel to crushed stone may increase the cohesion by about 25%.

It is thus concluded that the particle shape of the fine aggregate has a pronounced effect on the cohesion but that the effect of the particle shape of the coarse aggregate is much less.

It is a general practice to specify a minimum percentage of crushed coarse particles in asphalt aggregates since it has been found from experience that this results in more stable mixes. The experimental data suggests that a large percentage of crushed coarse particles may only be beneficial insofar as they reflect the degree of aggregate crushing required to produce the aggregate and thus indirectly reflect the amount of crushed fine aggregate produced as a result of the crushing operation.

Aggregate Grading

See also section 4.2.3.1.

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The data compiled in this investigation which shows the effect of the gradation on the cohesion is shown on figure 44. The figure in brackets beside the plotted points is the surface area of the aggregate in square feet per pound. It is seen that for the normal range of dense graded mixtures (aggregate surface areas of 30 to 60 square feet per pound) the cohesion is not significantly affected by changes in grading. Open graded mixtures may have a cohesion of about 50% of the cohesion for densely graded mixtures, while for one size aggregate mixtures, the cohesion drops to about 10%.

4.3.3.2 Bitumen

Penetration (or Viscosity) of Bitumen

Insofar as the penetration of a bitumen is a measure of the viscosity of the bitumen, and since the cohesion of a bituminous mixture contains a component dependent upon the viscosity of the bitumen, it is to be expected that the cohesion would decrease with increasing penetration (decreasing viscosity of the bitumen). Moreover this effect should be most pronounced in test results obtained under those conditions which emphasize the viscosity effect - that is the open cell test and high rates of strain.

The data compiled in this investigation which indicates the effect of the penetration of the bitumen on the cohesion is shown in figure 45. As expected, the cohesion decreases with increasing penetration of the bitumen. The following table gives additional information on the mixes which is useful in interpreting the test results:

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Test Series	Test Temperature	Test System	Type of Mix
4	100-110°F	Open Cell	Densely graded
7	"	"	"
10	"	"	"
102	68	Closed	"
103	99-104	"	"
114	68	"	Sheet asphalt
115	86	"	"
116	104	"	"
137	68	"	Densely graded
138	68	"	"

The samples of test series 137 were prepared by kneading compaction at a high bitumen content and tested in the closed cell system. This is believed to account for the unexpected results obtained in these tests. The closed cell tests appear to indicate that for this test method changes in the penetration of a bitumen over the range 100-200 have no effect on the cohesion. The open system tests on the other hand indicate a decrease in the cohesion of about 40% for an increase in penetration from 100 to 200.

It is thus concluded that the effect of the penetration of the bitumen on the cohesion is dependent upon the type of test and the rate of strain employed.

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Origin of Bitumen

Since bitumens from any one origin can be produced with a wide range of properties such as penetration or viscosity at a given temperature, some basis must be established on which bitumens can be compared. Such a basis might be equal penetration at a given temperature. Since the relationship between the penetration and other properties such as viscosity varies somewhat for different bitumens, it is to be expected that mixes with bitumens of constant penetration but of different origin might have different cohesion values since the other properties of the bitumen would not necessarily be constant.

The only published data which were found on the effect of the origin of the bitumen on the cohesion of bituminous mixtures were those published by Nijboer (4). He found that only where the penetration at the test temperature was less than about 50, did the origin of the bitumen have a significant effect on the cohesion. Since the penetration of commonly used bitumens at normal test temperature is well above 50, it may be concluded that for practical purposes the origin of the bitumen has no significant effect on the cohesion.

4.3.4 Volumetric Relationships at 5% Air Voids

4.3.4.1 Volume of Bitumen

The data compiled in this investigation which indicate the effect of the volume of the bitumen on the cohesion are shown on figure 46. The cohesion decreases from about 45 psi to 15 psi as the volume of bitumen increases from 6% to 18%. That is, the cohesion appears to be inversely proportional to the volume of bitumen within normal ranges of bitumen contents. The scatter

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in the results is believed largely due to the fact that the various mixes represented differed as to composition, preparation and test methods. It was shown earlier (section 4.3.3.1) that the cohesion of a mixture decreased as the grading became less dense or, in other words, the voids in the compacted mineral aggregate increased. At constant air voids, the volume of the bitumen increases as the voids in the mineral aggregate increase. Hence, it is to be expected that the cohesion should decrease as the volume of the bitumen (at constant air voids) increases.

It is thus concluded that the volume of bitumen at 5% air voids has a significant effect on the cohesion.

4.3.4.2 Bitumen - Filler Ratio

The data compiled in this investigation which indicate the effect of the bitumen-filler ratio on the cohesion are shown on figure 47. The data is inconclusive because of the wide variety of mixes considered and the effects of other variables. It is, for example, not certain whether the data should be represented by a straight line rising to the right and indicating that the cohesion is directly proportional to the bitumen-filler ratio, or by a family of parallel curves rising to the left and indicating that the cohesion is inversely proportional to the bitumen-filler ratio.

4.3.4.3 Bitumen Film Thickness

The data compiled in this investigation which indicate the effect of the bitumen film thickness on the cohesion are shown on figure 48. The data is inconclusive, probably due to the over-riding effects of other variables.

CHAPTER V

CONCLUSIONS FROM INVESTIGATION AND IMPLICATIONS TO FIELD PRACTICE

The conclusions drawn from this investigation are based on the test data available to the author. It will be understood that the amount of test data was limited, both as to number of test results and as to the number of factors which were evaluated. Thus, certain conclusions may be questioned because of the limited number of tests on which they were based and because of the possibility that the influence of certain factors has been overlooked. Nevertheless, it is suggested that the conclusions are reasonable in the light of the data that is currently available.

5.1 CONCLUSIONS FROM INVESTIGATION OF THE FACTORS AFFECTING THE ELASTIC MODULUS AND IMPLICATIONS TO FIELD PRACTICE.

5.1.1 Loading Versus Rebound Test

From the laboratory tests carried out by the author, it is concluded that a more consistent and unique value of elastic modulus is obtained for asphaltic concrete by measuring the strain due to the rapid release of a load than the strain due to the application of a load over a period of time. This would indicate that tests measuring rebound deflections are likely to be the most suitable for measuring the strength of pavements subjected to many repetitions of relatively suddenly applied and transient loads.

5.1.2 Effect of Stress Level and Numbers of Repetitions of Load on Elastic Modulus

The rebound elastic modulus was found to be substantially independent of the stress level and numbers of repetitions of

load. This observation lends support to the use of design methods using elastic theory and the assumptions of ideally elastic behaviour.

5.1.3 Effect of Deviator Stress Yield Strength on Elastic Modulus

The most significant observation from the study of the elastic modulus is considered to be the observation that the deviator stress rebound elastic modulus was directly proportional to the deviator stress yield strength. This observation permits the elastic modulus to be computed for wide ranges of confining pressure and test temperature on the basis of a small number of tests. Moreover, it points out the futility of attempting to obtain significant numerical values from unconfined compression tests. Furthermore, it must be recognized that while pavement temperatures might be simply and accurately measured in the field, the degree of lateral restraint (confining pressure) developed in a pavement under a wheel load is difficult if not impossible to calculate. Thus it is questionable whether numerical values obtained in laboratory tests can be applied to field conditions. However, as a first approximation, it is proposed to use the elastic modulus corresponding to a confining pressure equal to the unconfined compressive strength of the mix. Some theoretical and experimental justification for the assumption of this degree of confinement exists (12, 23). This procedure would give elastic moduli of 20,000 psi and 12,000 psi respectively for temperatures of 75°F and 120°F for the mix investigated. The difficulty of estimating the confining pressure that obtains under field conditions suggests that the elastic modulus is determined most reliably by calculation from measured rebounds under prototype loading of actual pavements.

5.2 CONCLUSIONS FROM INVESTIGATION OF THE FACTORS AFFECTING THE SHEAR STRENGTH PARAMETERS AND IMPLICATIONS TO FIELD PRACTICE

5.2.1 Effect of Mixing and Compacting Temperature

On the basis of indirect evidence, it is presumed that the mixing and compacting temperature do not significantly affect the angle of internal friction of asphaltic concrete provided that the temperatures are sufficiently high to permit satisfactory mixing and compacting. On a similar basis, it is presumed that the mixing temperature does not significantly affect the cohesion.

On the basis of Marshall Test data, it is concluded that the compacting temperature of asphaltic concrete has a very pronounced effect on the cohesion. Increasing the compacting temperature from 180°F to 260°F, which temperatures roughly correspond to the lower and upper limits in field practice, had the effect of increasing the cohesion by 100%. Increasing the temperature above 260°F did not increase the cohesion further. This data indicates the necessity of high field compaction temperatures, and the requirement for techniques and equipment, such as rubber-tired rollers, which permit compaction to be carried out at high temperatures.

5.2.2 Effect of Compaction Method and Triaxial Test Type

On the basis of test data compiled in the investigation, it is concluded that the compaction method (characterized on the basis of the amount of shear strain imparted to the specimen during compaction) and the triaxial test type (open or closed cell system) have significant effects on both the angle of internal friction and cohesion at higher bitumen contents, but little effect at lower bitumen contents. In the case of samples prepared by kneading compaction and tested by the closed cell system, the angle of internal

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friction and cohesion may be reduced by as much as 50%, as the air voids are reduced from 5% to 2%, which are approximately the upper and lower limits generally specified for surface course mix designs. In the case of specimens prepared by static compaction and tested by either cell system, or specimens prepared by kneading compaction and tested in the open cell system, such large decreases in the shear strength parameters with increasing bitumen content were generally not observed. These observations point out the necessity for lab compaction and test methods that simulate or reproduce field conditions and that have been correlated with field performance. Thus the most reliable test and design methods are not necessarily those which are most rational from a theoretical point of view, but may well be those empirical methods having the largest degree of correlation with field performance. This no doubt accounts for the great popularity of the Marshall Test (9) with practicing Engineers.

5.2.3 Effect of Compactive Effort and Density

The experimental data compiled in this investigation indicate that an increase in compactive effort, while increasing the density, may have no significant effect on the angle of internal friction. This observation is unexpected and contrary to experience with granular materials. The observation is based on a limited number of tests and may not apply to other mixes. Increasing the compactive effort from a low to a high value increased the cohesion between 50 to 100 percent. Thus the additional cost and care required to obtain a high degree of compaction in an asphaltic pavement is certainly justified.

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5.2.4. Effect of Rate of Strain and Test Temperature

The available test data indicate that the angle of internal friction of normal asphaltic concrete is not significantly affected by the rate of strain or test temperature within the ranges of rates of strain and test temperature normally employed.

The cohesion increases with increasing rate of strain, although the relationship is complex. Within the range of normal rates of strain the cohesion may be roughly doubled for an increase in the rate of strain of one log cycle. This raises the question of a representative strain rate to be used in the lab when determining the cohesion value to be applied to a pavement design problem. To overcome this difficulty, it is suggested that constant incremental loading be used to obtain a static yield value as described in section 3.3.1. This might be used with a safety factor of about 1.5 to 2.0 in the design of pavements subject to slowly moving or parked vehicles. Pavements subject to rapidly moving traffic might be designed with a safety factor approaching unity.

As expected, the cohesion was found to decrease in a general way with increasing test temperature or decreasing bitumen viscosity. An increase in temperature of 20°F, which corresponds approximately to a decrease in bitumen viscosity of one log cycle, may decrease the cohesion between 0 and 50 percent, depending on the type of test and strain rate. It is proposed that design test temperatures between 100°F and 140°F be used for Canadian conditions. The exact temperature to be used for a given locality should be determined by field measurement because of the large effect of the test temperature

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on the cohesion. The use of the constant incremental loading test as proposed earlier yields a cohesion value which corresponds to a low rate of strain, and which is therefore considerably less sensitive to temperature changes than results obtained from high rate of strain tests. Hence the effect of errors in selecting the design temperature would be minimized by the use of the static yield value obtained from the incremental loading test.

5.2.5 Effect of Drainage Conditions

The available test data indicate that the drainage conditions in the triaxial test have no significant effect on the angle of internal friction or cohesion of normal asphaltic concrete mixes. Thus the simplest form of triaxial test equipment may be used.

5.2.6 Effect of Aggregate Particle Shape and Surface Texture

The available test data indicate that the particle shape and surface texture of the coarse aggregate do not have a significant effect on the angle of internal friction. Replacing a rounded natural sand fine aggregate by a manufactured crushed fine aggregate may increase the angle of internal friction by about 5 degrees. The use of crushed stone instead of rounded coarse aggregate may increase the cohesion by about 25%, while the use of crushed fine aggregate instead of rounded sand may increase the cohesion by 50 to 100 percent. The predominating influence of the fine aggregate in the available test data indicates that this portion of the aggregate deserves greater attention than is currently accorded to it, and suggests that specifications requiring crushed coarse particles

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may be effective, in part, by virtue of requiring a high degree of crushing, which produces a large amount of crushed fine aggregate. However, the widely demonstrated superior performance of aggregates containing crushed coarse aggregate rather than rounded aggregate suggests that maximum angles of internal friction and cohesion derived from laboratory tests may not, by themselves, be adequate measures of the strength of a material and that other factors such as the strain required to develop these maximum values should be considered also.

5.2.7 Effect of Aggregate Grading

The available test data indicate that the aggregate grading within the limits of gradations normally used for asphaltic concrete does not have a significant effect on either the angle of internal friction or cohesion. This suggests that quite wide grading bands might be used in aggregate specifications for reasons of economy and to permit use of local materials. However, in order to achieve a uniform product the specification should then require close adherence to one particular grading, which should be selected within the wide range permitted. A change from a dense grading to an open grading may increase the angle of internal friction slightly, while decreasing the cohesion by about 50 percent. This suggests that dense graded aggregates should be used for surface course mixes where high cohesive strength is required, while open graded aggregates are more suited for bases at lower levels where greater confining pressures are available to mobilize the more prominent

frictional strength, or for traffic having large tire contact areas which can take advantage of the frictional strength.

5.2.8 Effect of Penetration of Bitumen

The available test data indicate that the penetration of the bitumen within the range of 100 to 200 penetration does not have a significant effect on the angle of internal friction under normal test conditions, or on the cohesion of mixes tested in the closed cell system test, but that the cohesion of a mix tested by the open cell system may be reduced by about 40% as the penetration of the bitumen is increased from 100 to 200 units.

5.2.9 Effect of Origin of Bitumen

Insufficient data was found to indicate the effect of the origin of the bitumen on the angle of internal friction or cohesion. Such evidence as is available suggests that the effect would be slight.

5.2.10 Effect of Volume of Bitumen at 5% Air Voids

The available test data indicate that the volume of bitumen, at 5% air voids, in a mix has a significant effect on both the angle of internal friction and cohesion. For an increase in the volume of bitumen from 8% to 12% by volume, at 5% air voids, which is the range normally encountered in asphaltic concrete, the angle of internal friction may decrease by about 4° and the cohesion decrease by about 10 p.s.i. An increasing volume of bitumen at constant air voids, of course, indicates either a more open grading, or a lower degree of compaction. The decreases in strength may be due to either one or both of these factors.

5.2.11 Effect of Bitumen-Filler Ratio and Bitumen Film Thickness at 5% Air Voids

The available data do not indicate that the bitumen-filler ratio or the bitumen film thickness have a significant effect on either the angle of internal friction or the cohesion. This is believed due to the large scatter in the data which possibly obscures significant trends.

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SOURCE OF TEST DATA

TEST SERIES	REFERENCE NUMBER
1 - 18	15
19 - 24	24
25 - 32	23
33 - 40	14
41 - 43	25
44 - 60	26
61 - 87	27
88 - 97	10
98 - 101	20
102 - 130	4
131 - 134	19
135 - 147	13
148	16
149 - 153	28
154 - 156 and all tests for the elastic modulus study were carried out by the author.	

FIGURES

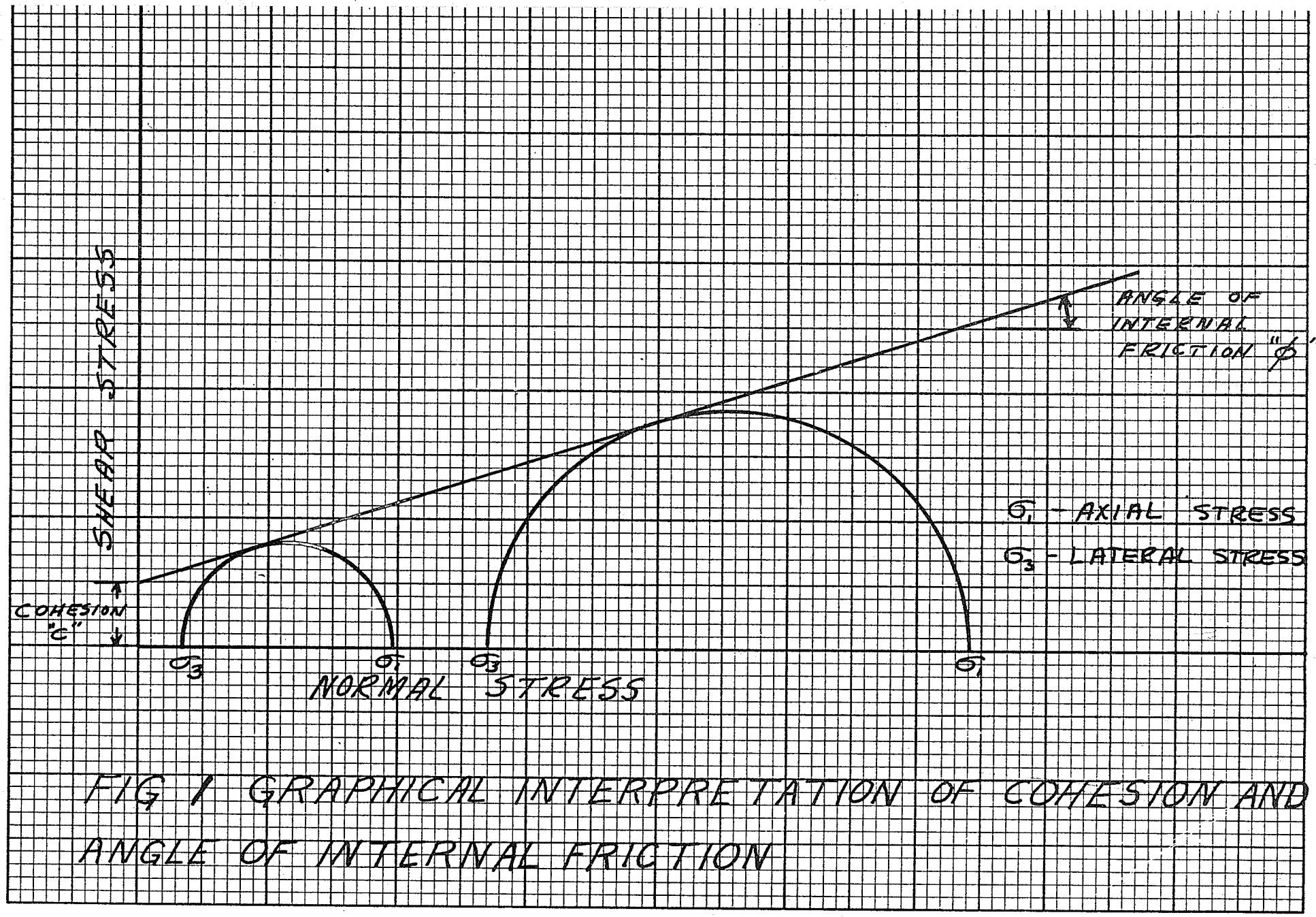
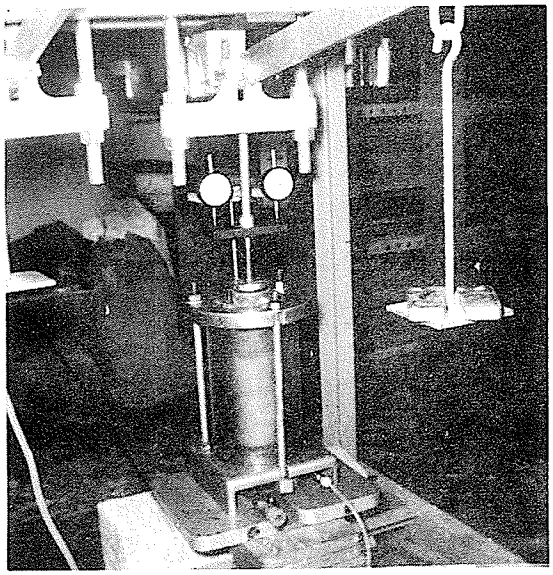
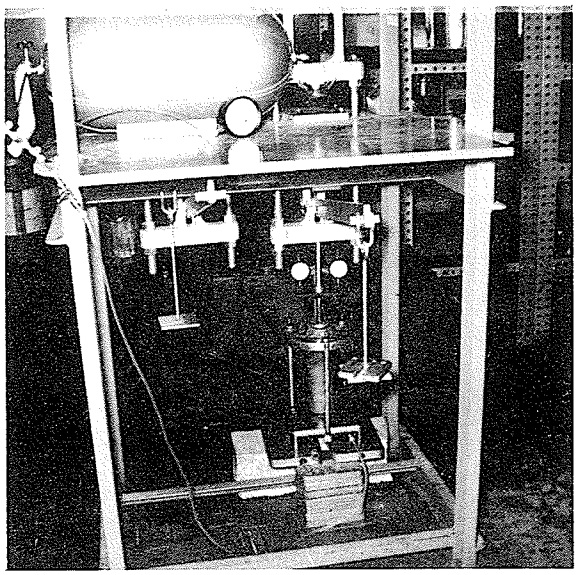


FIG 1 GRAPHICAL INTERPRETATION OF COHESION AND ANGLE OF INTERNAL FRICTION



Close up of Triaxial Cell in Loading Device. Water Bath has been Removed



Loading Device and Triaxial Cell

Typical Failed Test Specimens

Typical Failed Test Specimens

FIG. 2 PHOTOGRAPHS OF APPARATUS FOR ELASTIC MODULUS TESTS AND TEST SPECIMENS

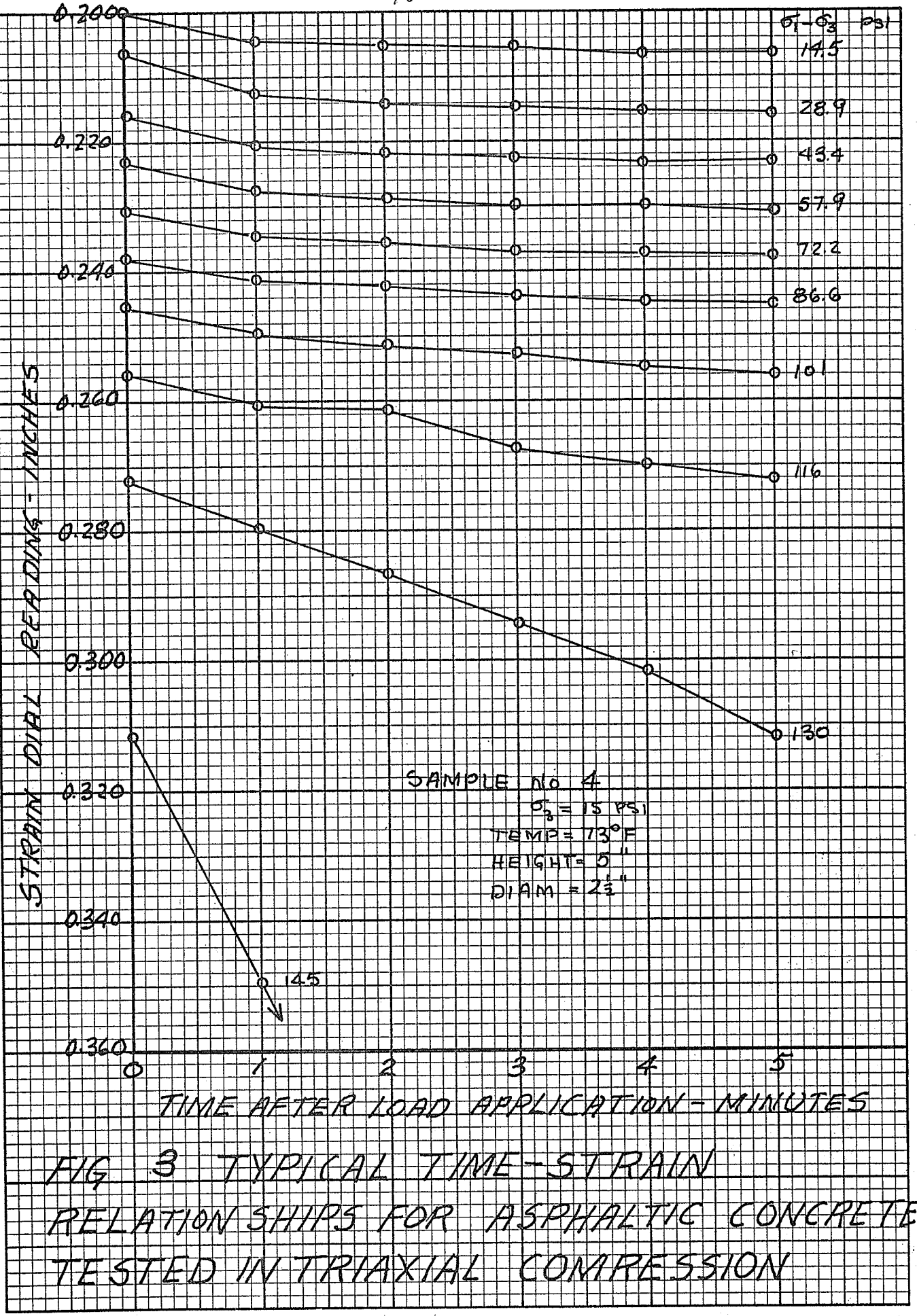


FIG 3 TYPICAL TIME-STRAIN RELATION SHIPS FOR ASPHALTIC CONCRETE TESTED IN TRIAXIAL COMPRESSION

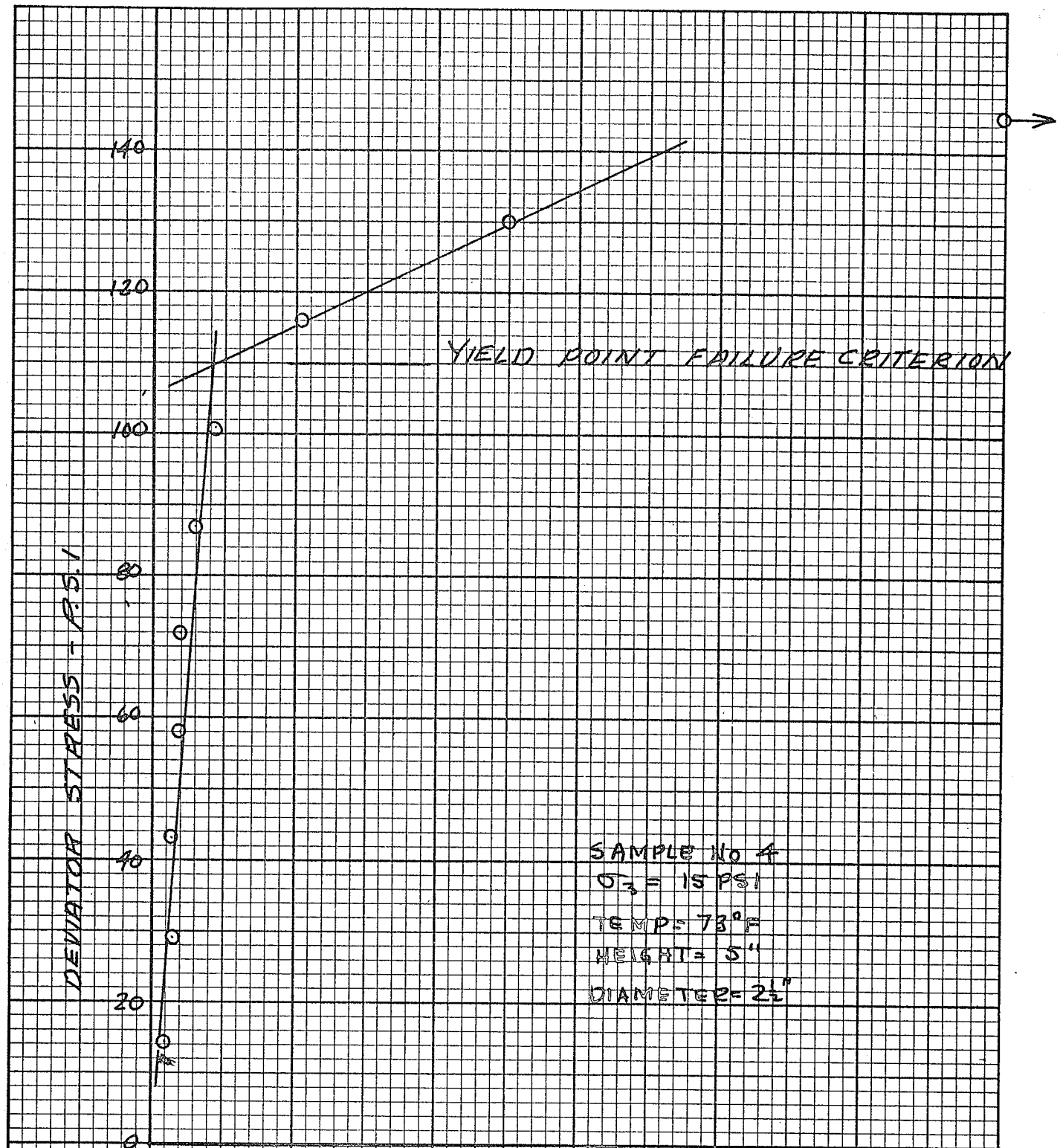


FIG 4 TYPICAL STRESS-RATE OF STRAIN RELATIONSHIP INDICATING THE YIELD POINT FAILURE CRITERION

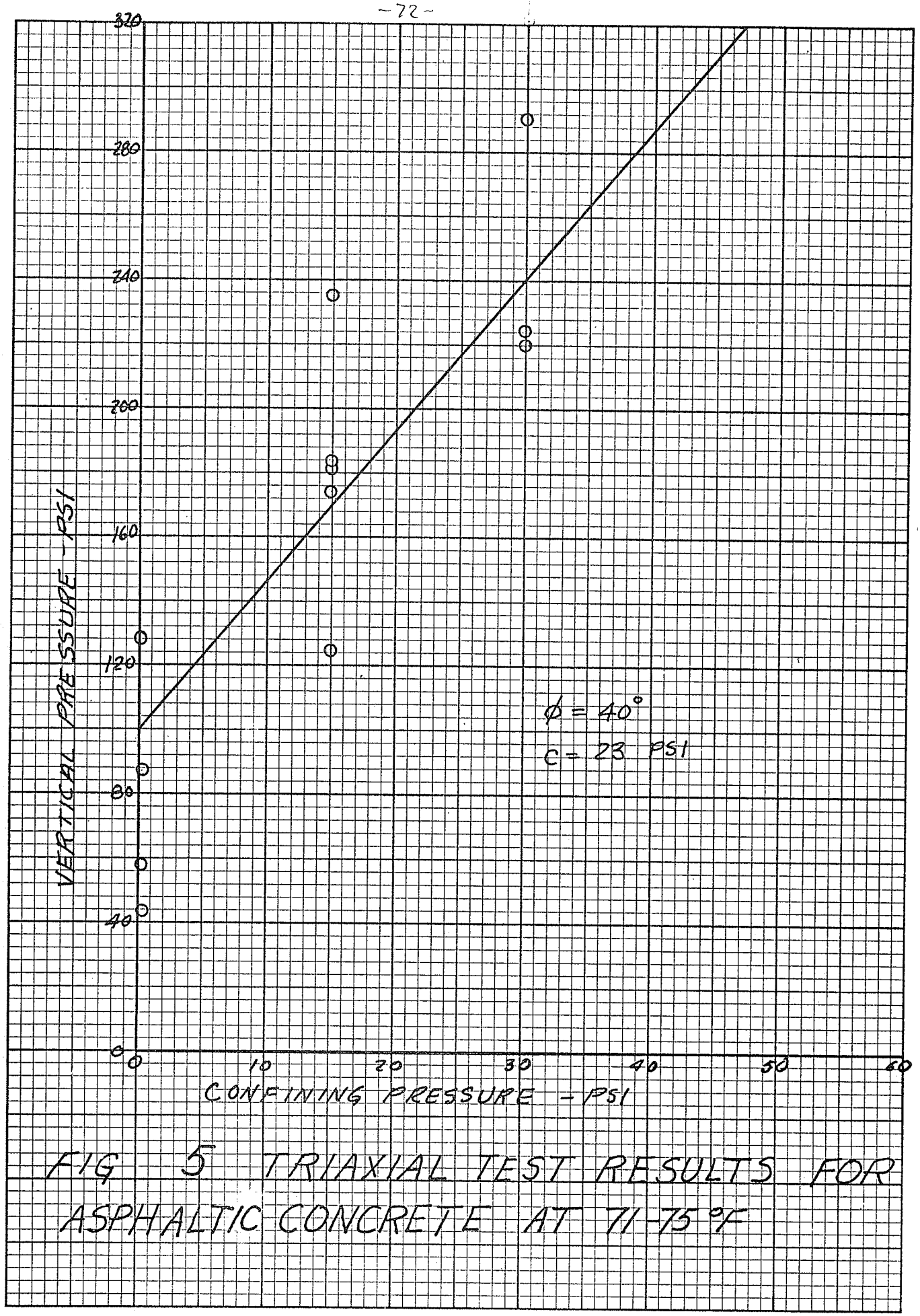


FIG 5 TRIAXIAL TEST RESULTS FOR ASPHALTIC CONCRETE AT 71-75 °F

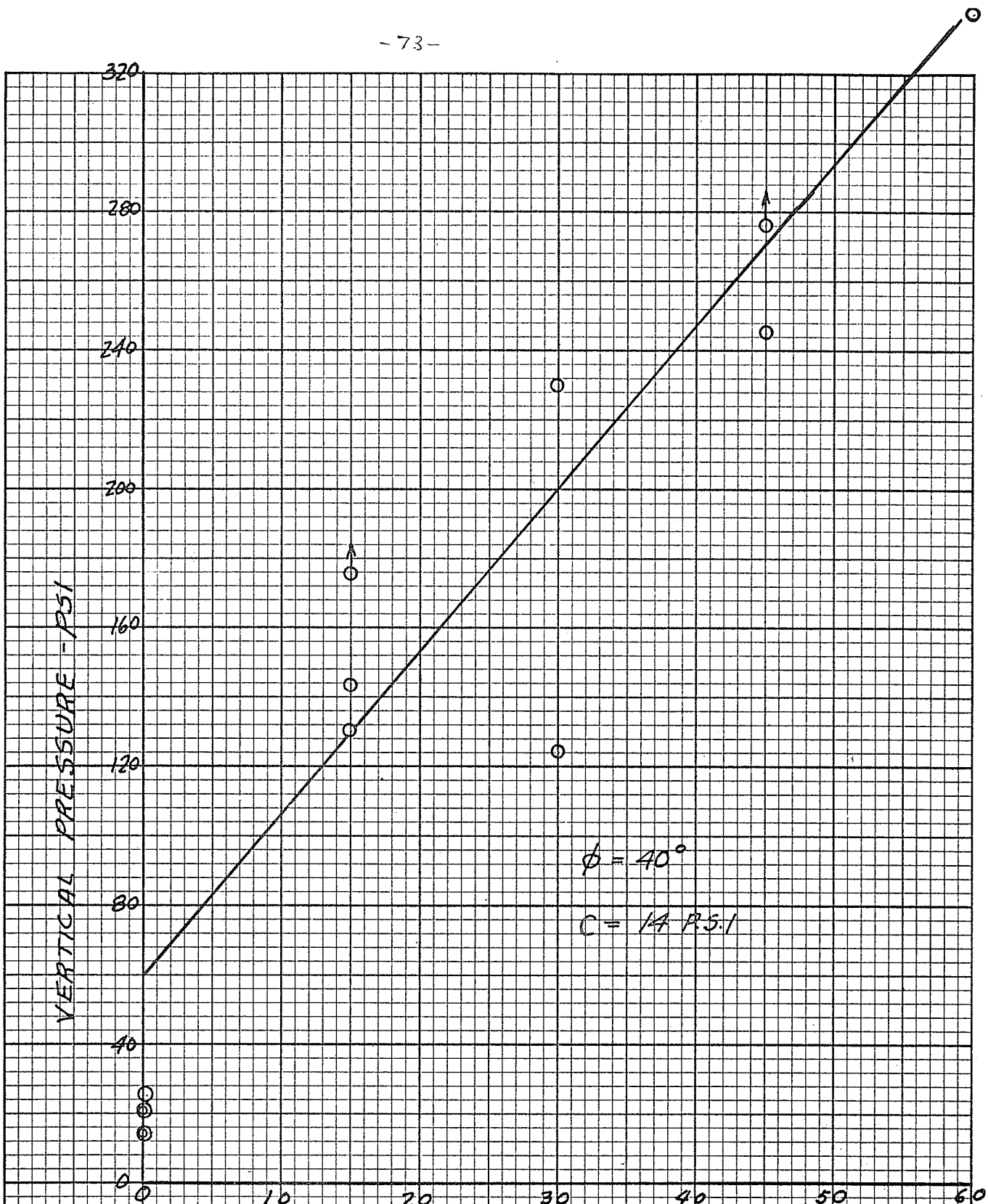


FIG 6 TRIAXIAL TEST RESULTS FOR ASPHALTIC CONCRETE AT 115-120°F

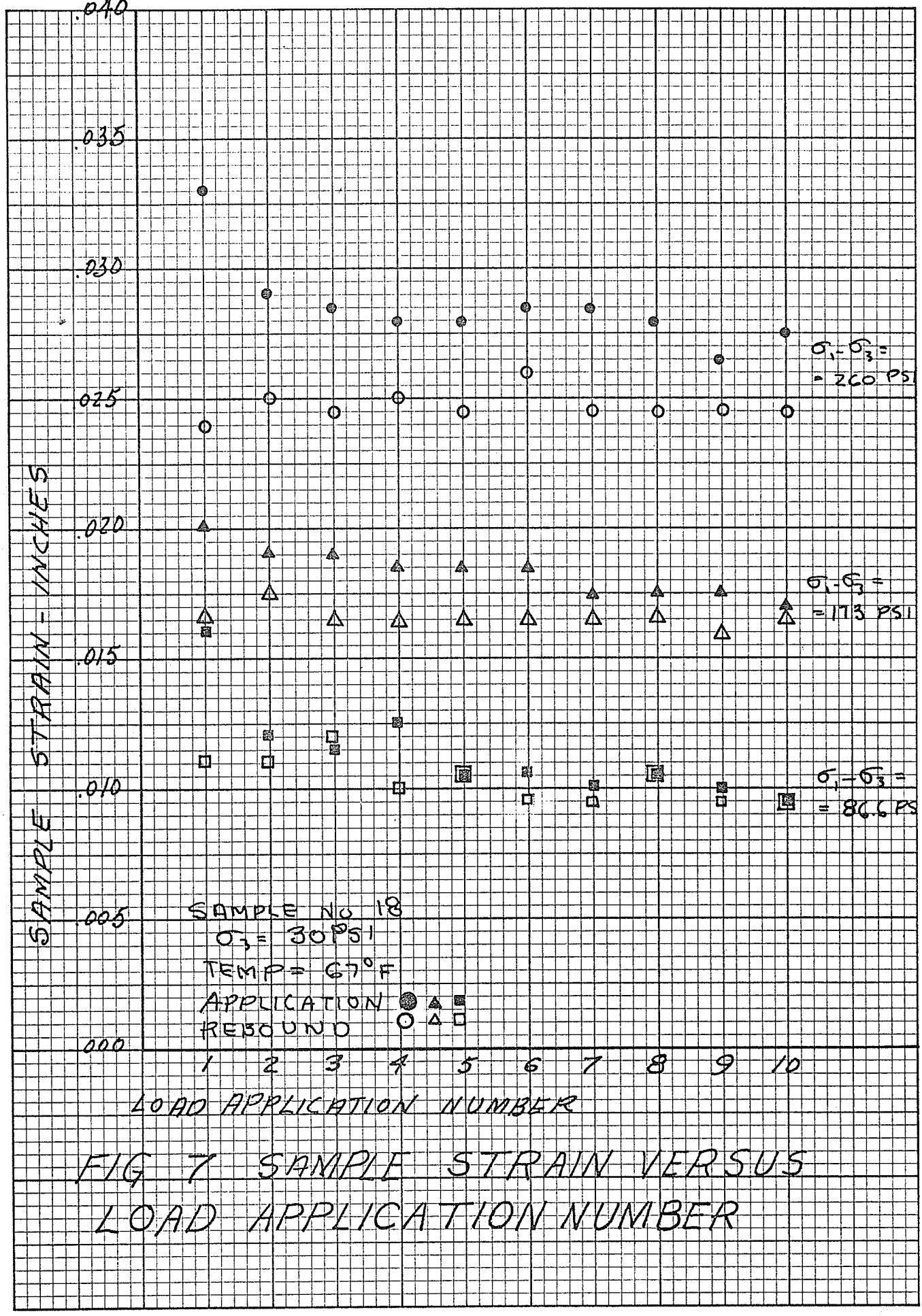


FIG 7 SAMPLE STRAIN VERSUS LOAD APPLICATION NUMBER

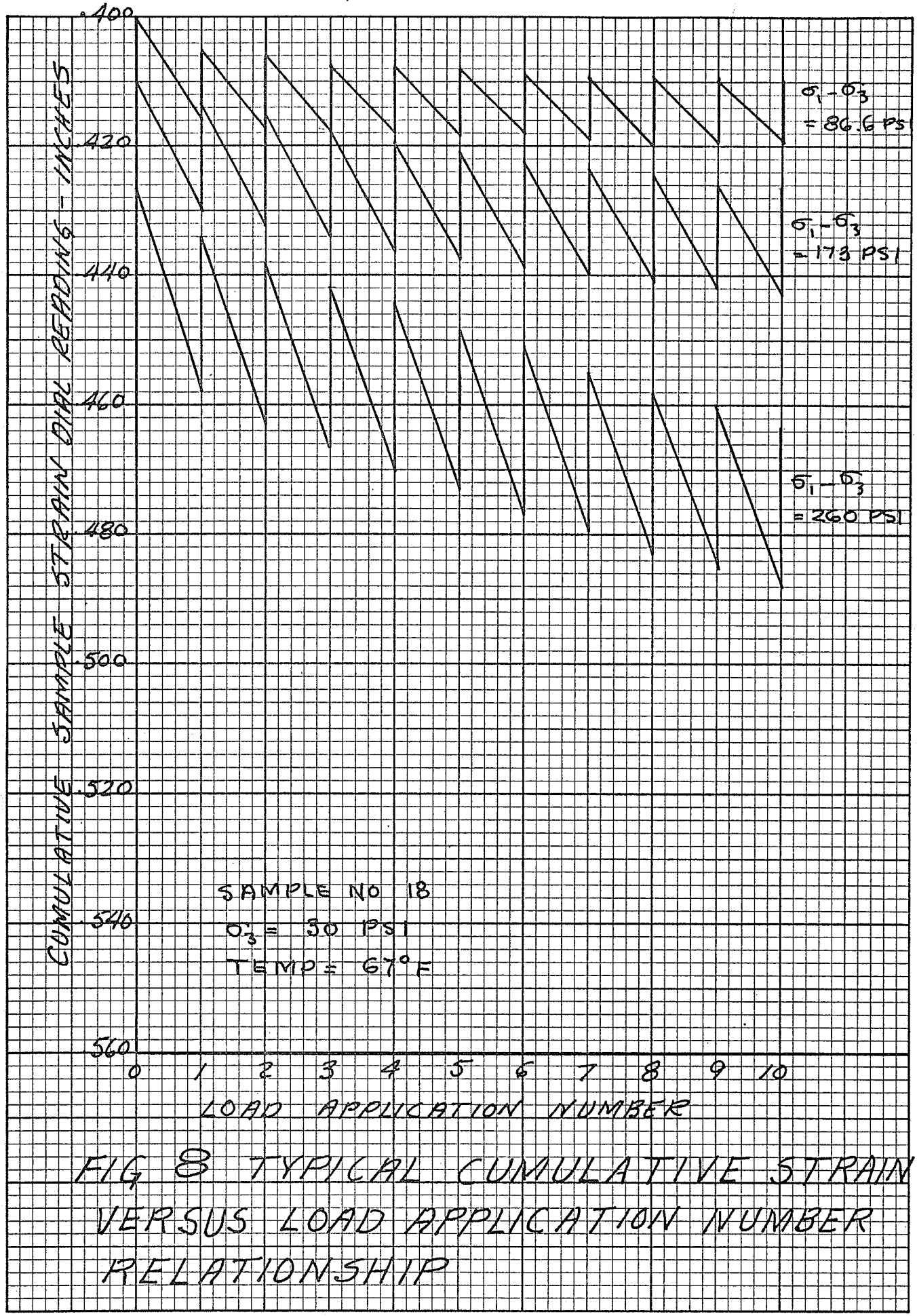


FIG 8 TYPICAL CUMULATIVE STRAIN VERSUS LOAD APPLICATION NUMBER RELATIONSHIP

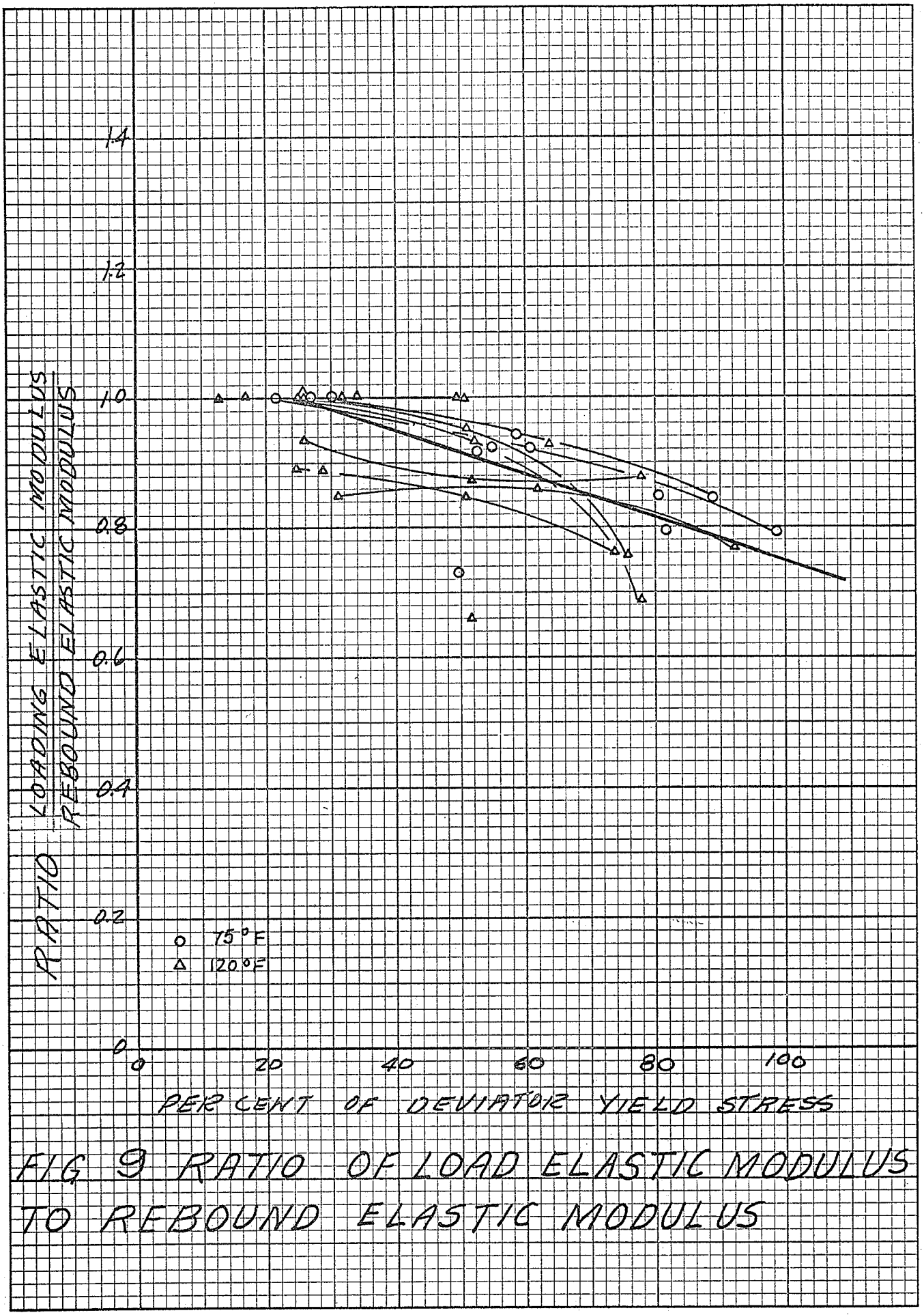


FIG 9 RATIO OF LOAD ELASTIC MODULUS TO REBOUND ELASTIC MODULUS

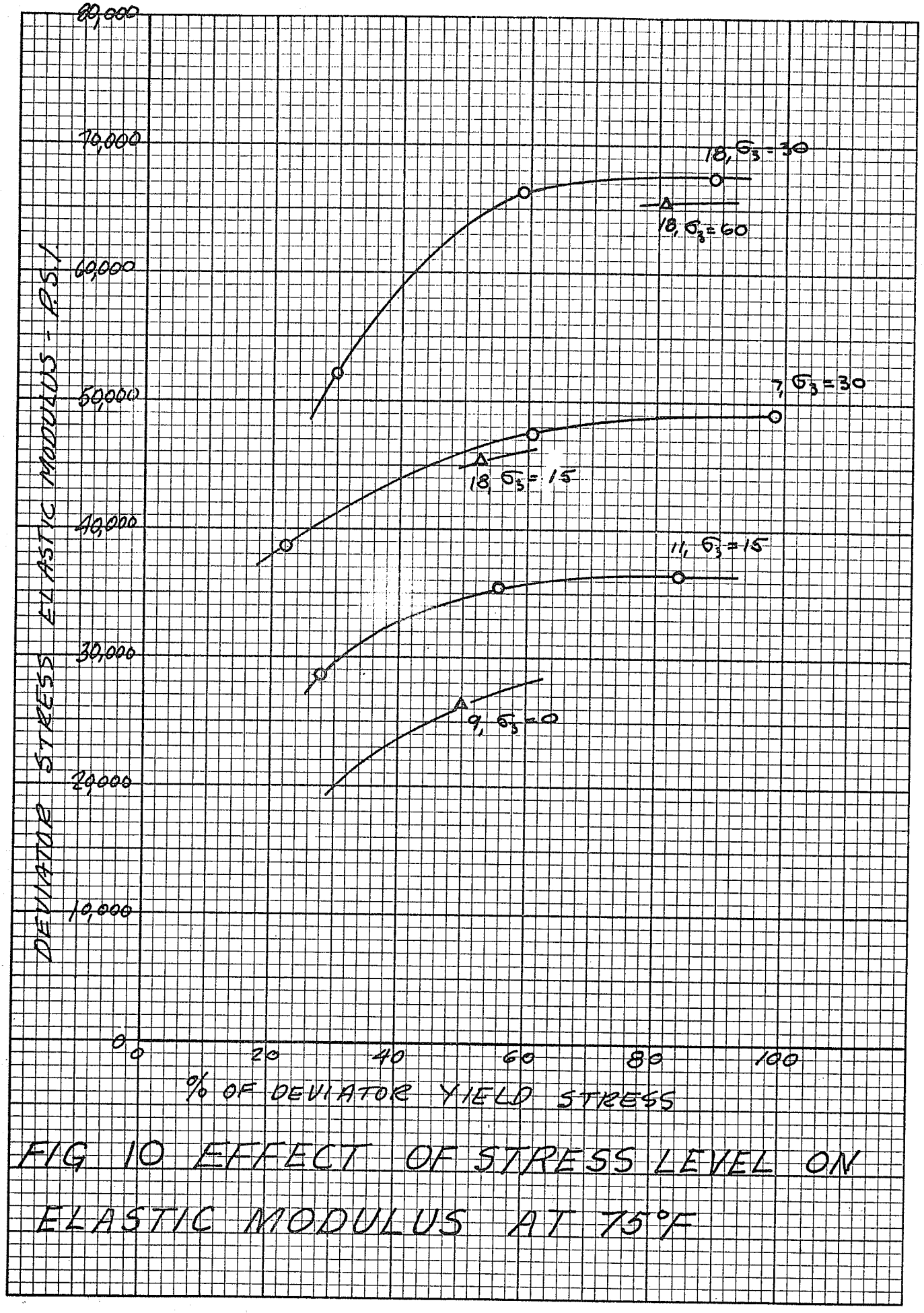


FIG 10 EFFECT OF STRESS LEVEL ON ELASTIC MODULUS AT 75°F

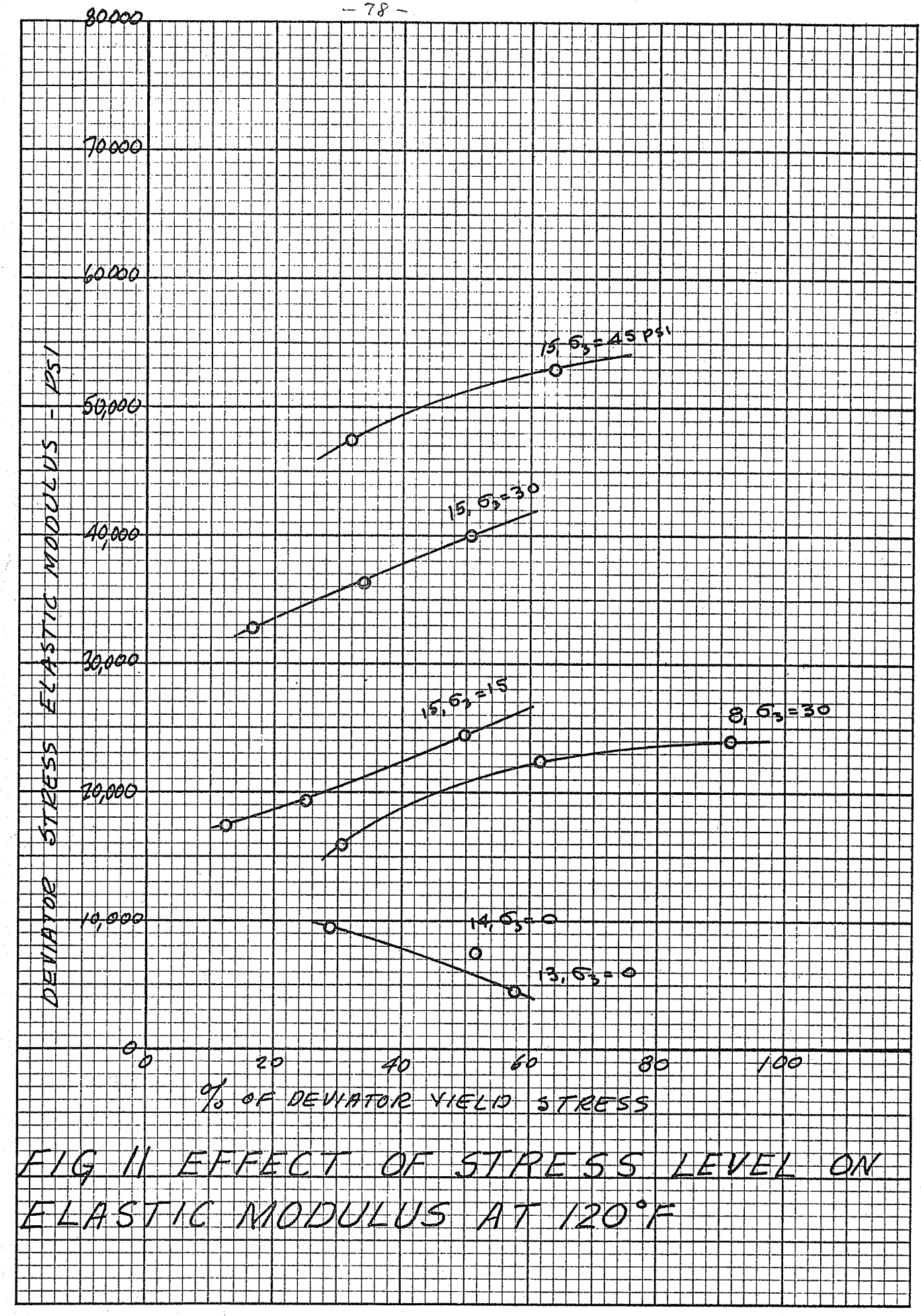


FIG 11 EFFECT OF STRESS LEVEL ON ELASTIC MODULUS AT 120°F

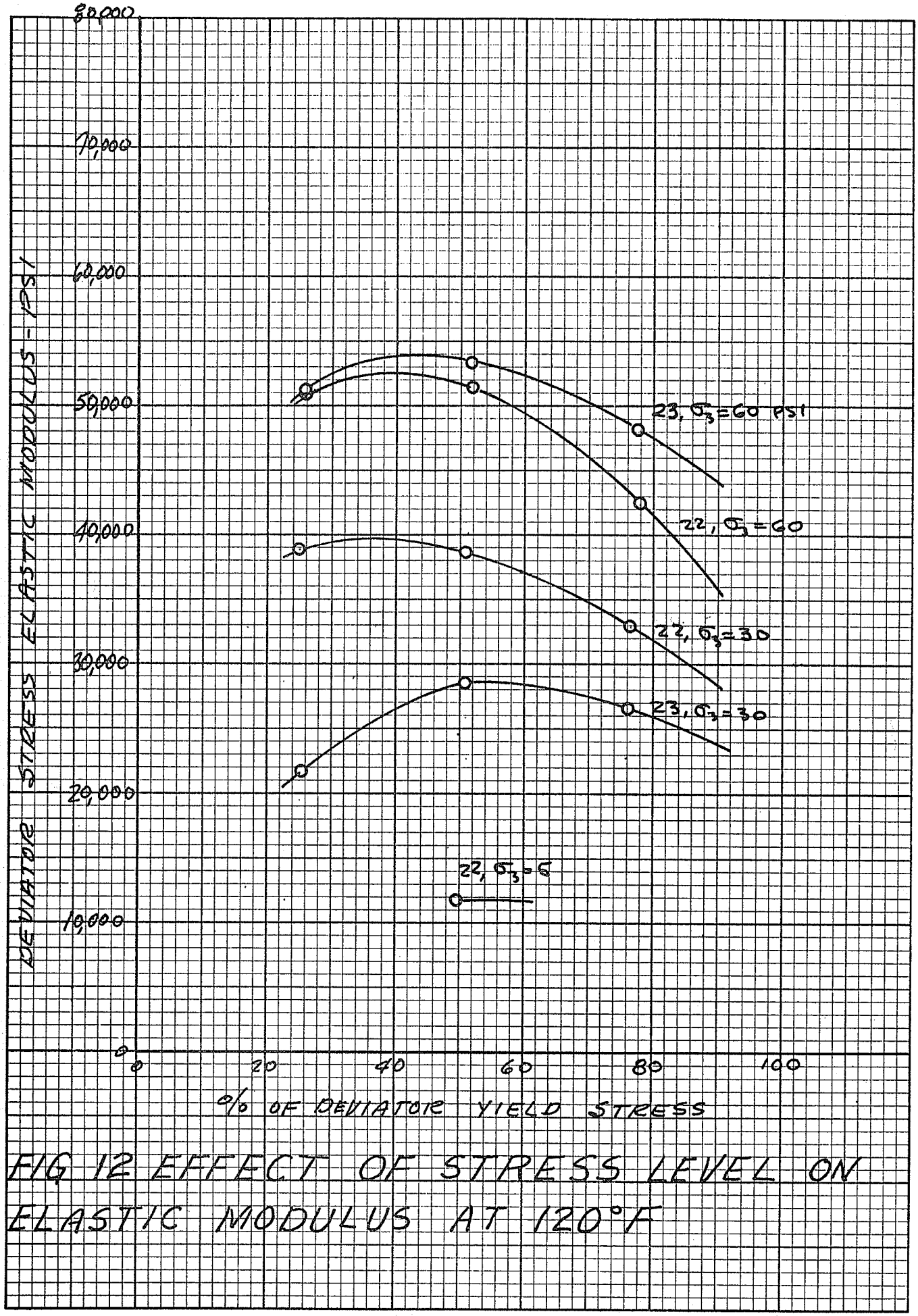


FIG 12 EFFECT OF STRESS LEVEL ON ELASTIC MODULUS AT 120°F

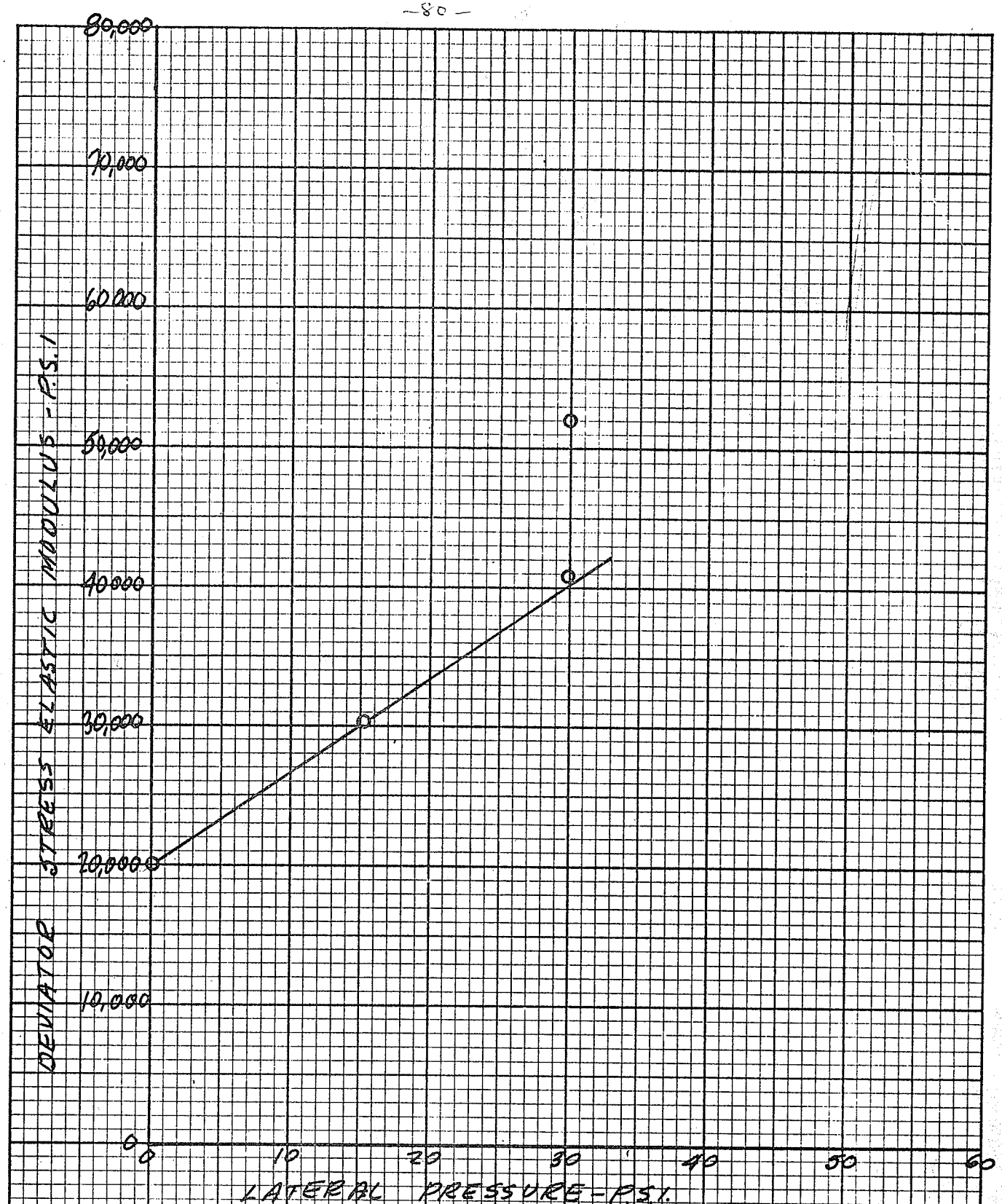


FIG 13 EFFECT OF LATERAL PRESSURE ON ELASTIC MODULUS AT 30 PER CENT OF YIELD STRESS AND 75°F

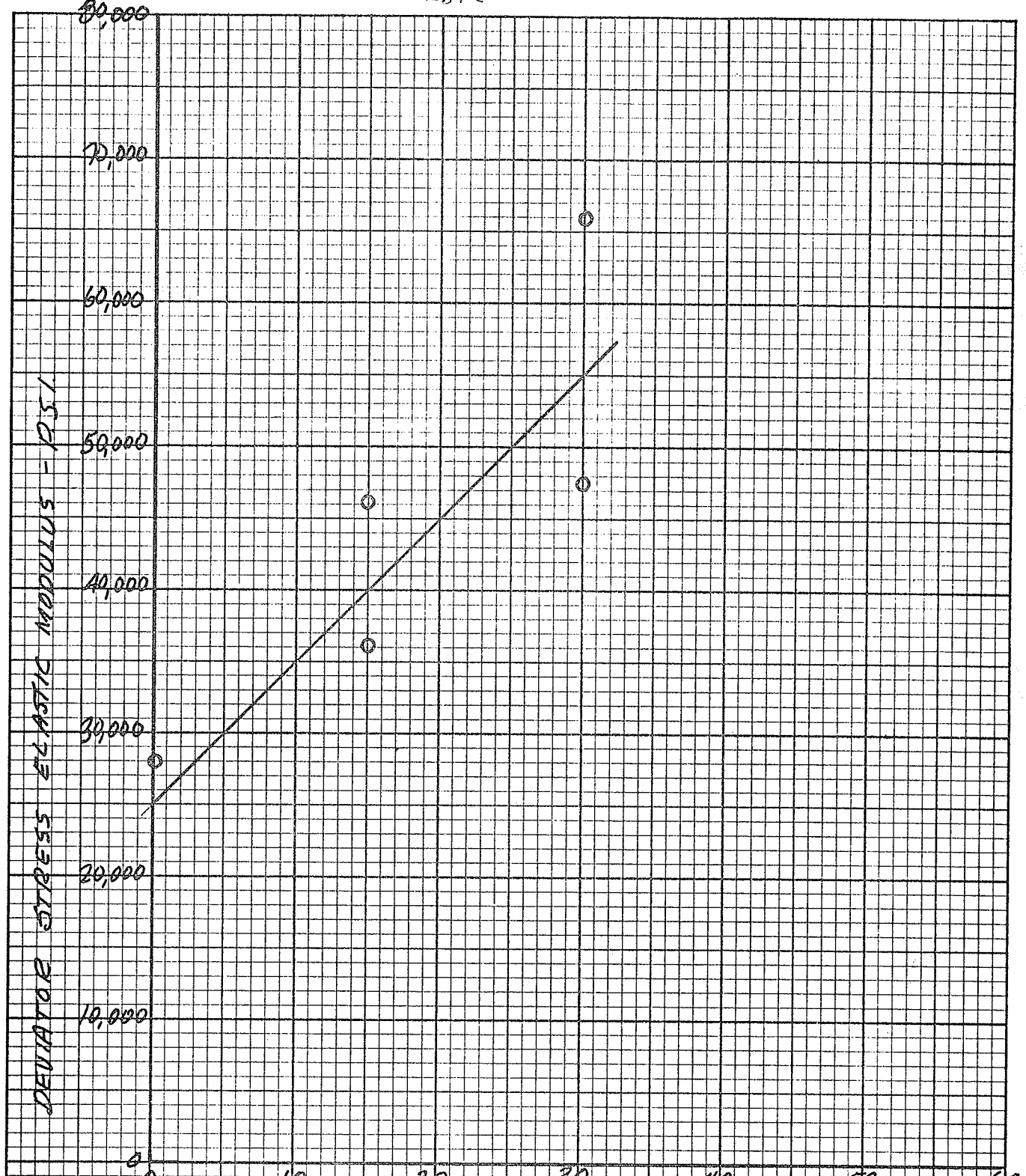


FIG 14 EFFECT OF LATERAL PRESSURE ON ELASTIC MODULUS AT 60 PER CENT OF YIELD STRESS AND 75 °F

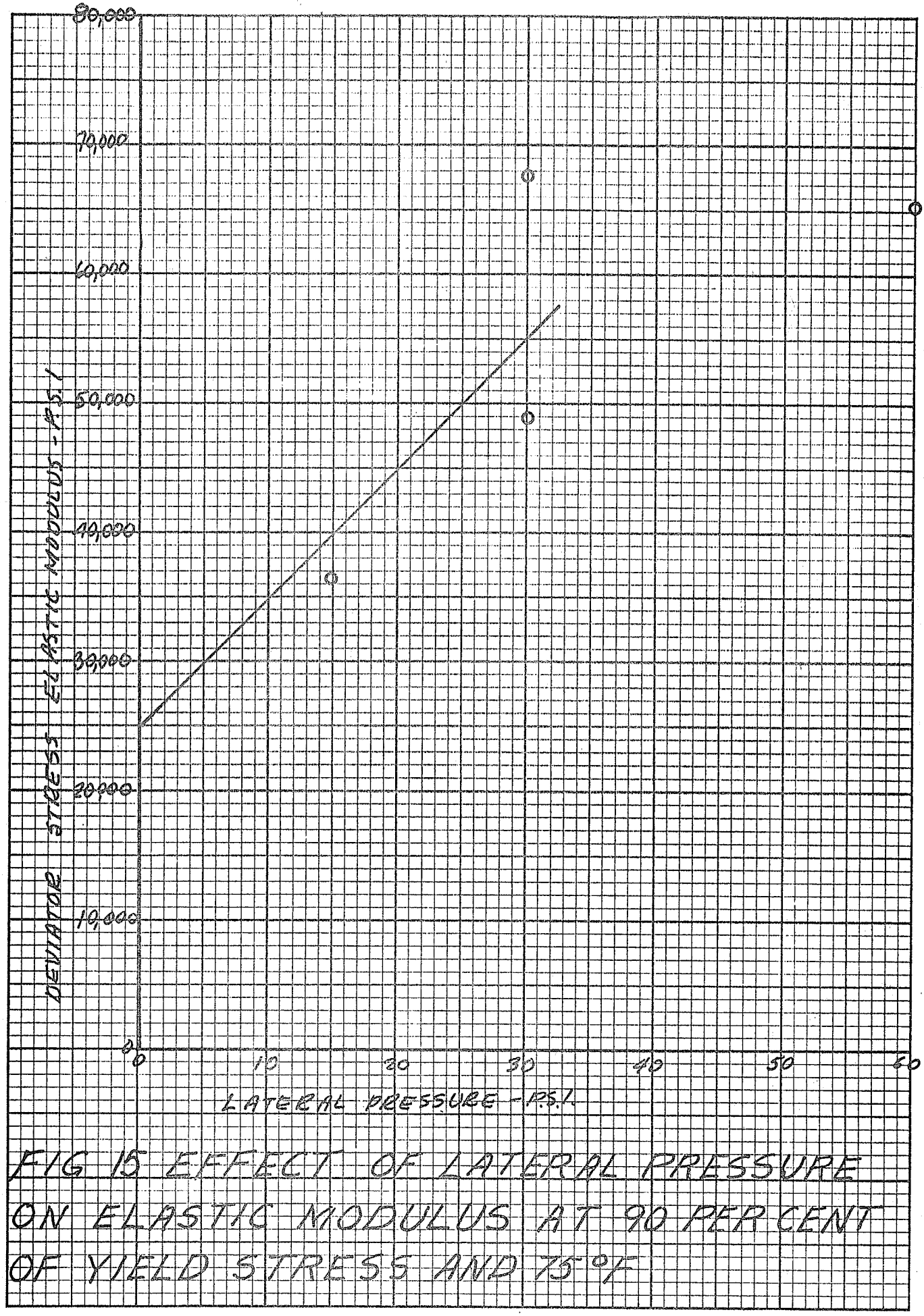


FIG 15 EFFECT OF LATERAL PRESSURE ON ELASTIC MODULUS AT 90 PER CENT OF YIELD STRESS AND 75°F

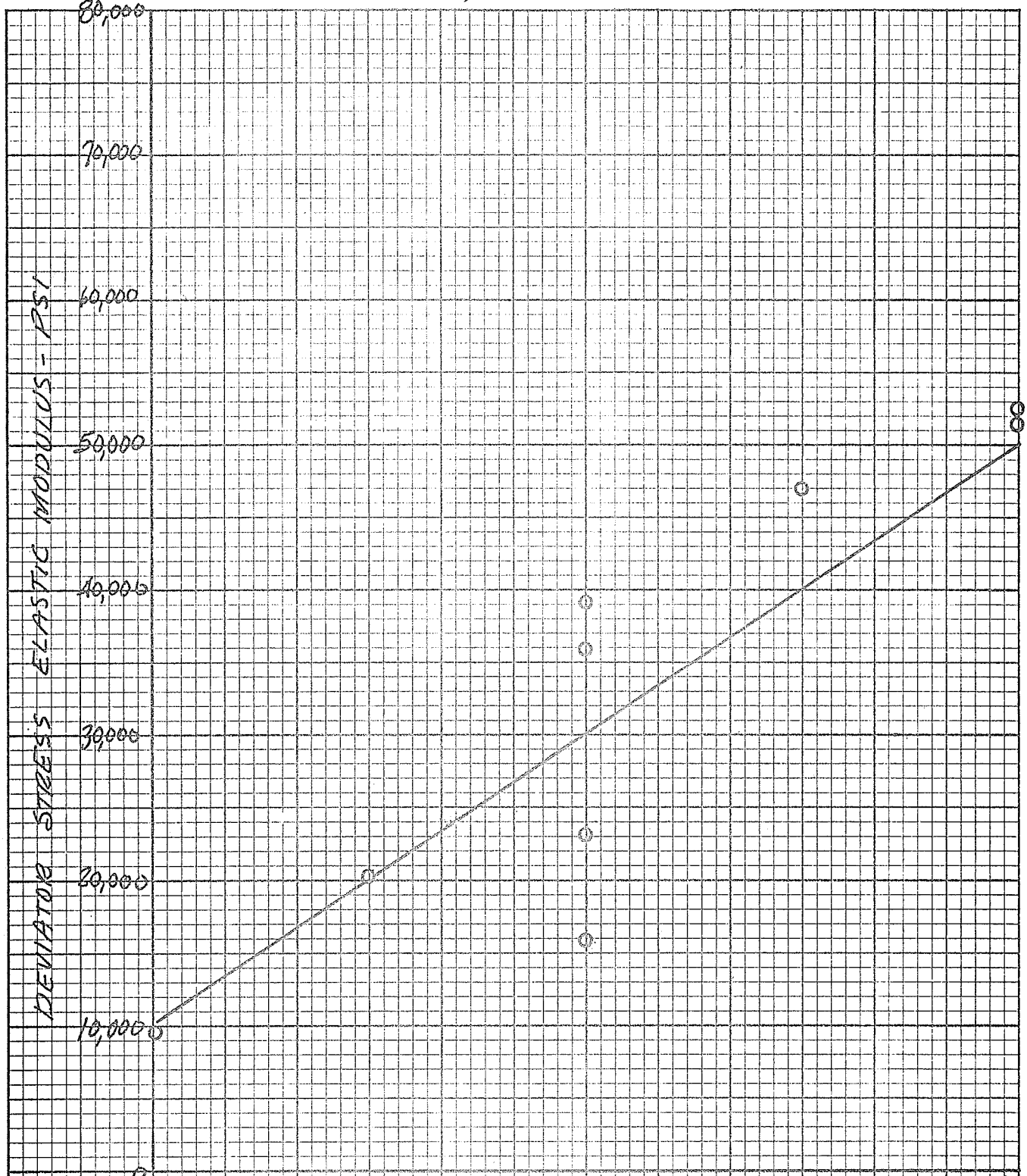


FIG 16 EFFECT OF LATERAL PRESSURE ON ELASTIC MODULUS AT 30 PER CENT OF YIELD STRESS AND 120°F

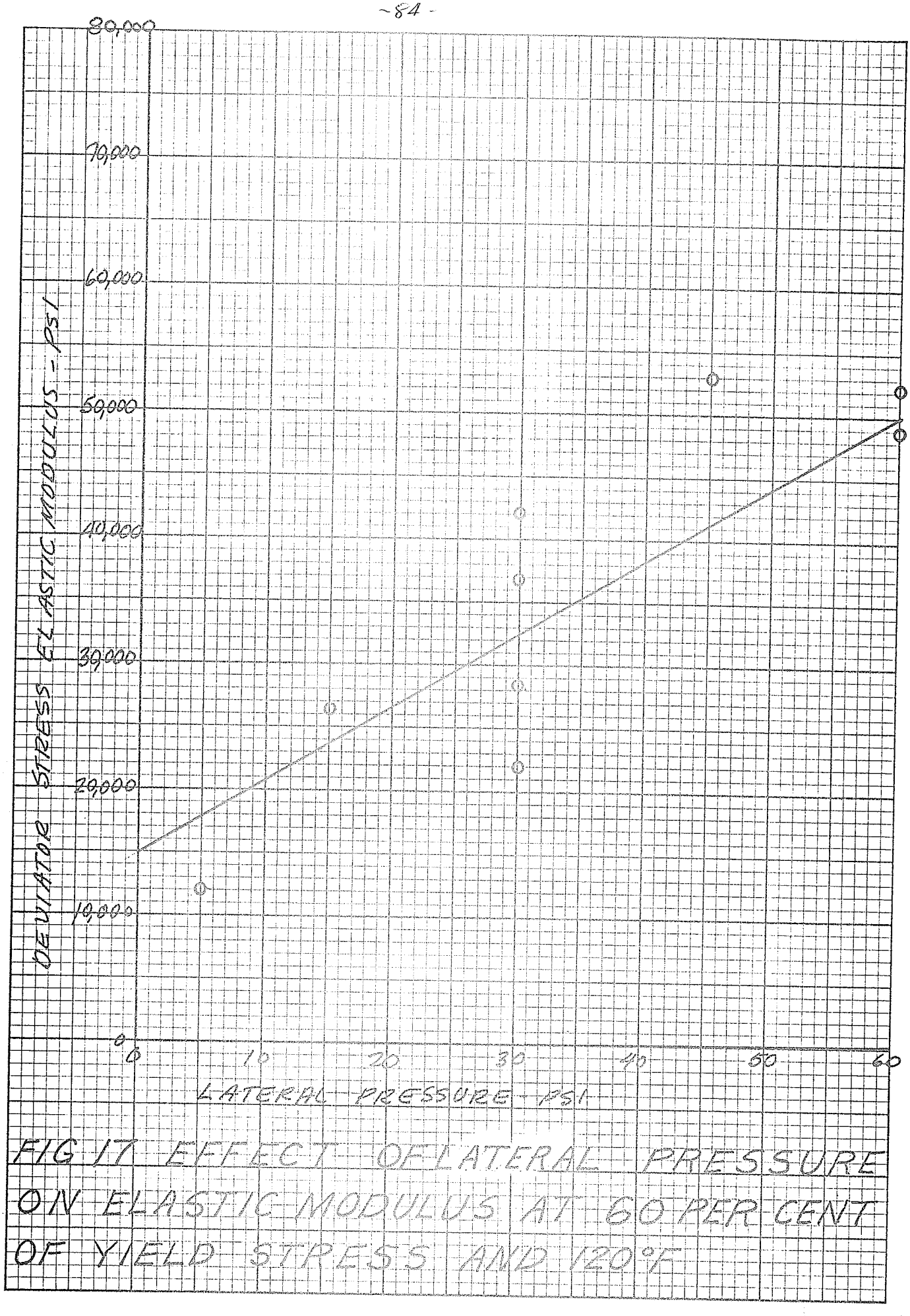


FIG 17 EFFECT OF LATERAL PRESSURE ON ELASTIC MODULUS AT 60 PER CENT OF YIELD STRESS AND 120°F

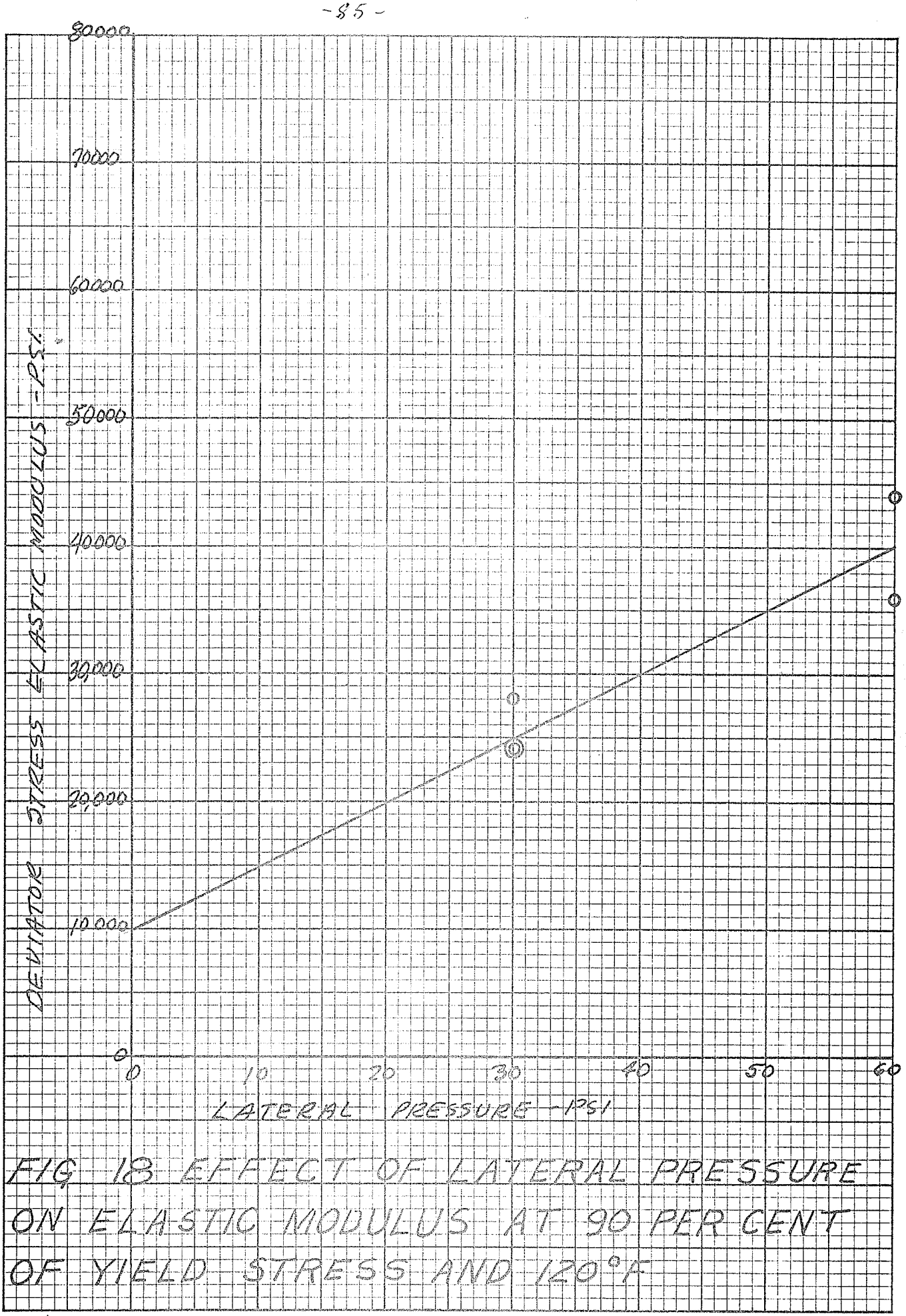


FIG 18 EFFECT OF LATERAL PRESSURE ON ELASTIC MODULUS AT 90 PER CENT OF YIELD STRESS AND 120°F

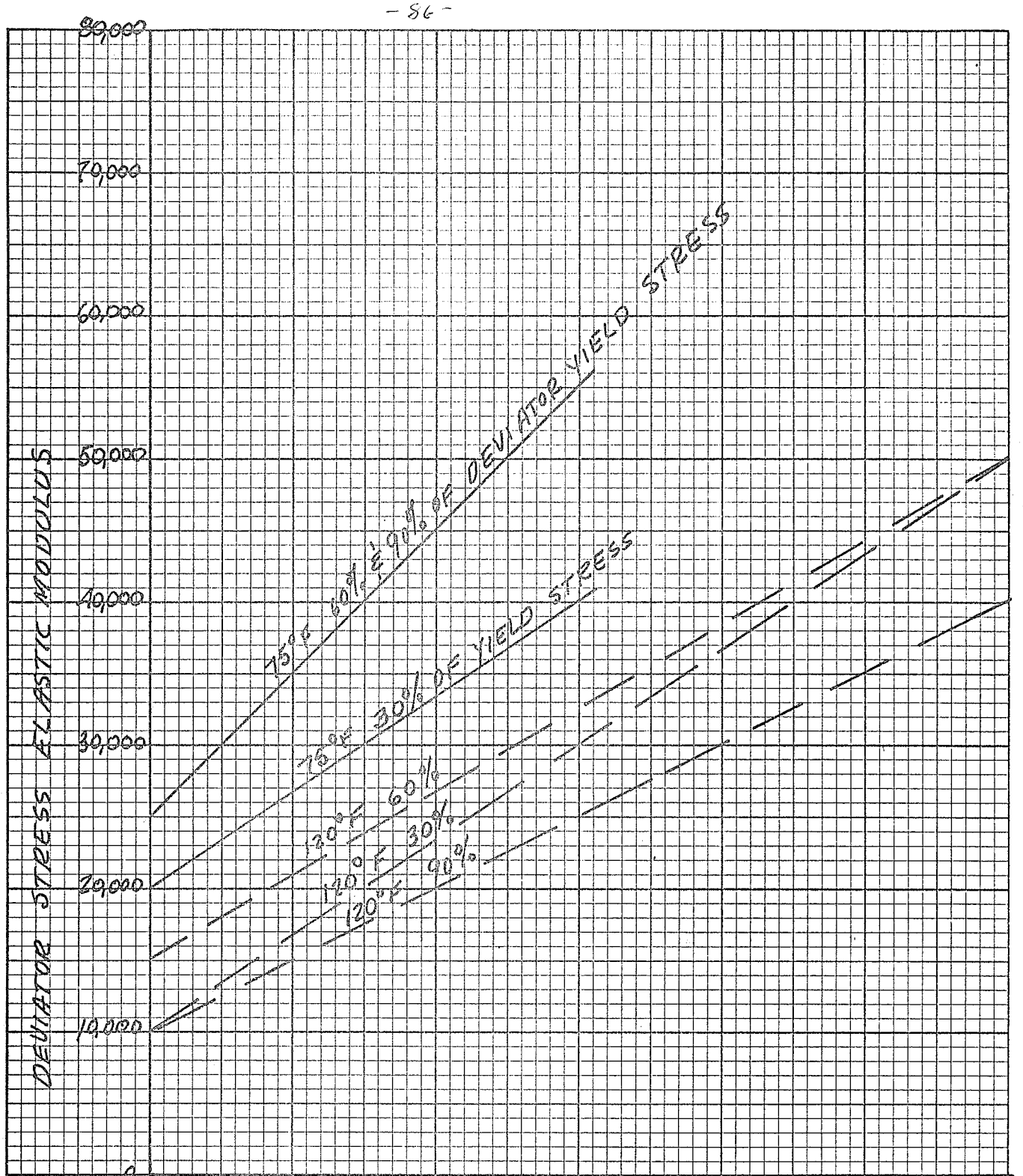


FIG 19 SUMMARY OF EFFECT OF LATERAL PRESSURE ON ELASTIC MODULUS UNDER VARIOUS TEST CONDITIONS

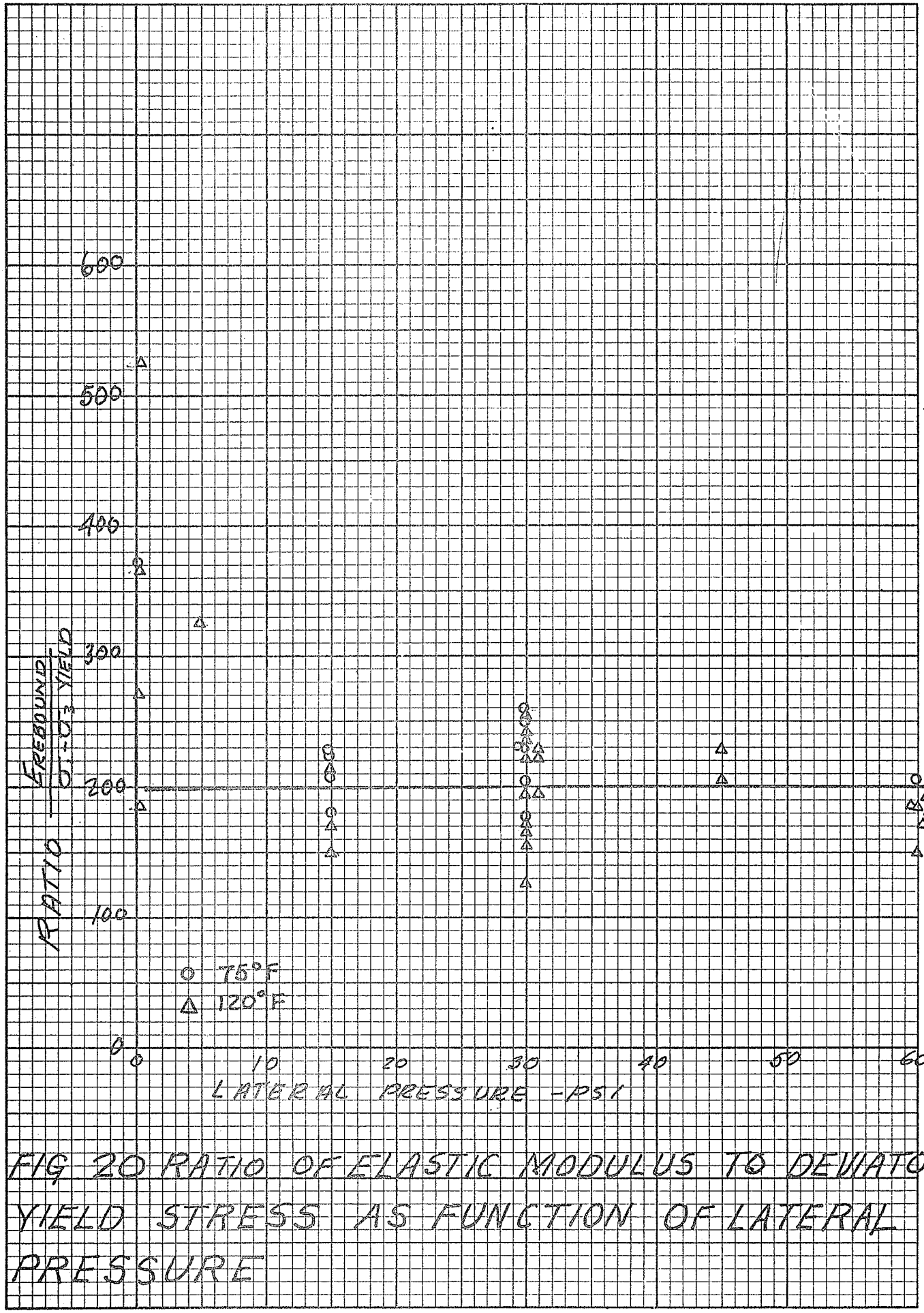


FIG 20 RATIO OF ELASTIC MODULUS TO DEVIATOR YIELD STRESS AS FUNCTION OF LATERAL PRESSURE

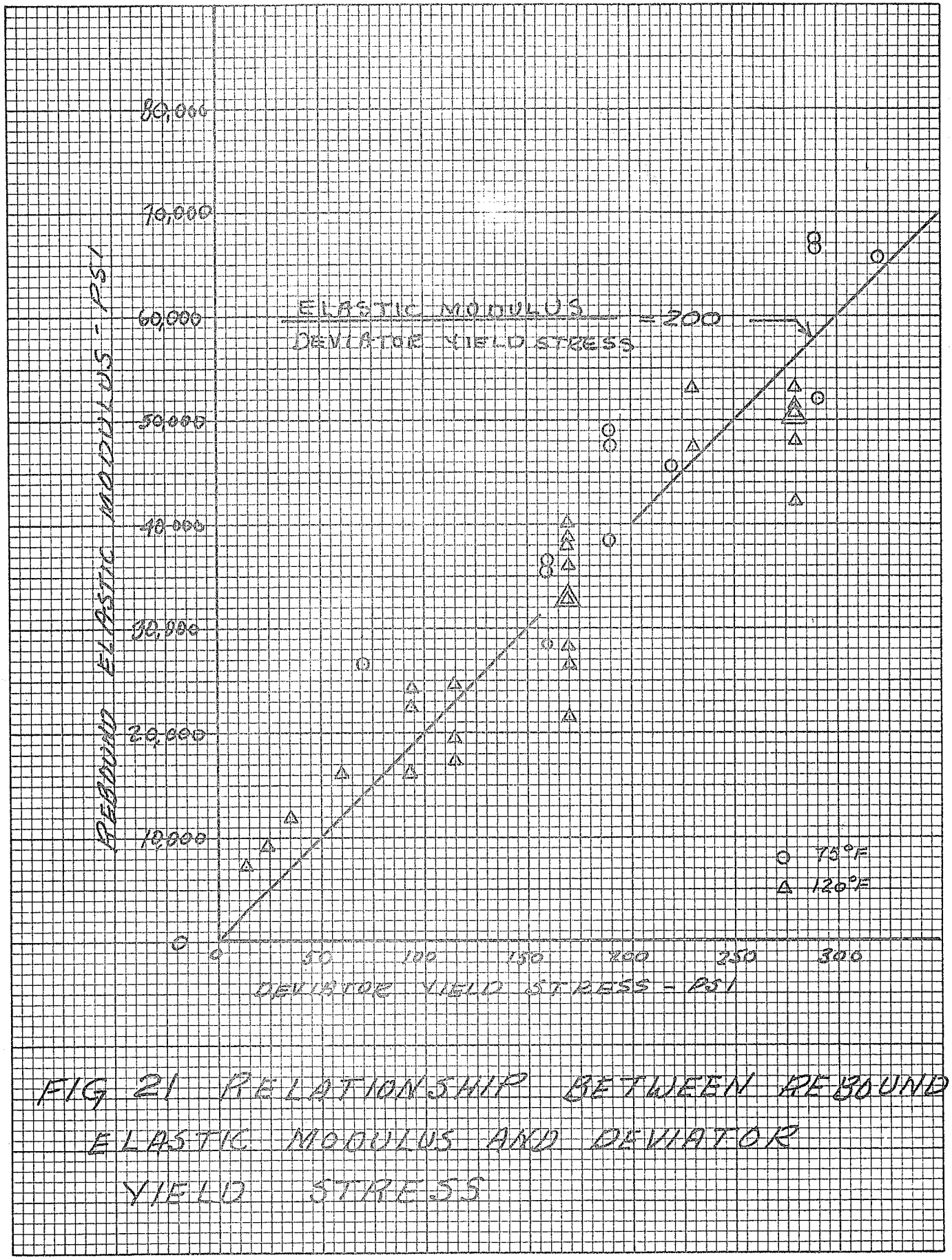


FIG 21 RELATIONSHIP BETWEEN REBOUND ELASTIC MODULUS AND DEVIATOR YIELD STRESS

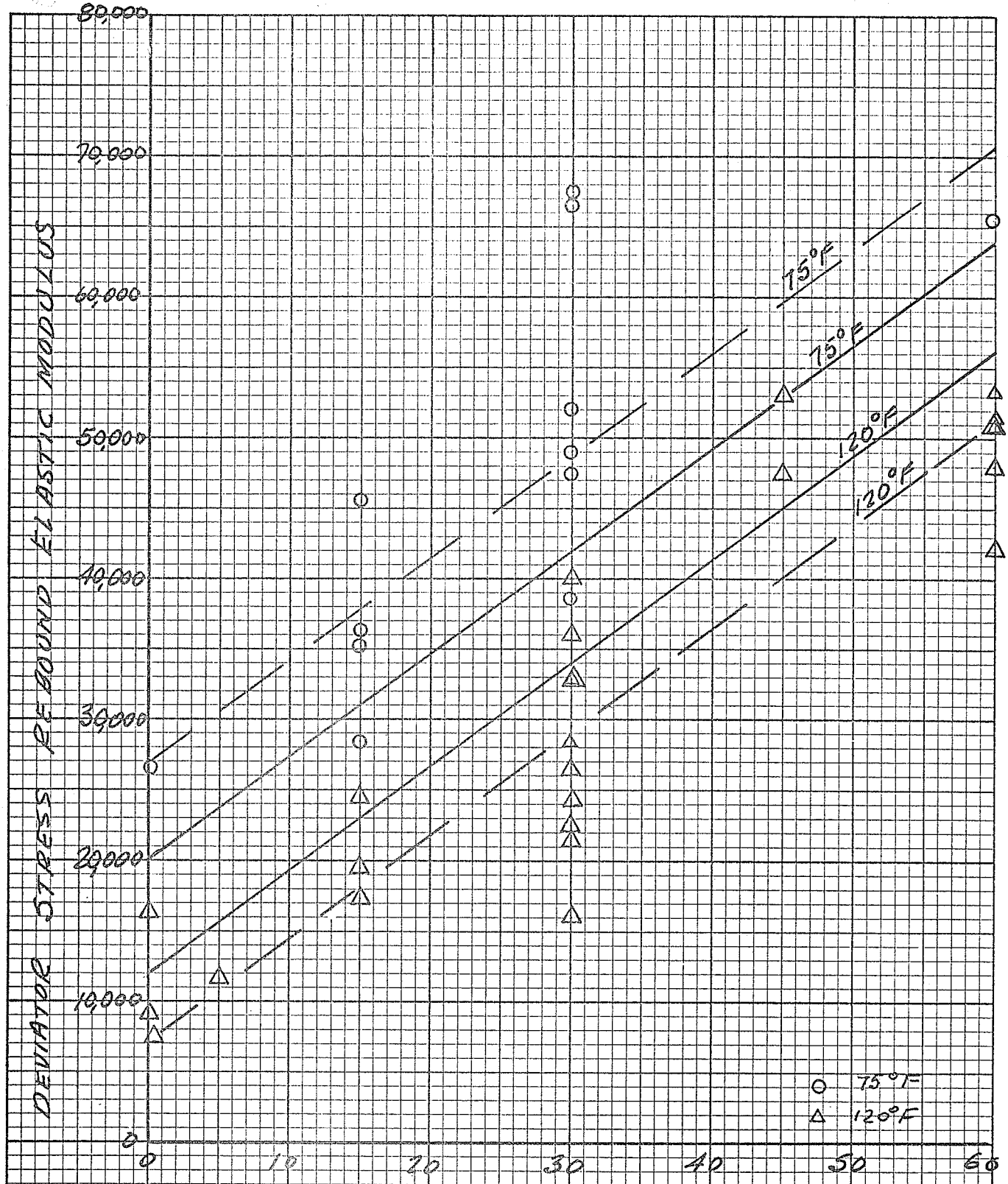


FIG 22 EFFECT OF TEST TEMPERATURE ON DEVIATOR STRESS REBOUND ELASTIC MODULUS

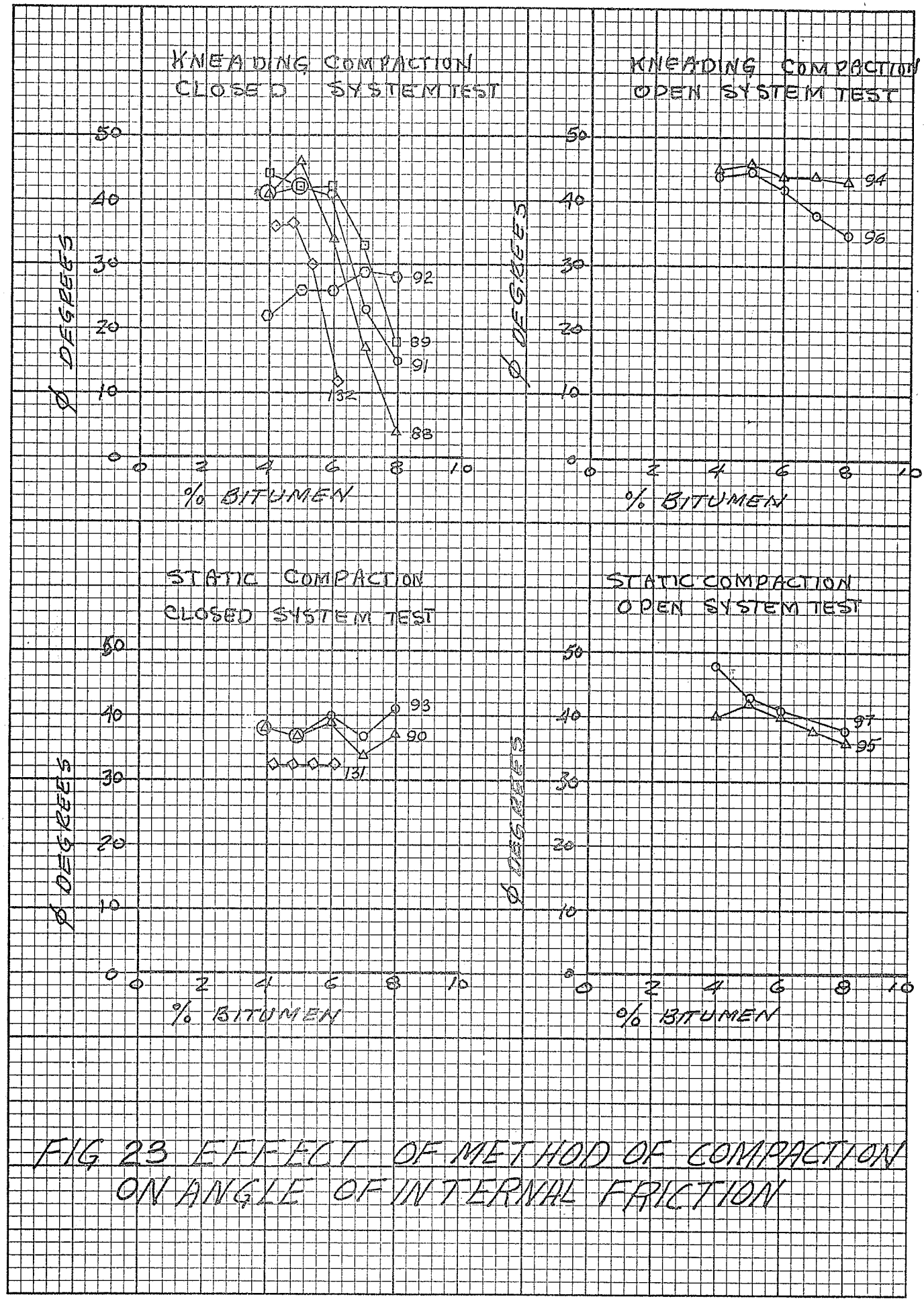


FIG 23 EFFECT OF METHOD OF COMPACTION ON ANGLE OF INTERNAL FRICTION

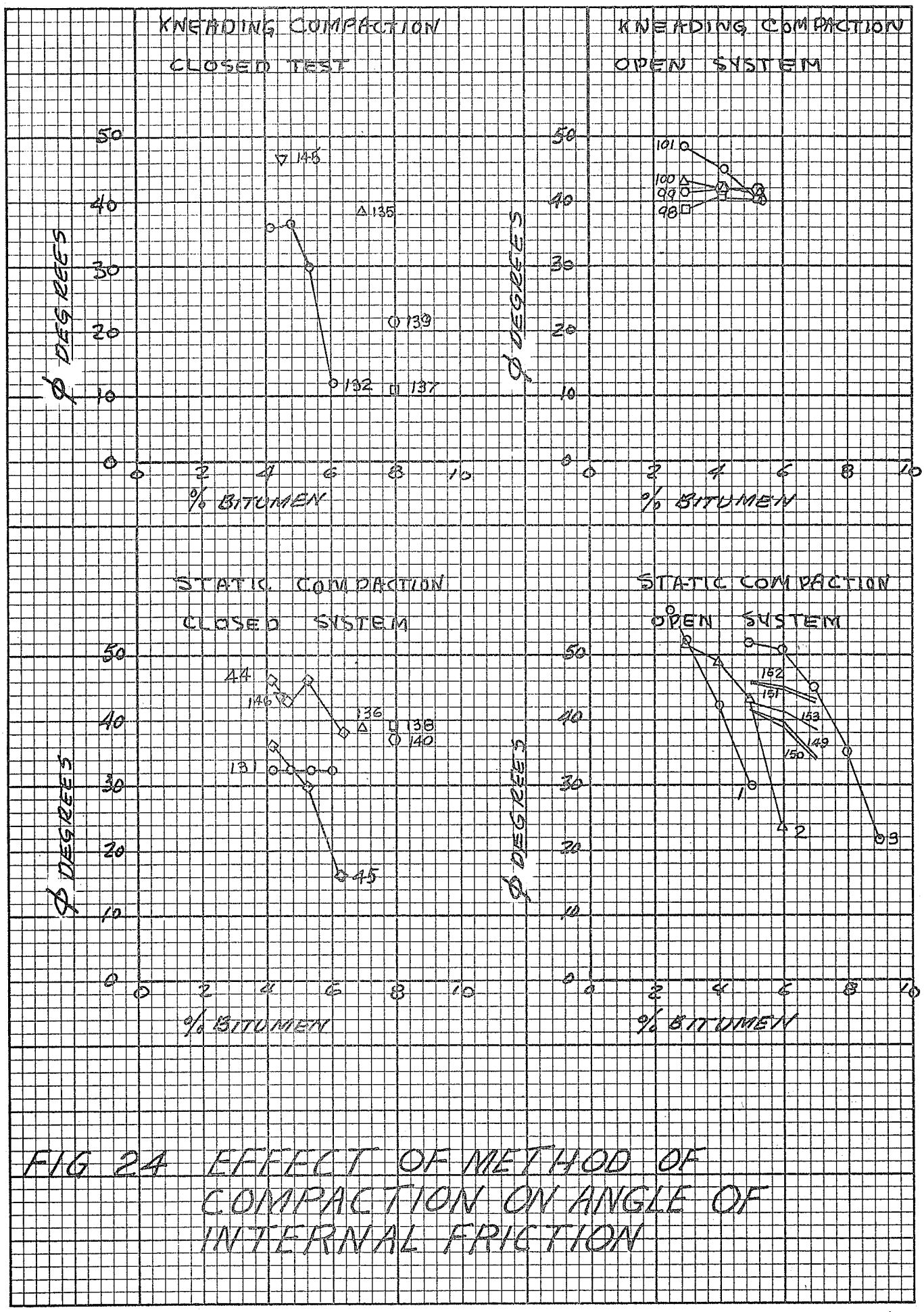


FIG 24 EFFECT OF METHOD OF COMPACTION ON ANGLE OF INTERNAL FRICTION

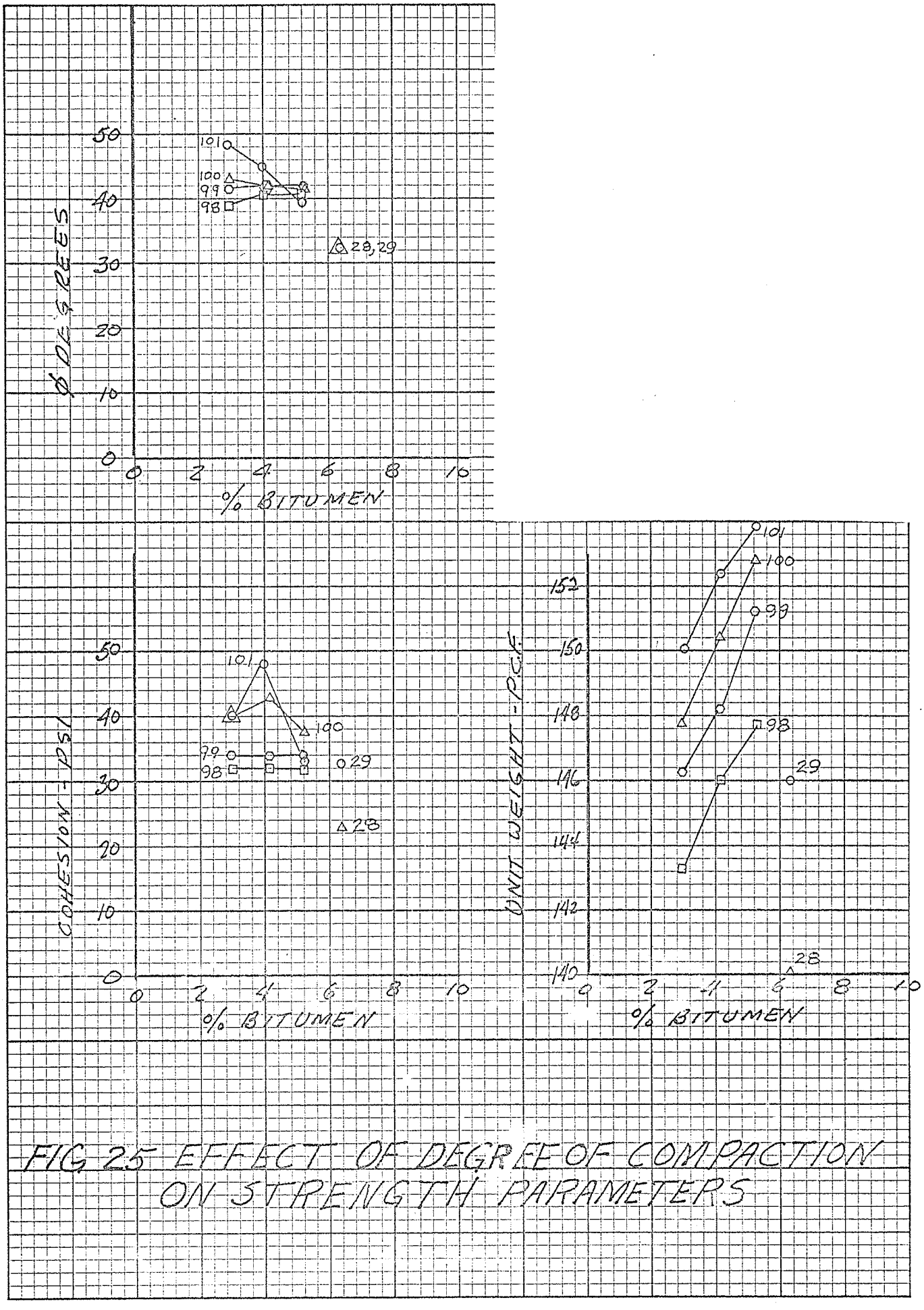


FIG 25 EFFECT OF DEGREE OF COMPACTION ON STRENGTH PARAMETERS

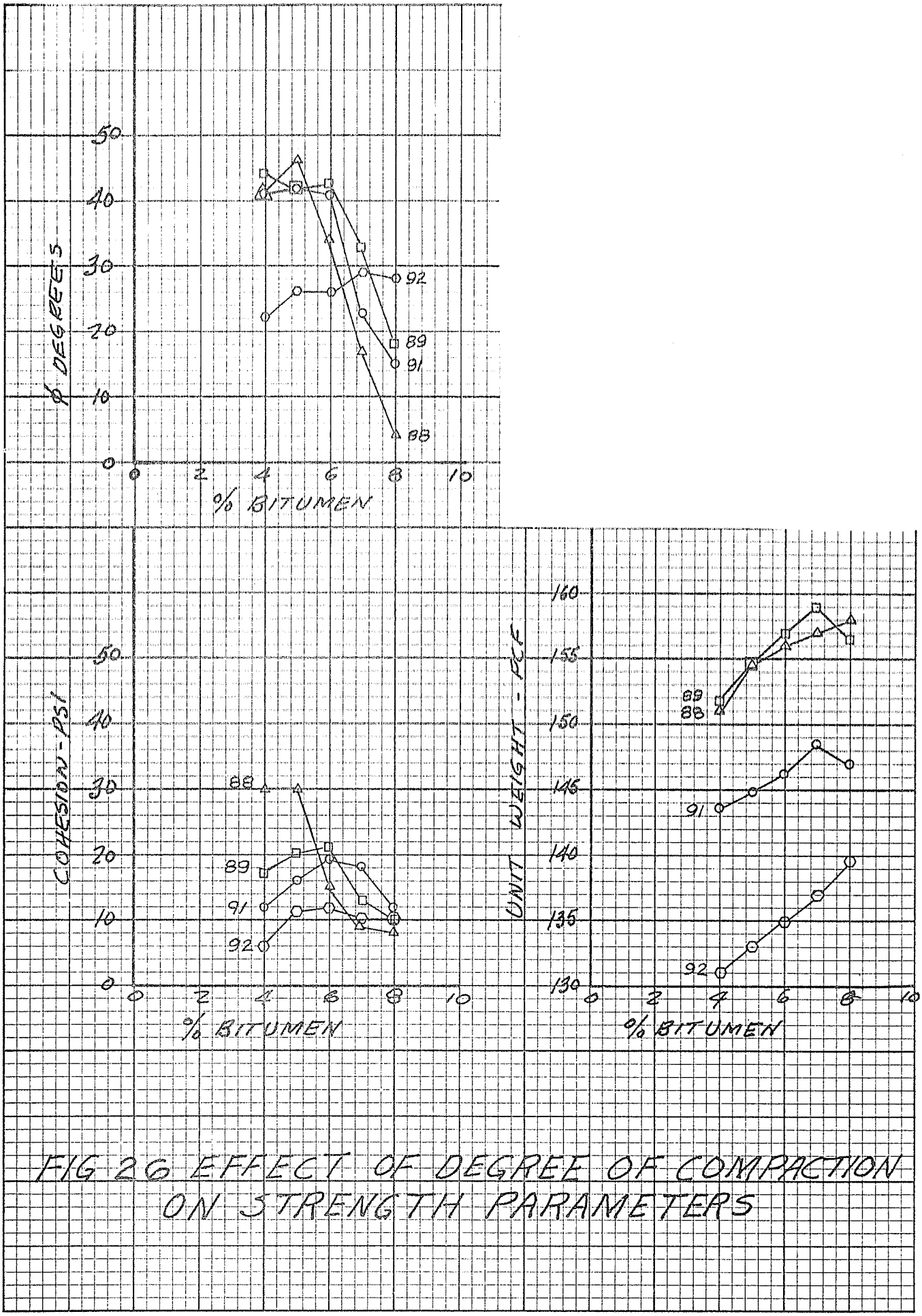


FIG 26 EFFECT OF DEGREE OF COMPACTION ON STRENGTH PARAMETERS

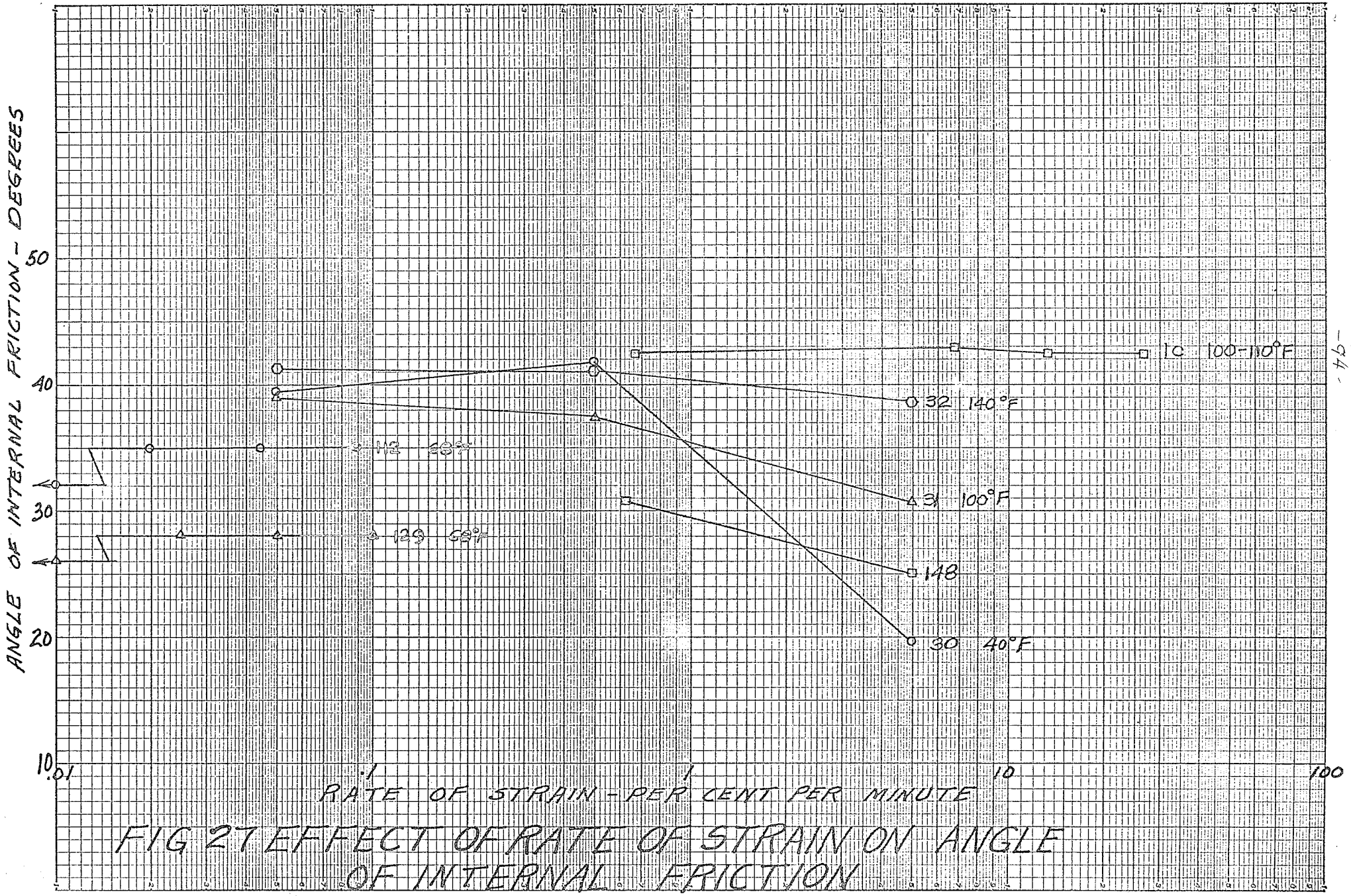


FIG 27 EFFECT OF RATE OF STRAIN ON ANGLE OF INTERNAL FRICTION

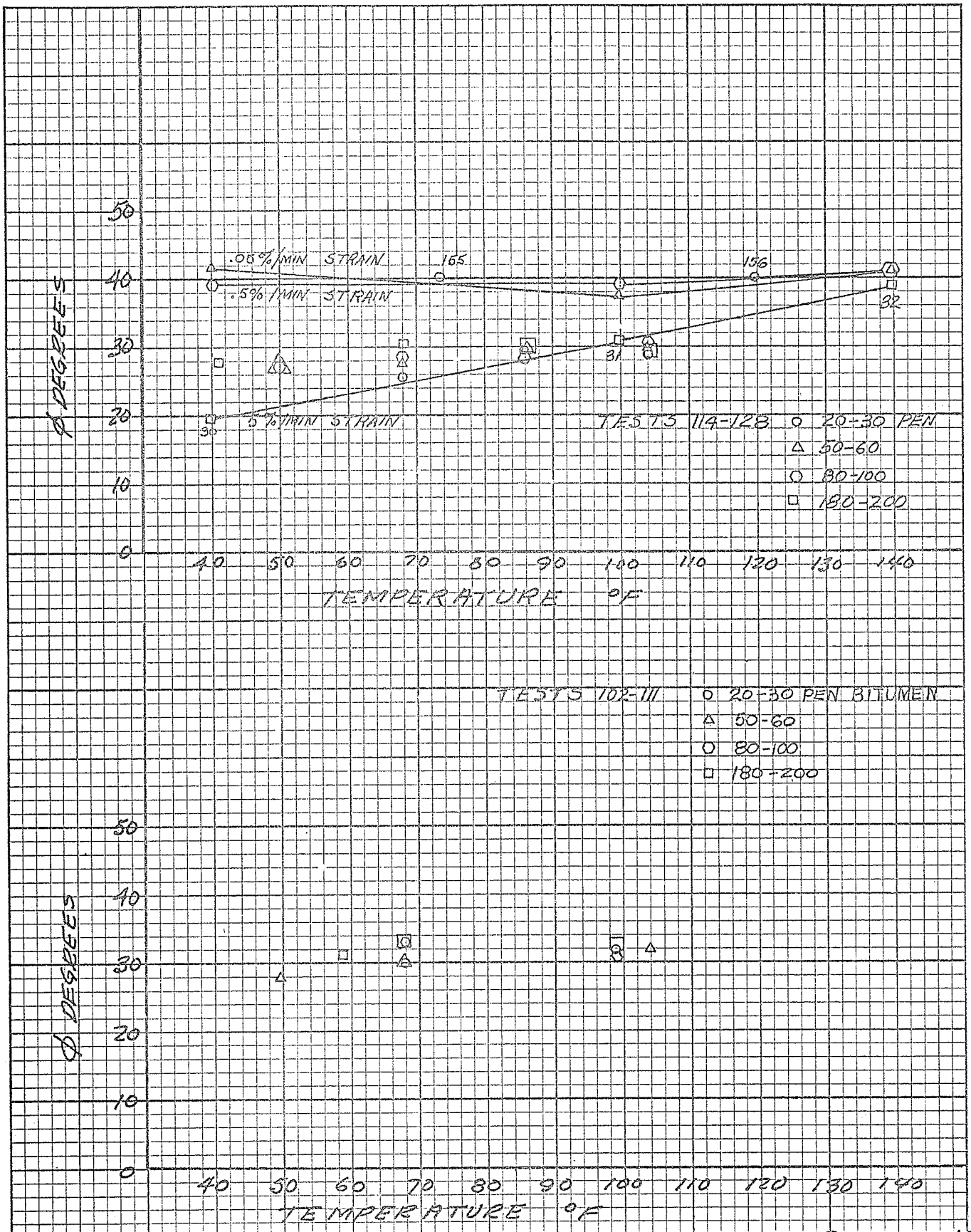


FIG 28 EFFECT OF TEST TEMPERATURE ON ANGLE OF INTERNAL FRICTION

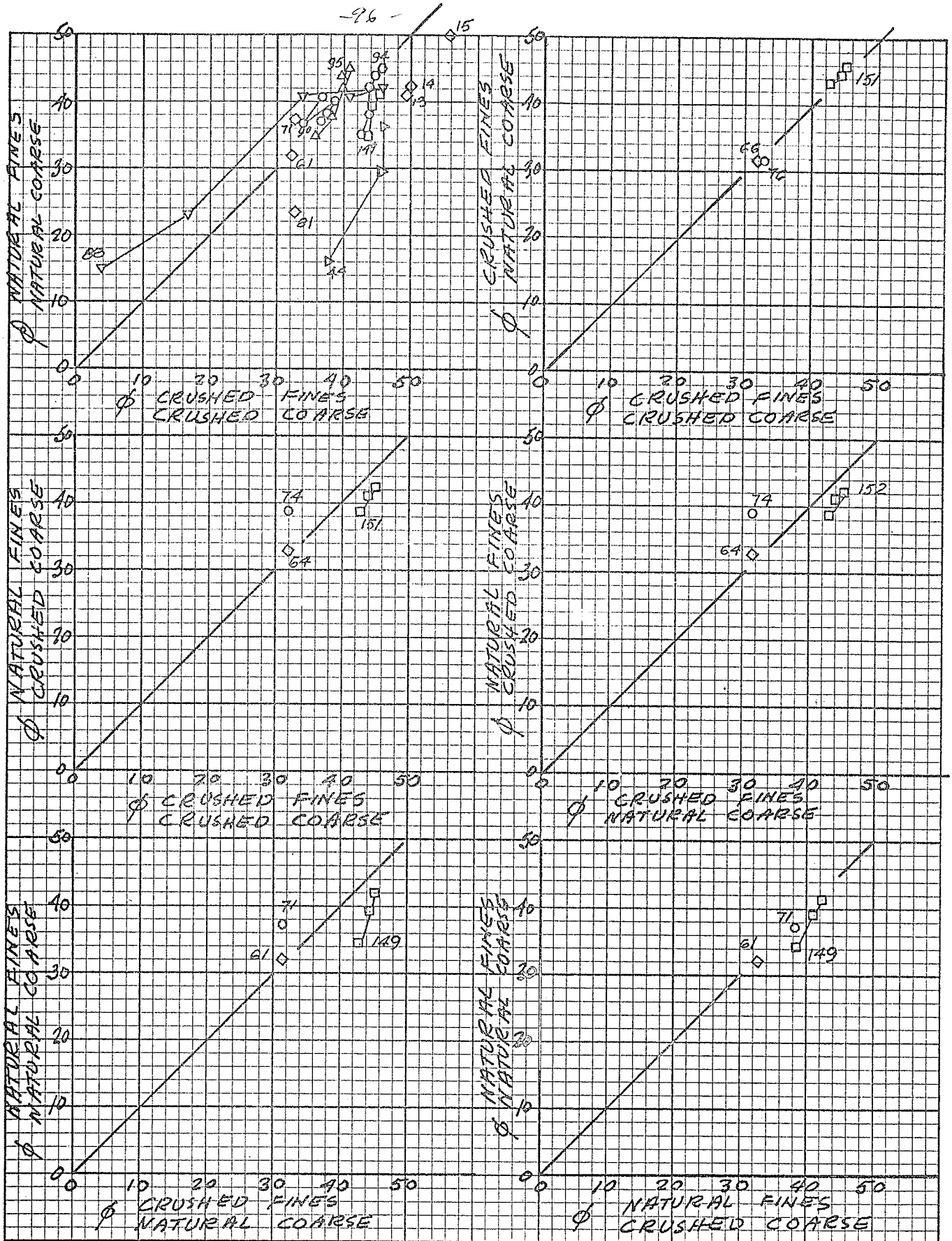


FIG 29 EFFECT OF PARTICLE SHAPE AND SURFACE TEXTURE ON ANGLE OF INTERNAL FRICTION

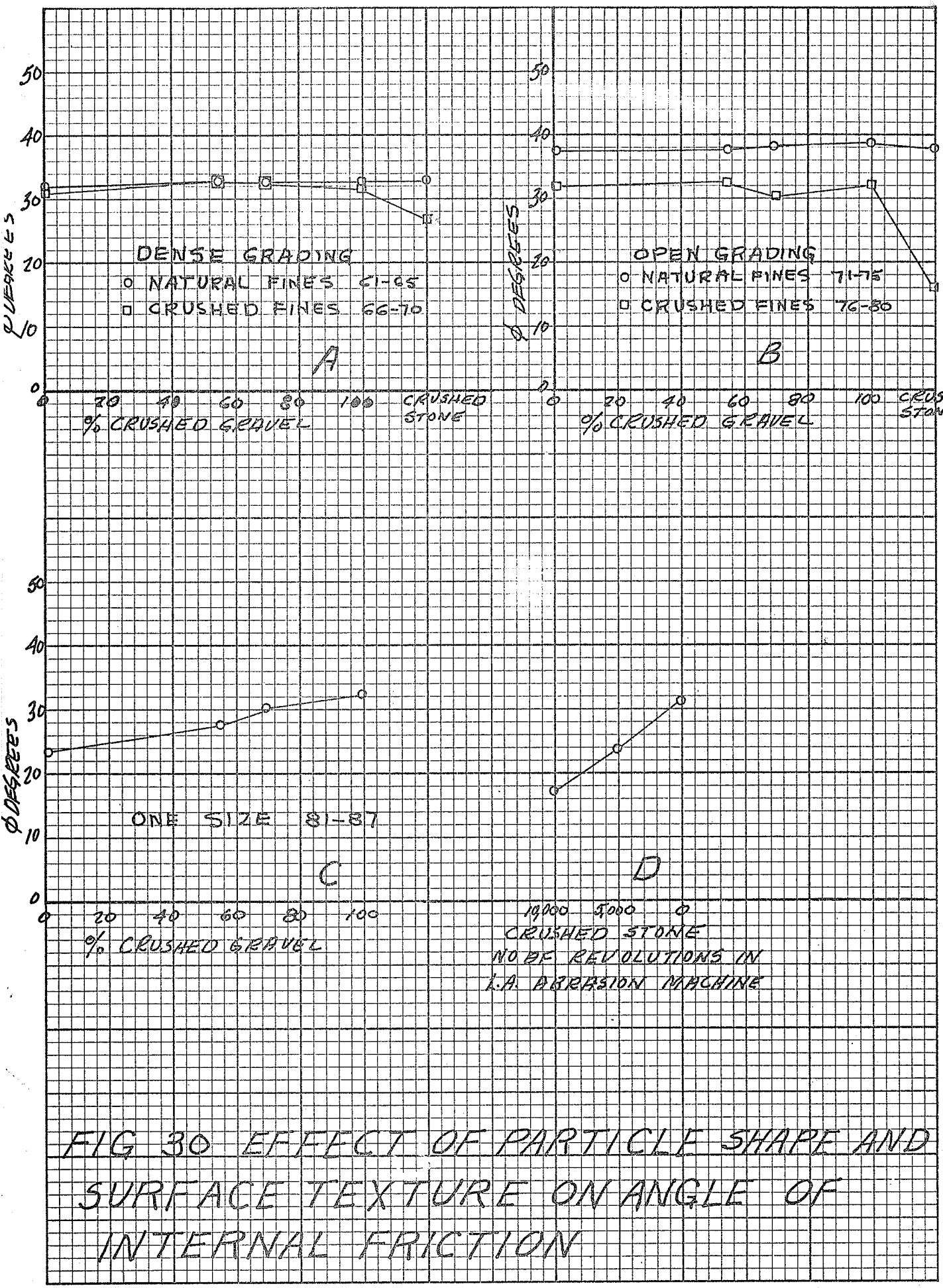


FIG 30 EFFECT OF PARTICLE SHAPE AND SURFACE TEXTURE ON ANGLE OF INTERNAL FRICTION

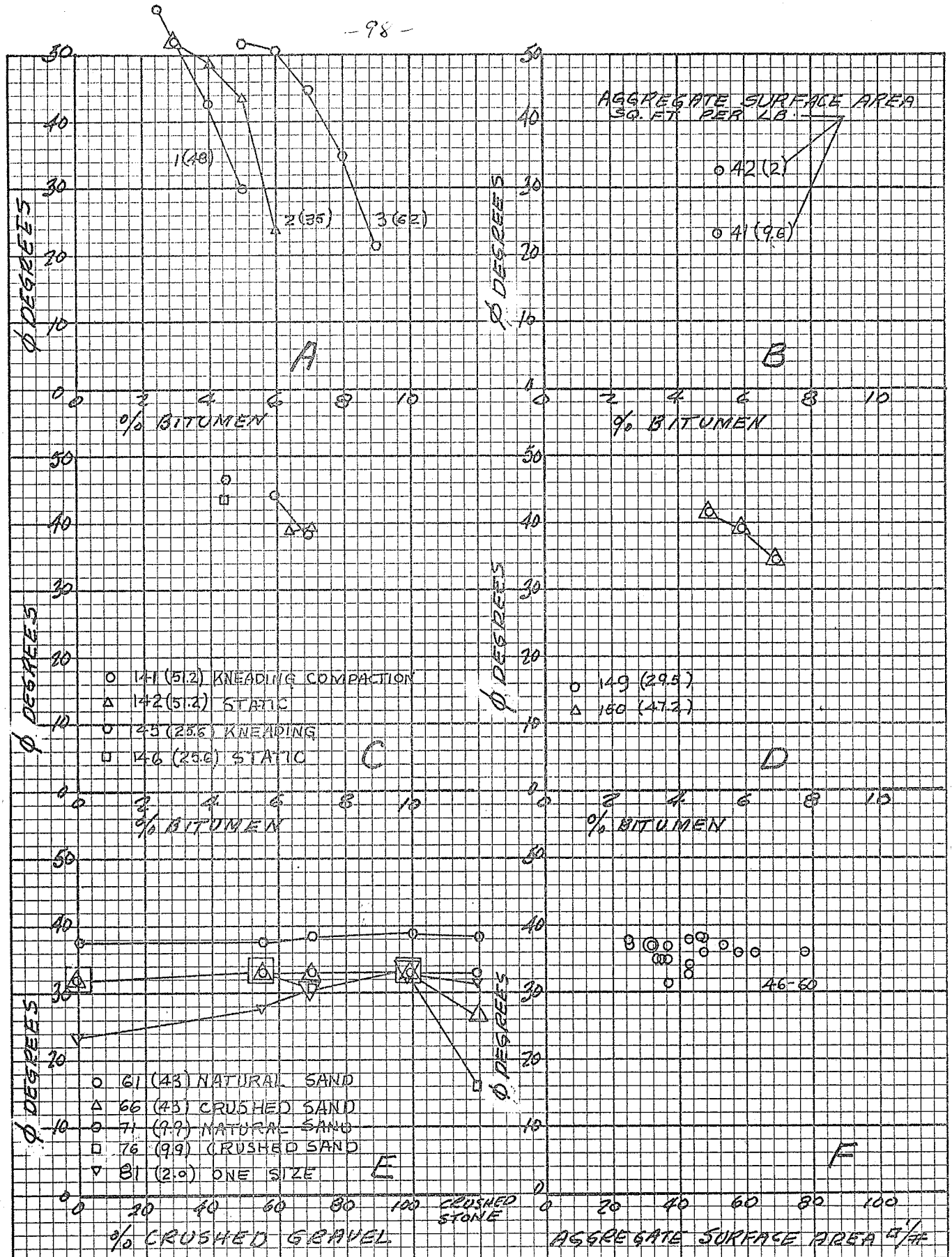


FIG 31 EFFECT OF AGGREGATE GRADING ON ANGLE OF INTERNAL FRICTION

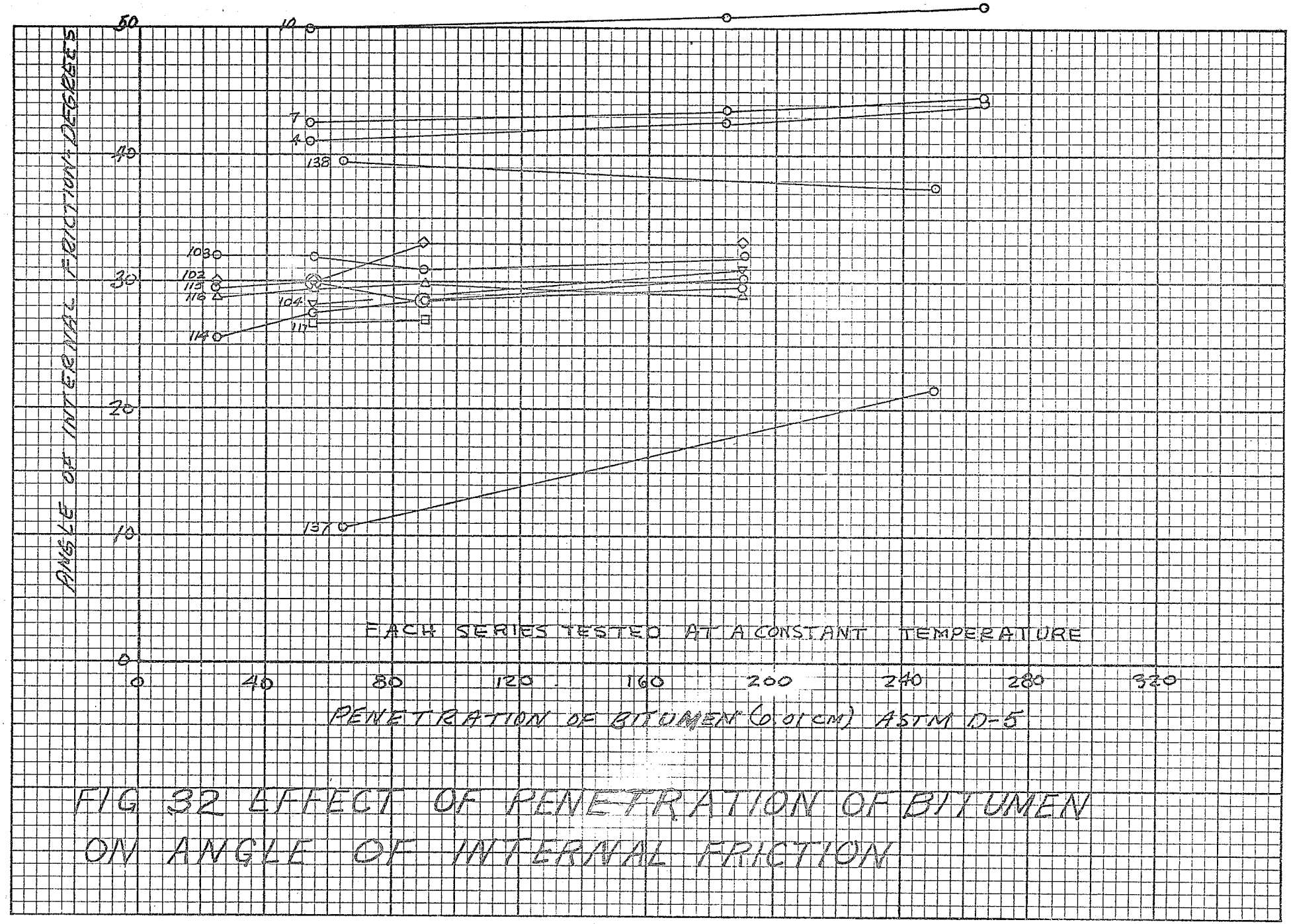


FIG 32 EFFECT OF PENETRATION OF BITUMEN ON ANGLE OF INTERNAL FRICTION

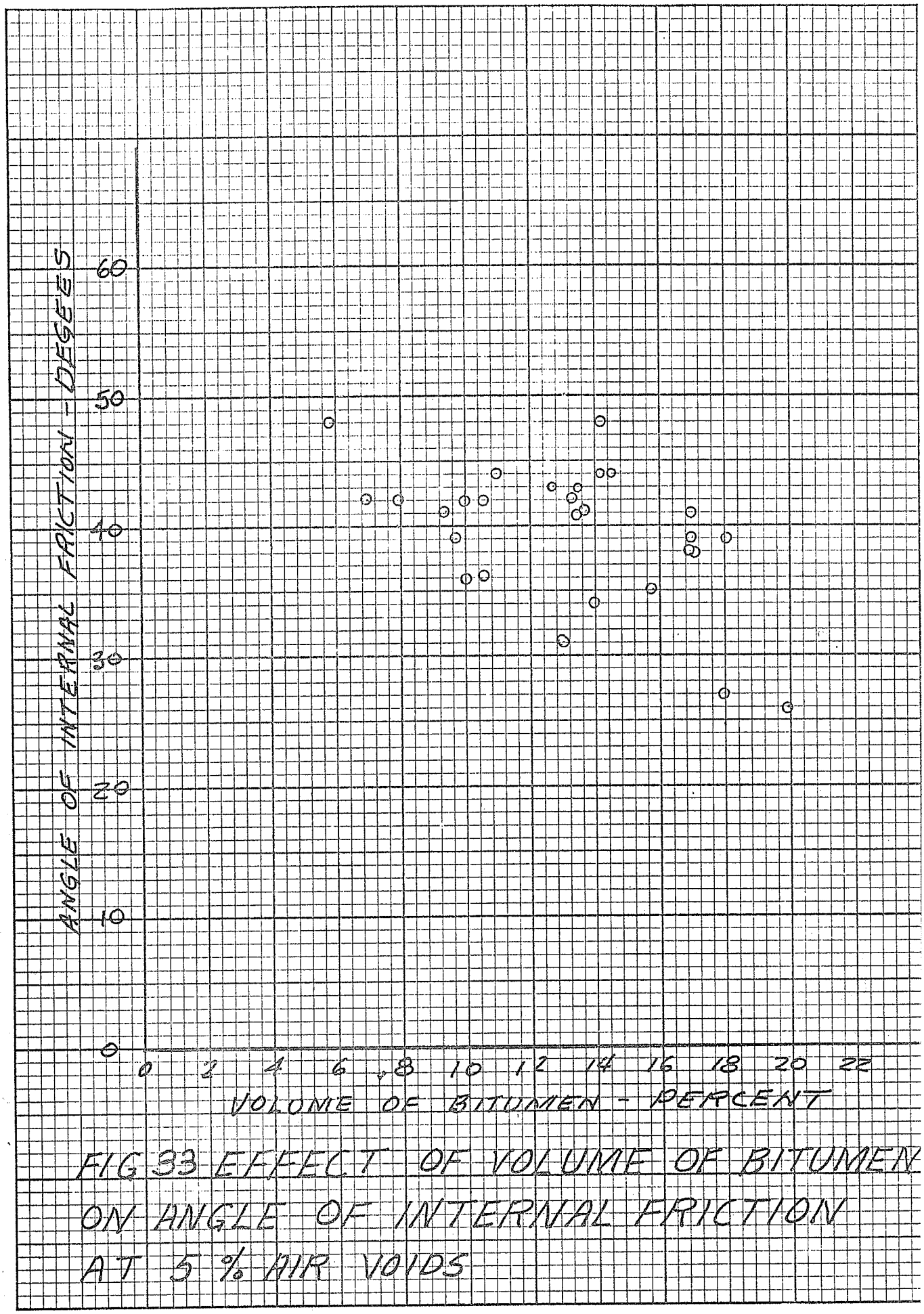


FIG 33 EFFECT OF VOLUME OF BITUMEN ON ANGLE OF INTERNAL FRICTION AT 5 % AIR VOIDS

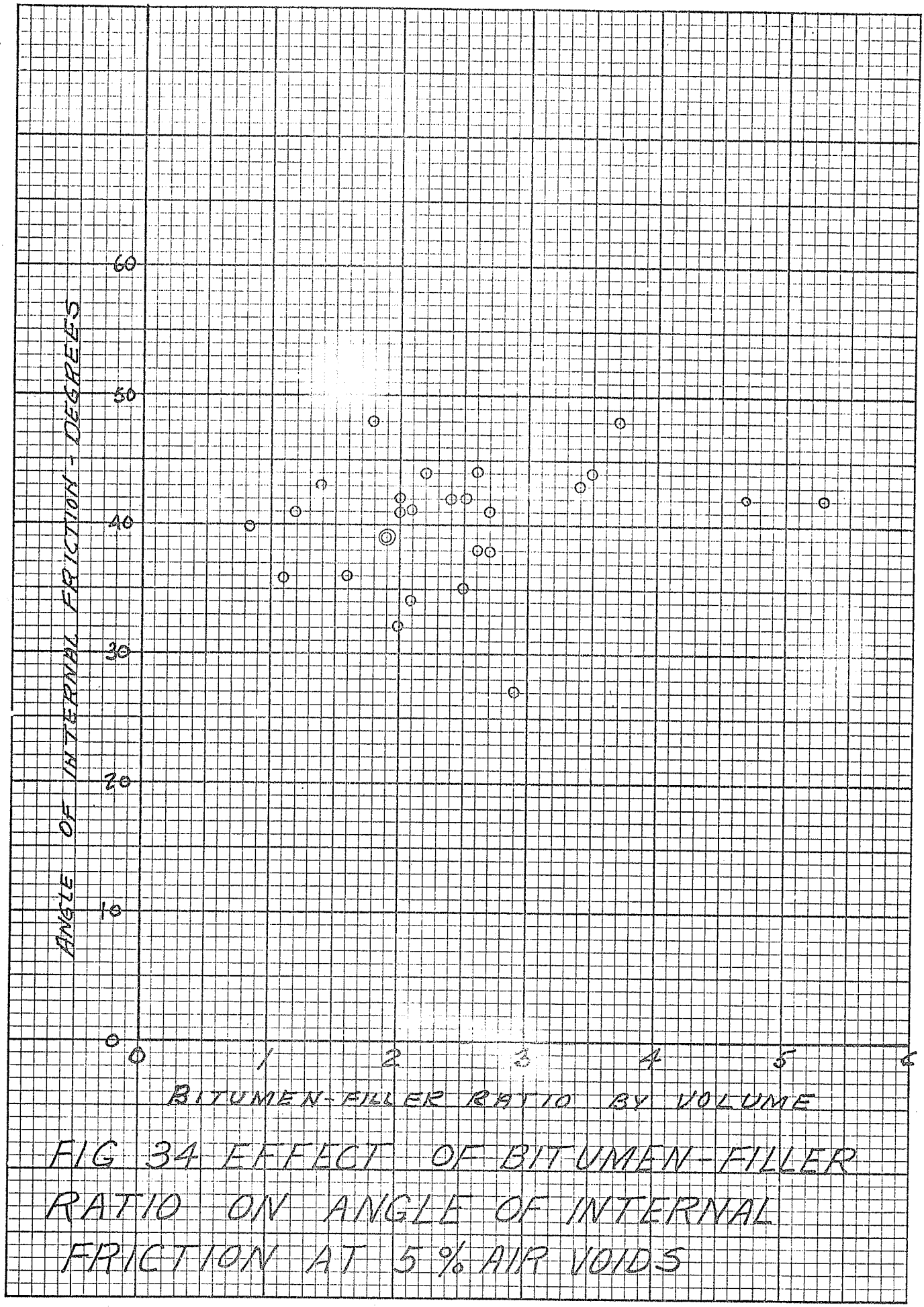


FIG 34 EFFECT OF BITUMEN-FILLER RATIO ON ANGLE OF INTERNAL FRICTION AT 5% AIR VOIDS

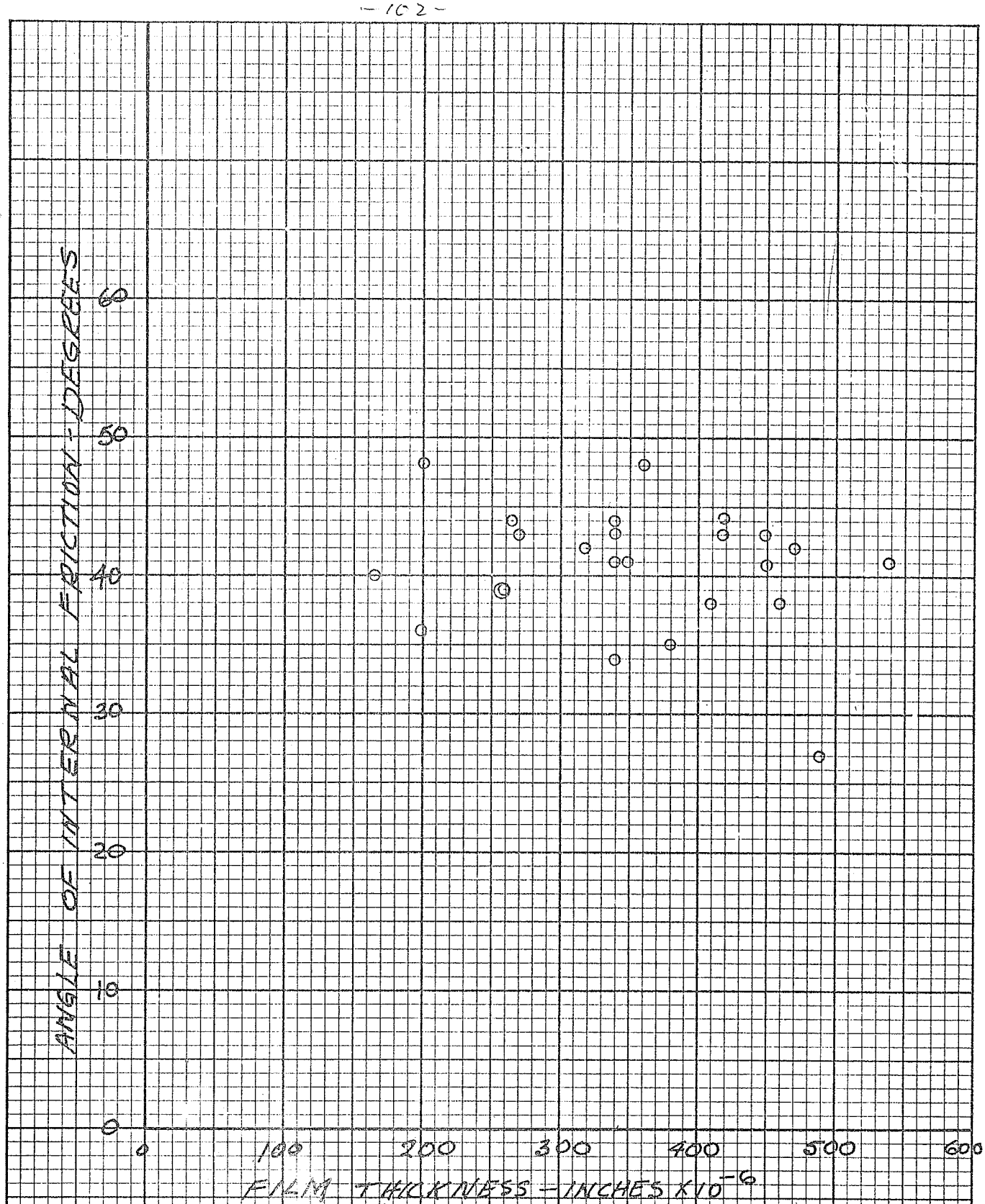


FIG 35 EFFECT OF BITUMEN FILM THICKNESS ON ANGLE OF INTERNAL FRICTION AT 5% AIR VOIDS

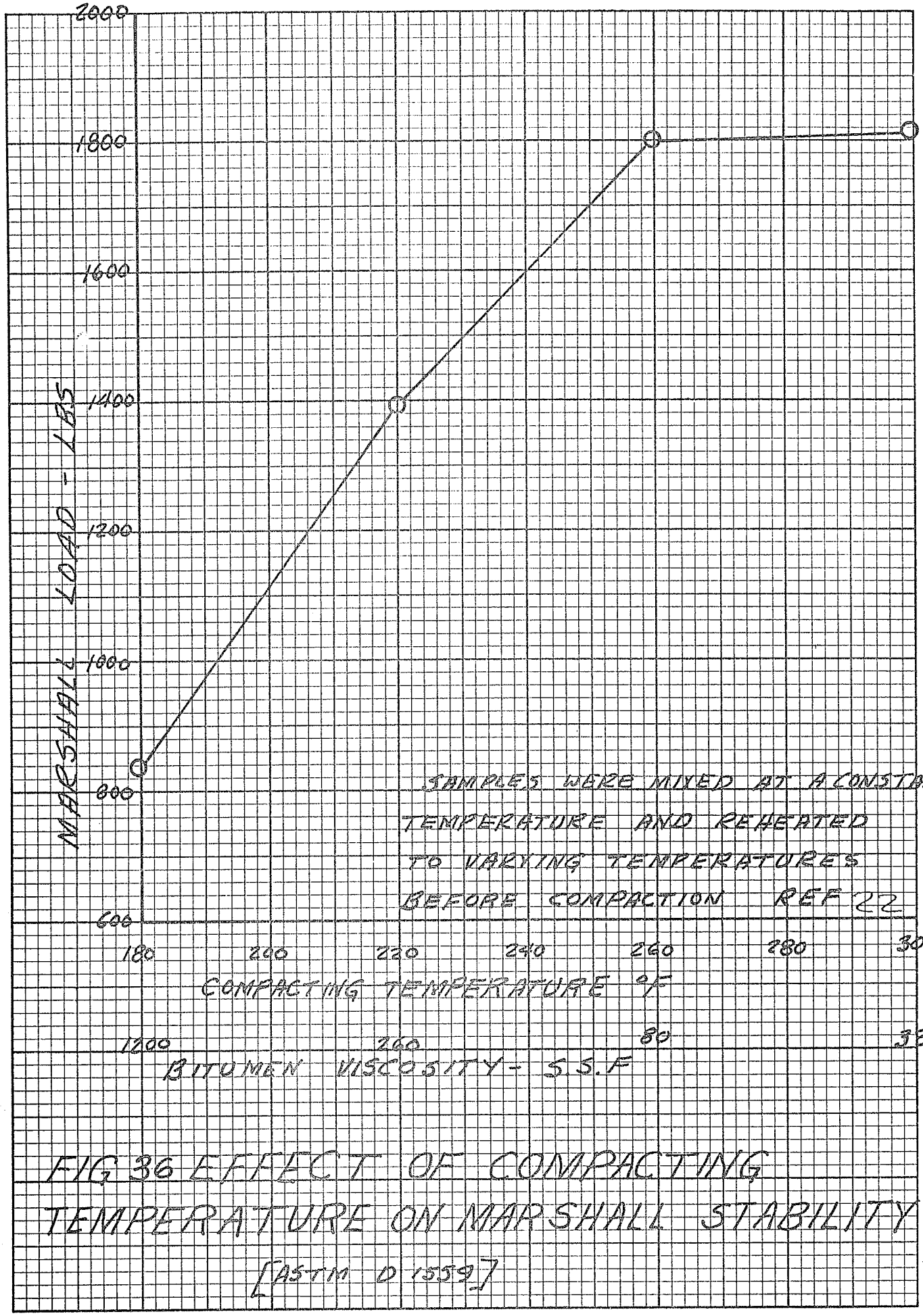


FIG 36 EFFECT OF COMPACTING TEMPERATURE ON MARSHALL STABILITY [ASTM D 1559]

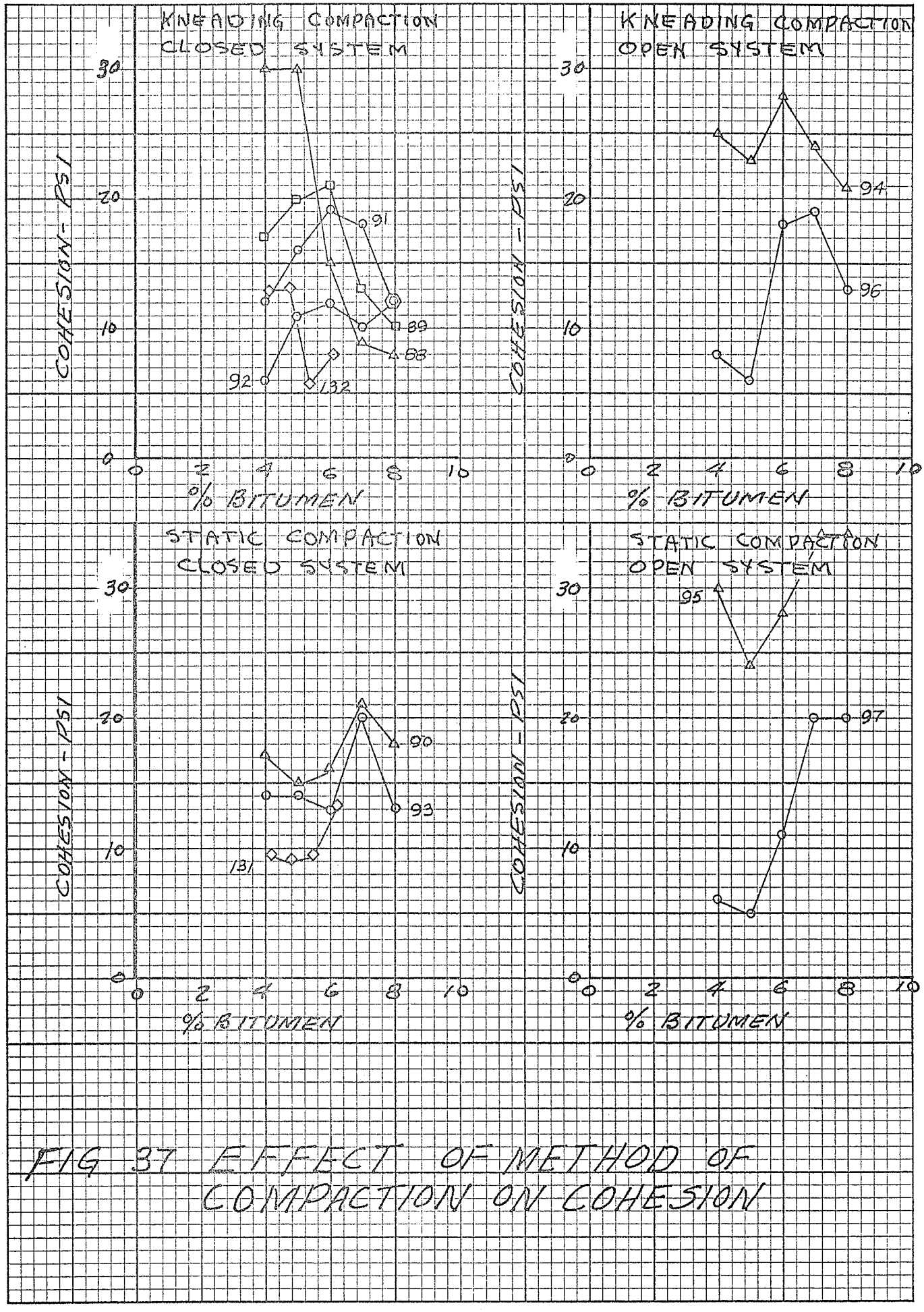


FIG 37 EFFECT OF METHOD OF COMPACTION ON COHESION

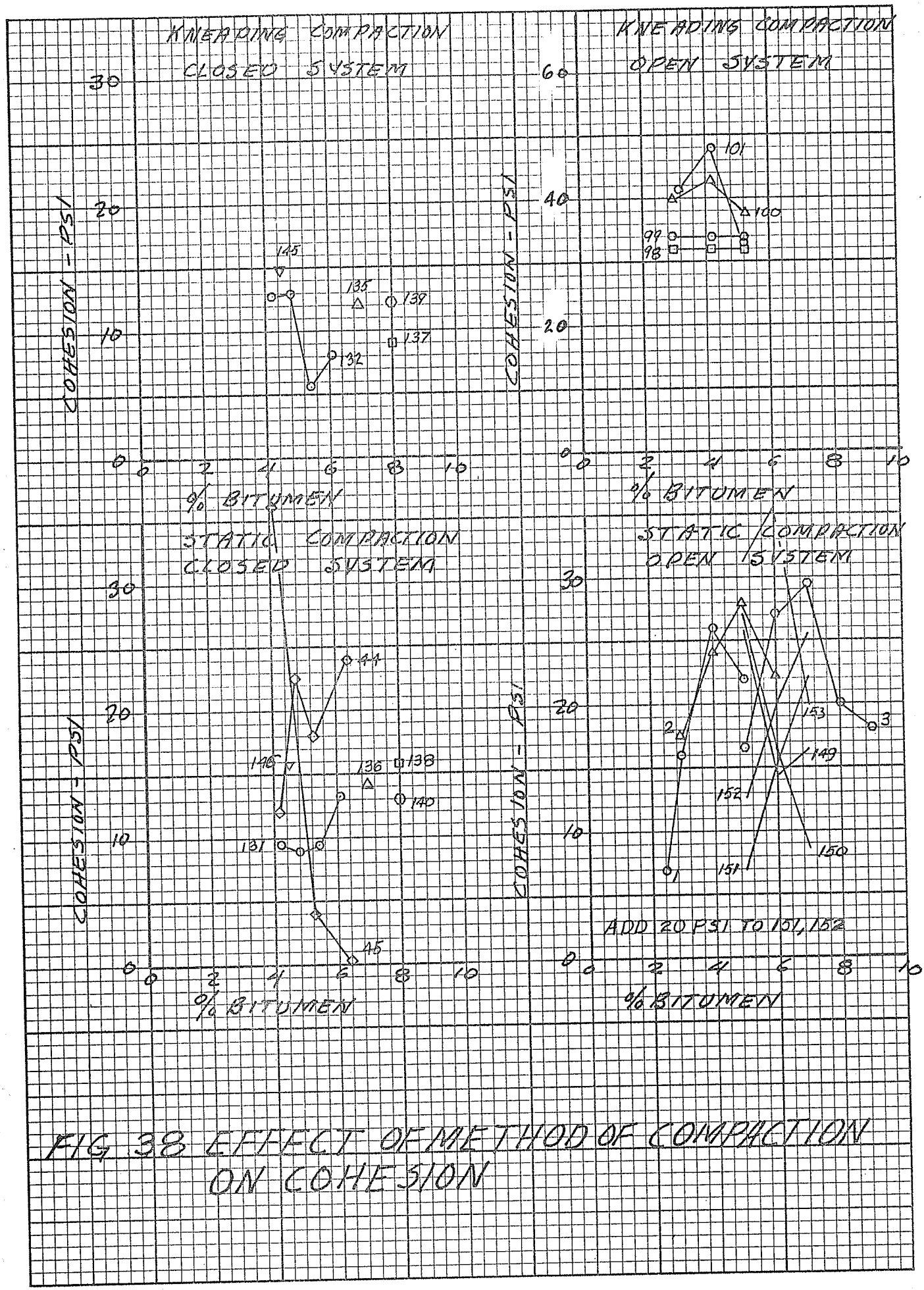


FIG 38 EFFECT OF METHOD OF COMPACTION ON COHESION

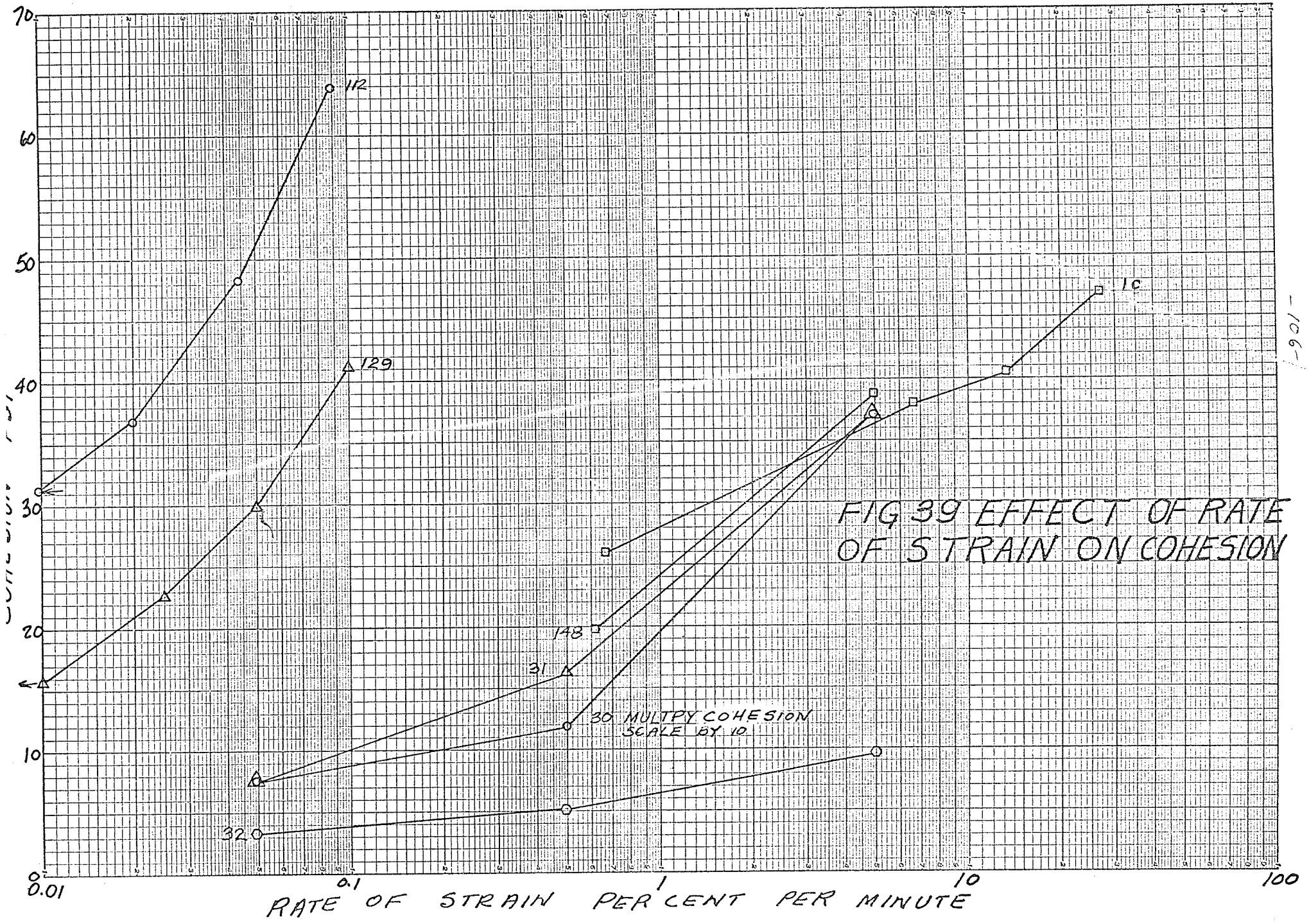


FIG 39 EFFECT OF RATE OF STRAIN ON COHESION

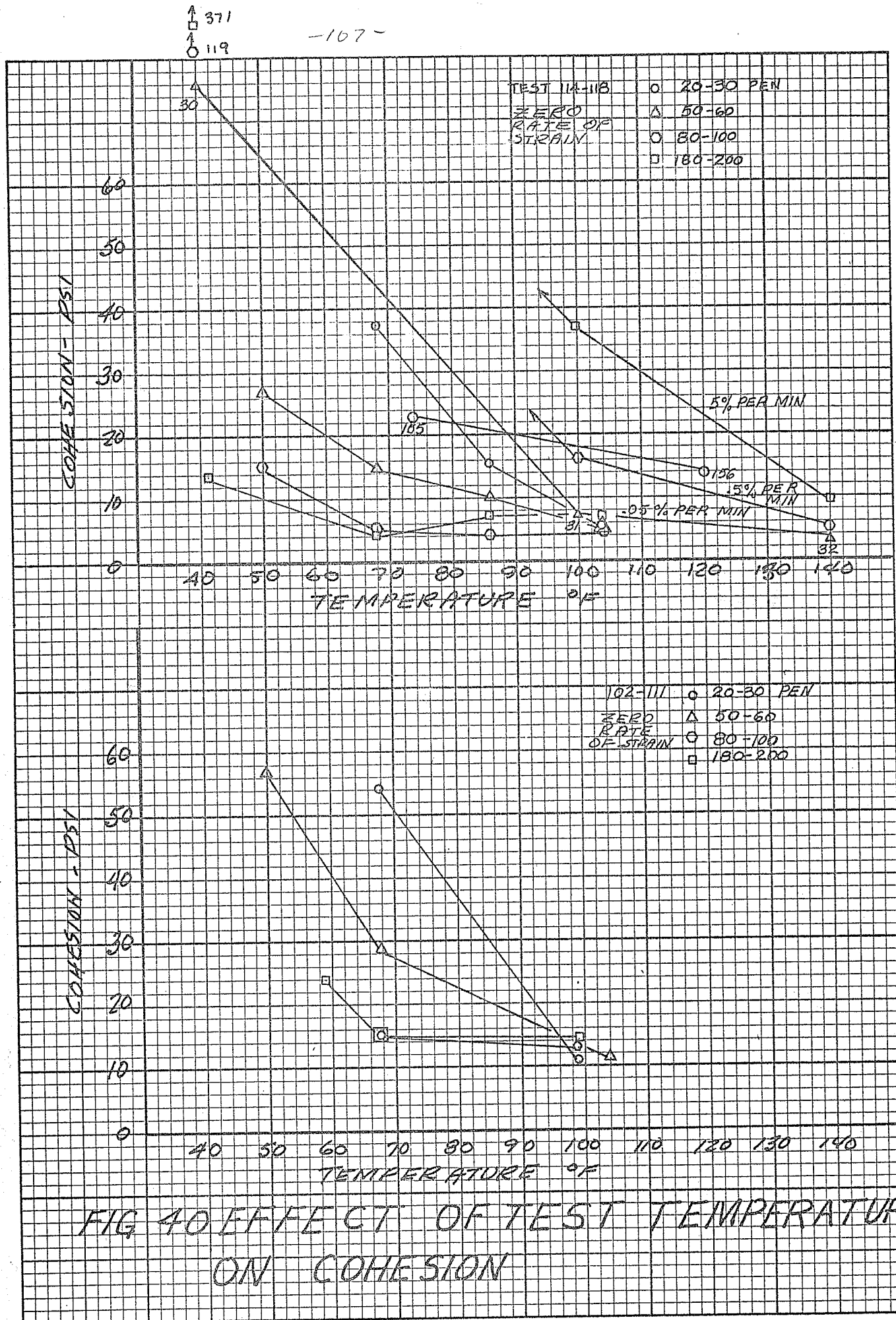


FIG 40 EFFECT OF TEST TEMPERATURE ON COHESION

NO. 31.288. 10 DIVISIONS PER INCH (70 DIVISIONS) BY FOUR 2½-INCH CYCLES RATIO RULING.

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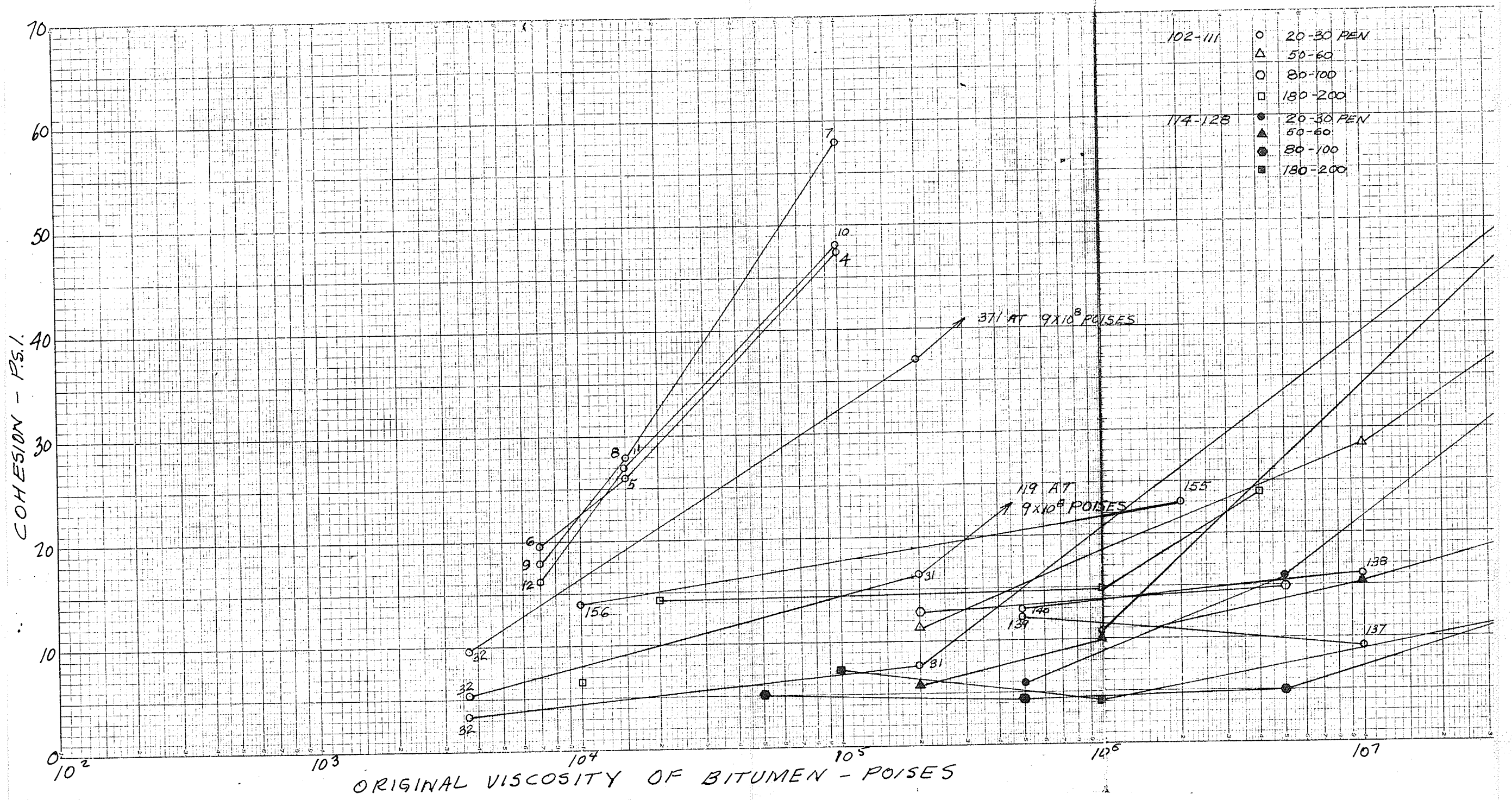
NO. 31.288. 10 DIVISIONS PER INCH (70 DIVISIONS) BY FOUR 2½-I



S RATIO RULING. CODEX BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS.
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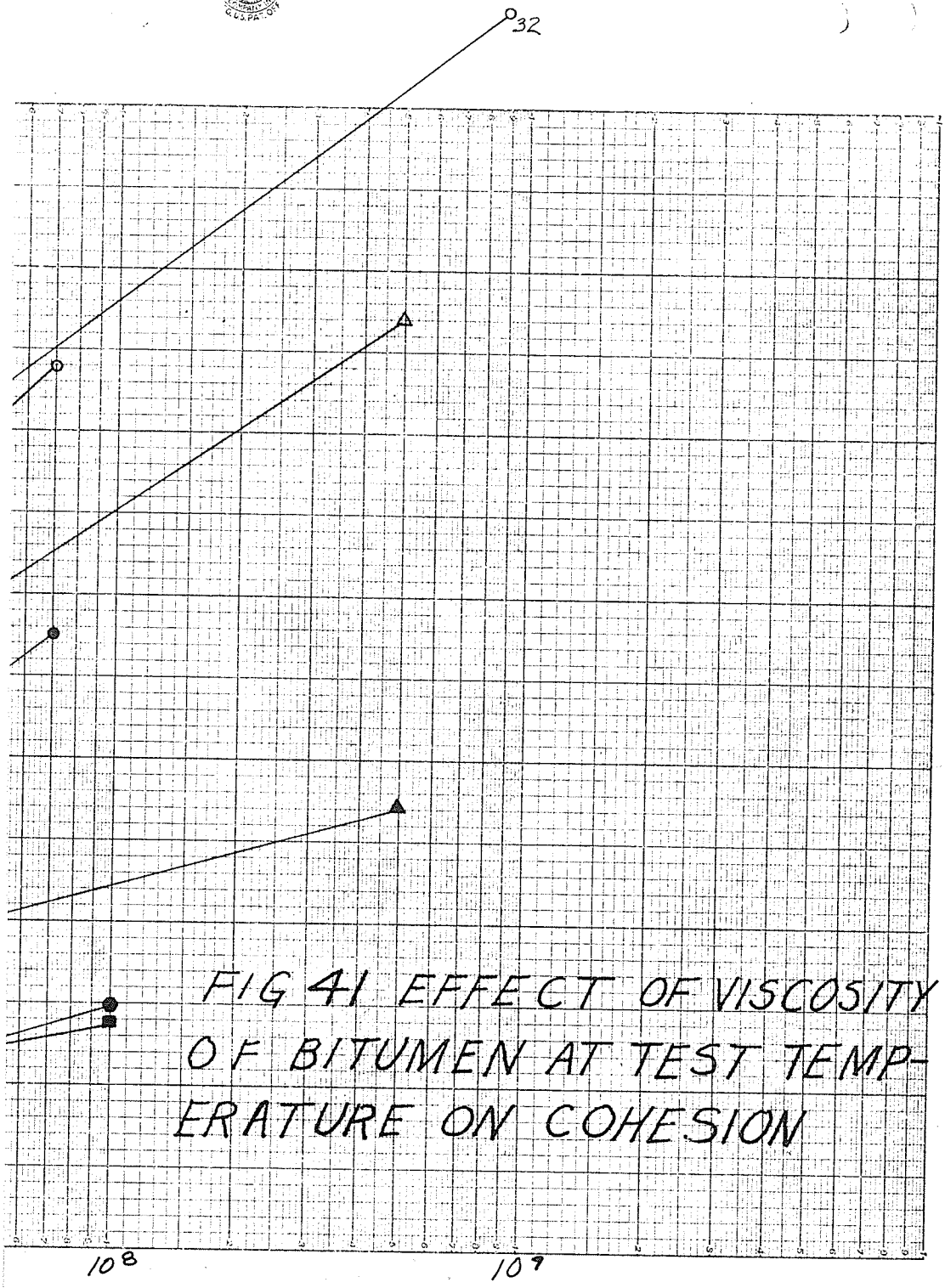


FIG 41 EFFECT OF VISCOSITY OF BITUMEN AT TEST TEMPERATURE ON COHESION

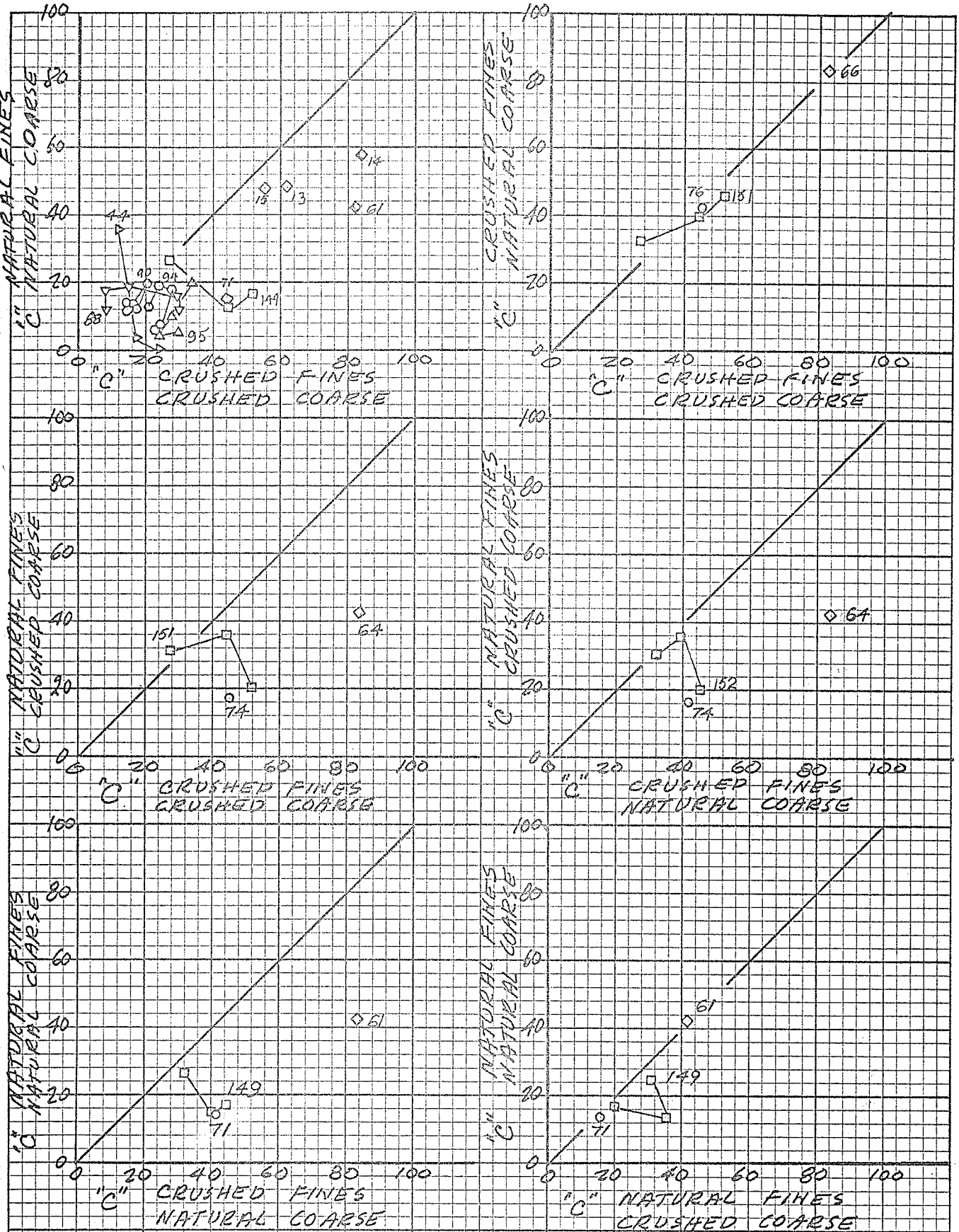


FIG 42 EFFECT OF PARTICLE SHAPE AND SURFACE TEXTURE ON COHESION

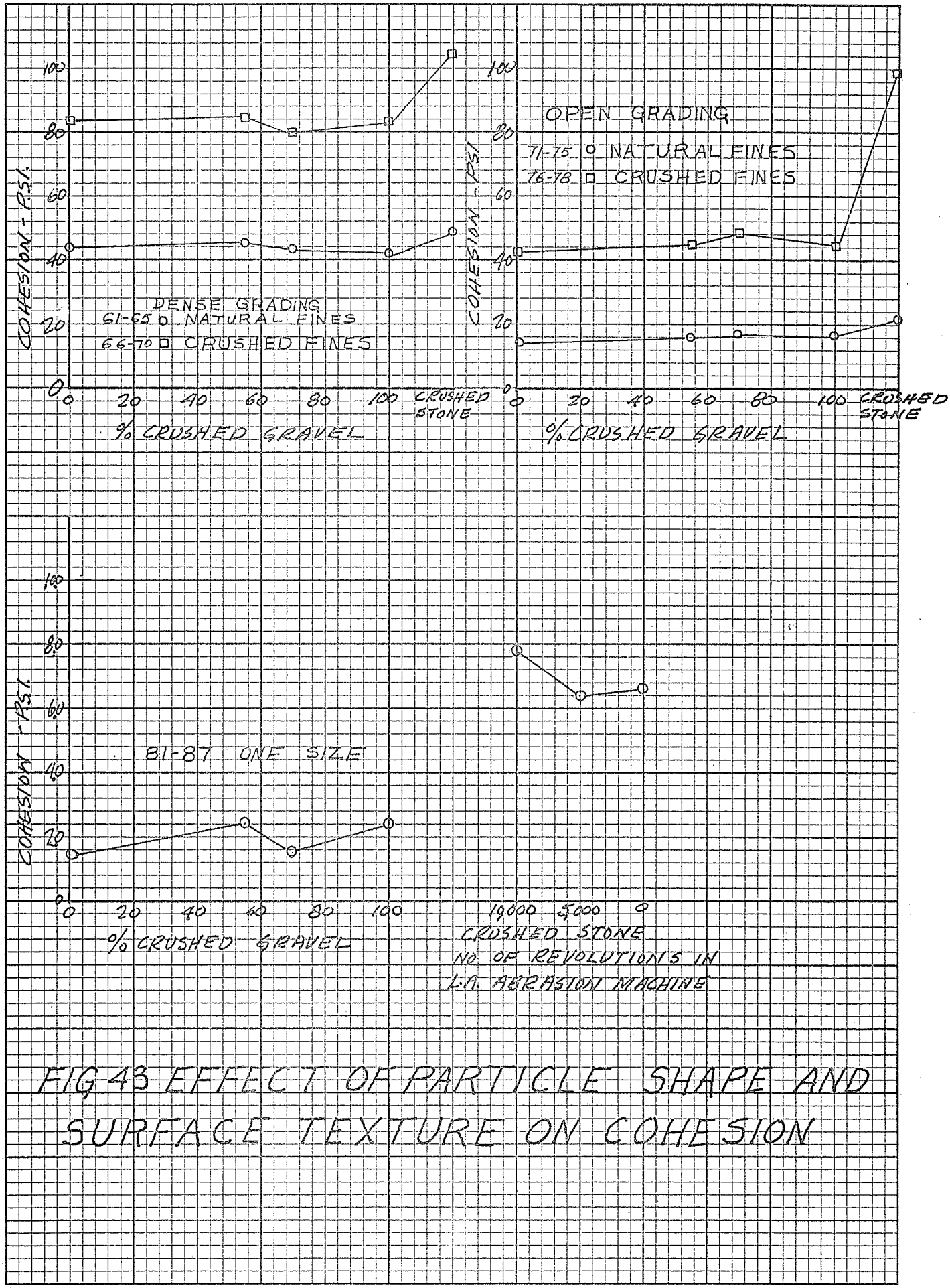


FIG 43 EFFECT OF PARTICLE SHAPE AND SURFACE TEXTURE ON COHESION

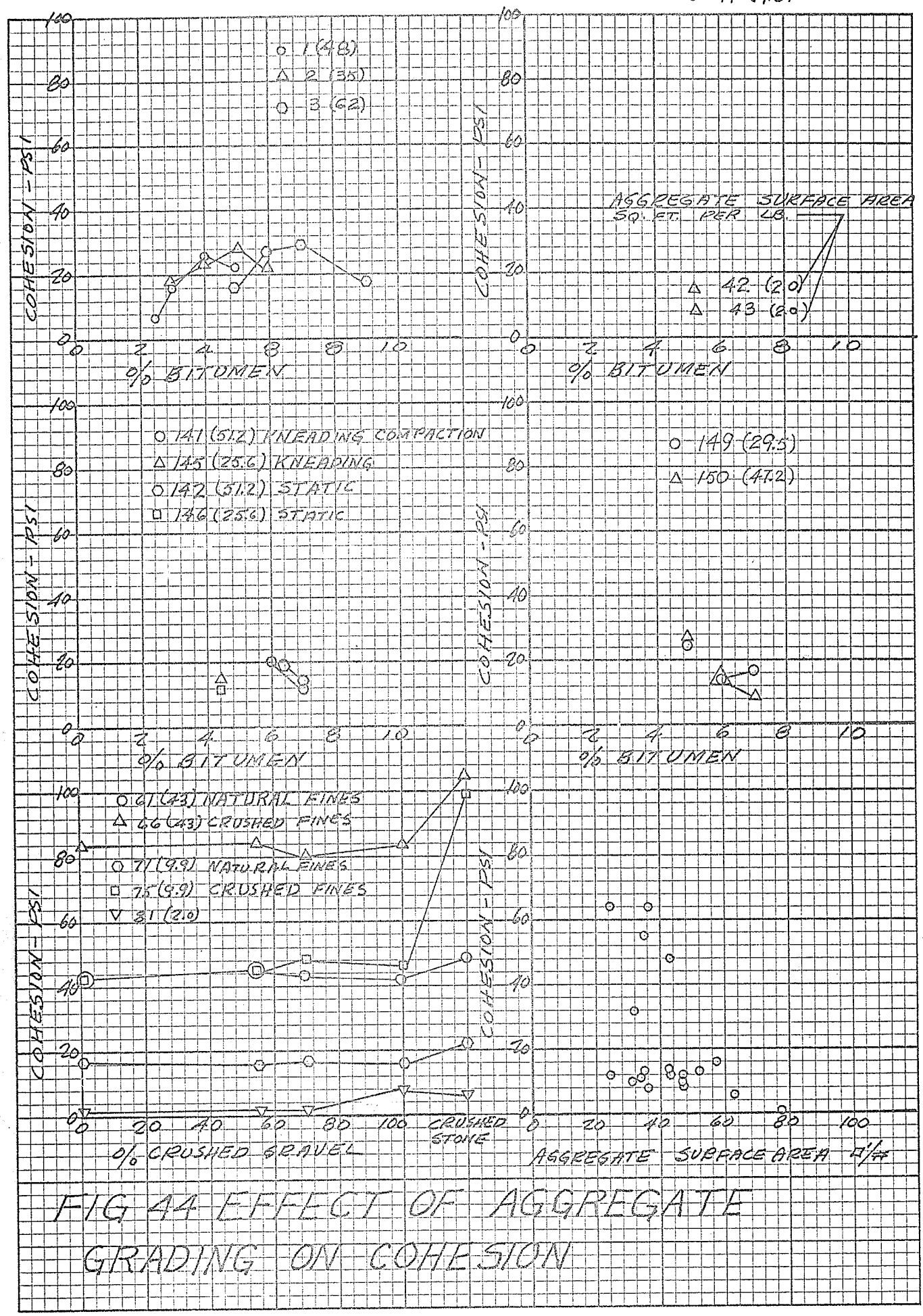


FIG 44 EFFECT OF AGGREGATE GRADING ON COHESION

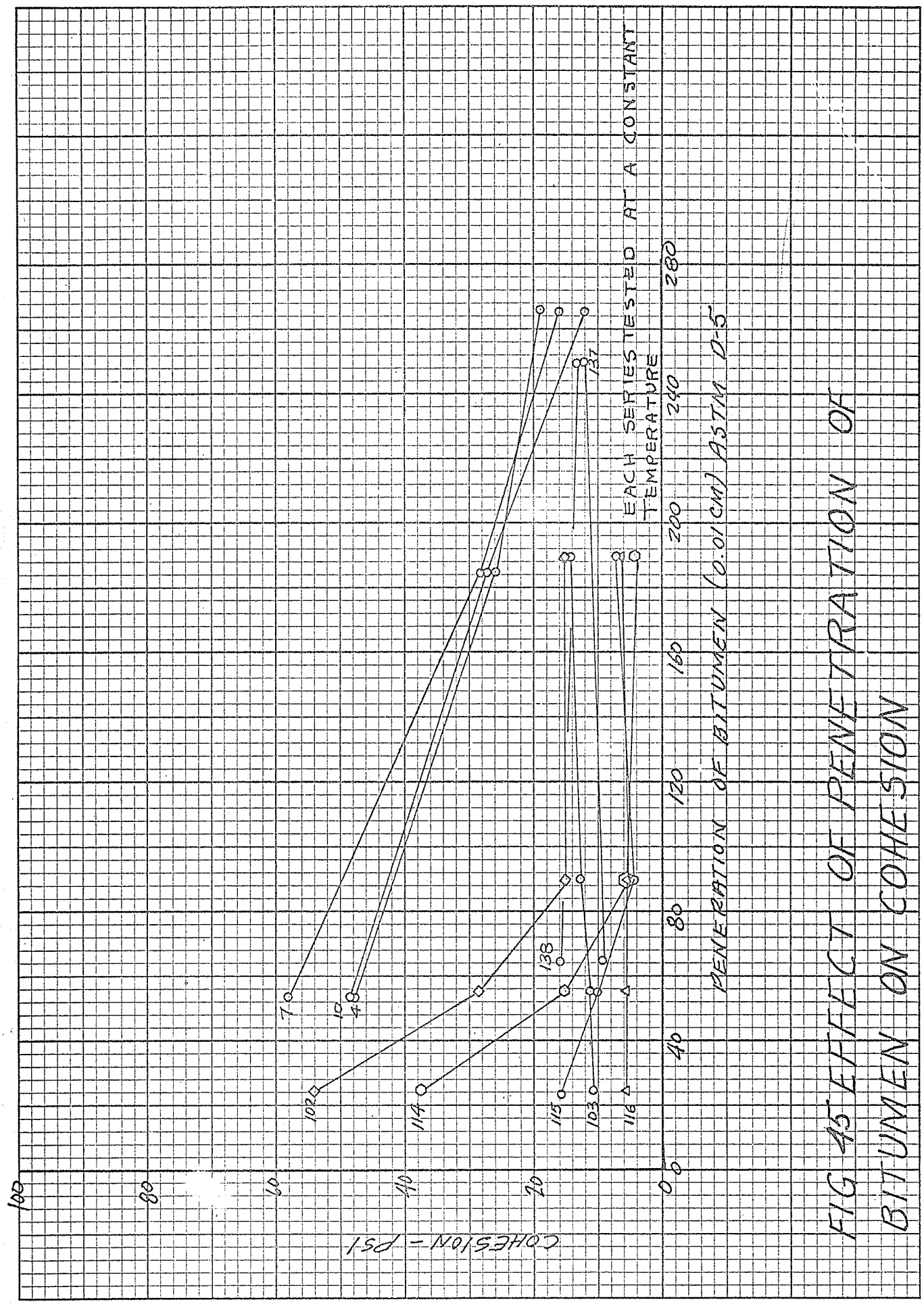


FIG 45 EFFECT OF PENETRATION OF BITUMEN ON COHESION

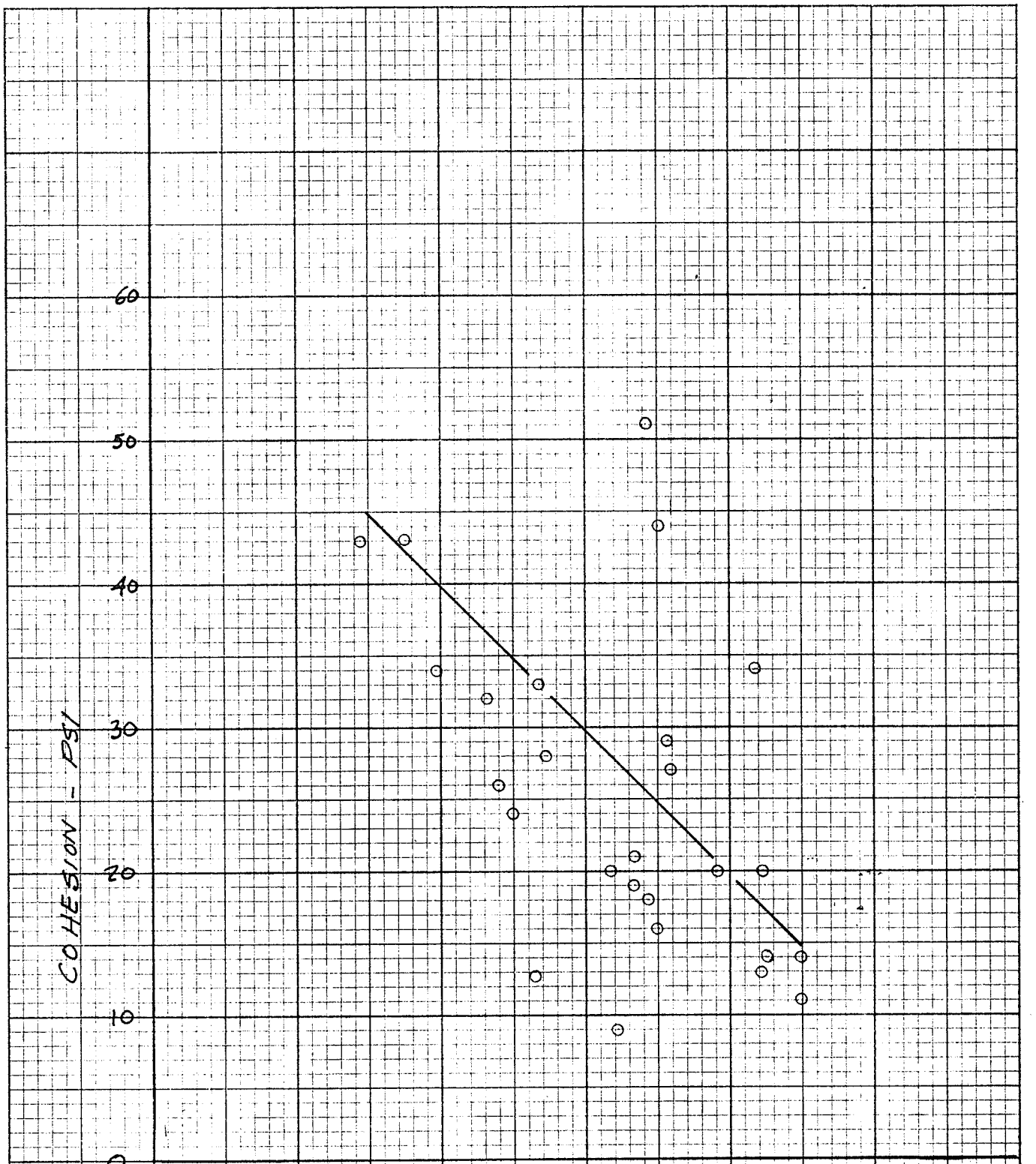


FIG 46 EFFECT OF VOLUME OF BITUMEN ON COHESION AT 5% AIR VOIDS

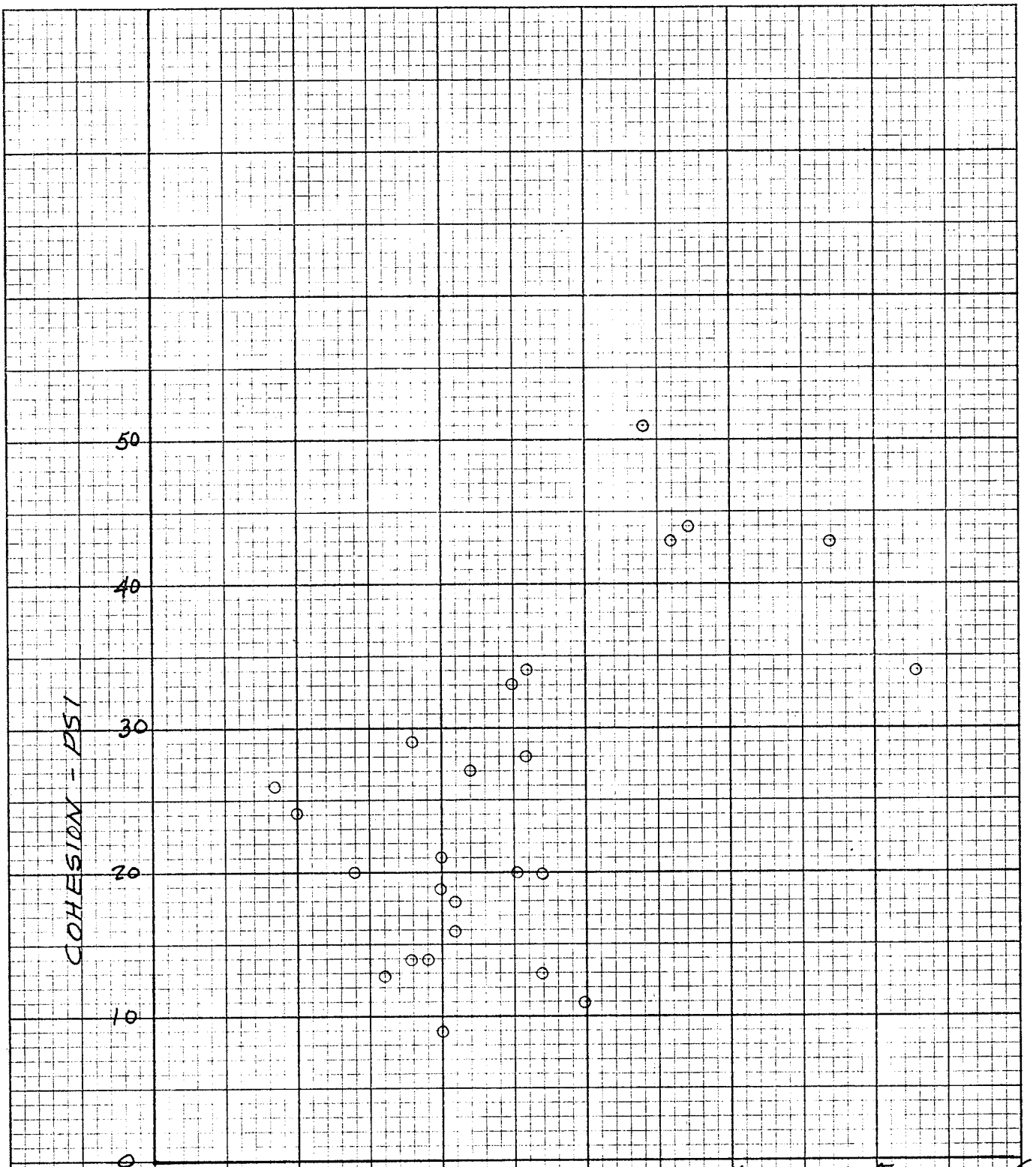


FIG 47 EFFECT OF BITUMEN-FILLER RATIO ON COHESION AT 5% AIR VOIDS

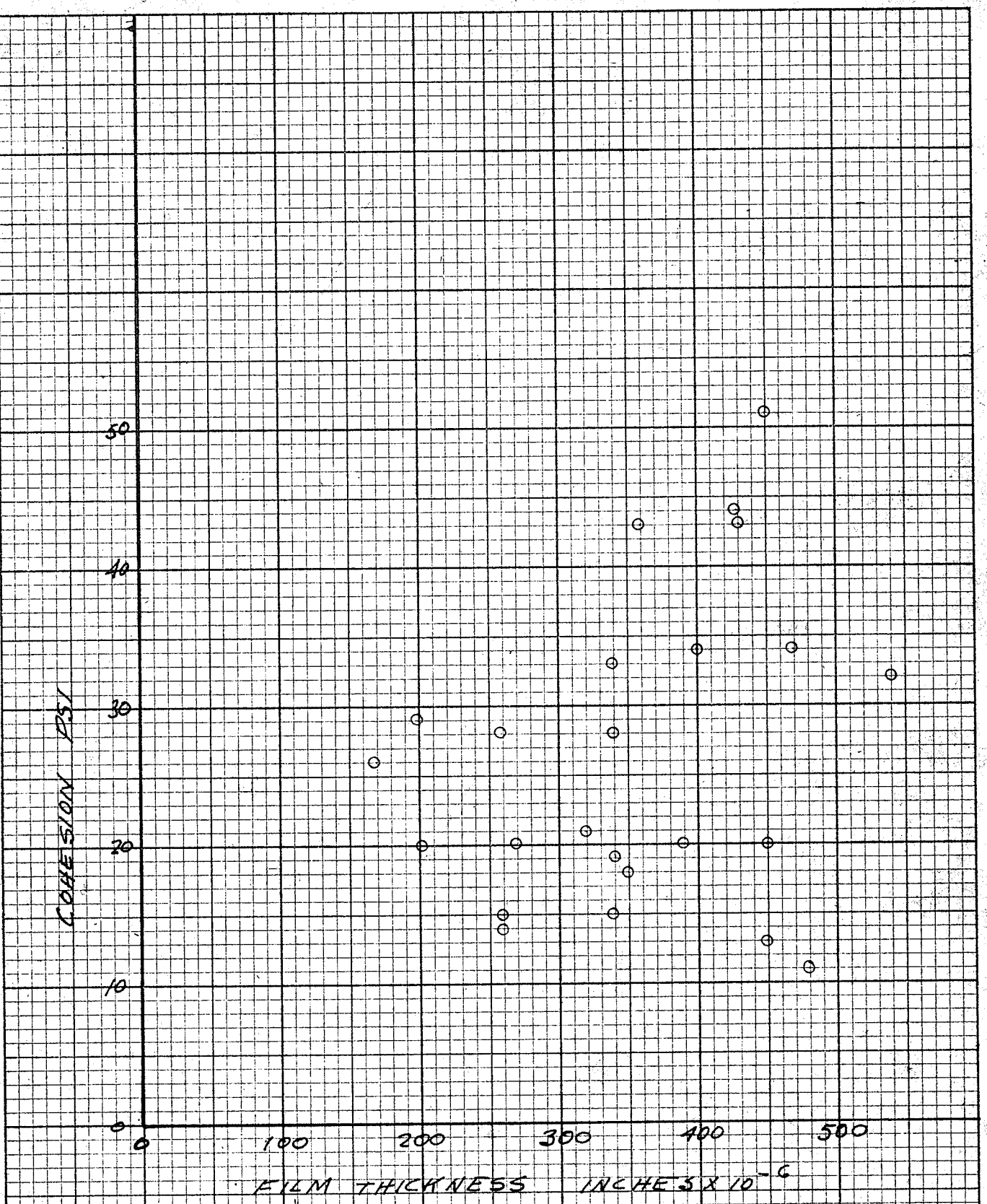


FIG 48 EFFECT OF BITUMEN FILM THICKNESS ON COHESION AT 5 % AIR VOIDS

APPENDIX I

MARSHALL MIX DESIGN DATA

DEPARTMENT OF TRANSPORT

ASPHALTIC CONCRETE DESIGN

SITE _____ REGION _____
CONTRACT Nº _____ DATED _____
MIX DESIGNATION B
DATE TESTED 9-3-63 BY F.P
TESTING LAB _____

AGGREGATE SUMMARY

Nº	DESCRIPTIONS	% of Total	%Fractures	GRADATIONS – % PASSING 1	1/2	4	10	40	80	200
1	STONE ½ - ⅜	15			100	0				
2	⅜ - #4	25			100	0				
3	SCREENINGS #4 - #10	20			100	100	0			
4	#10 - PAN	25					100	36.8	25.2	14.4
5	SAND #10 - PAN	15					100	89.1	16.6	2.5
6	BLENDED MIX	100			100	60	40	22.6	8.8	4.0

LOS ANGELES ABRASION _____ %
SAND EQUIVALENT _____
SHALE _____ %

RICE VACUUM TEST

TOTAL BIT LBS/ 100 LBS	MAXIMUM DENSITY	ABS. BIT LBS/100 LBS
4	161.0	0.4
5	158.6	0.4
6	156.5	0.4
MEAN ABSORBTION		

AGGREGATE SPECIFIC GRAVITY
USE BULK DRY ASTM C 127, C 128

AGG.		% OF TOTAL	SPECIFIC GRAVITY	% / 100 x Sp.Gr.
1	COARSE	15	2.75	.412
	FINE			
2	COARSE	25	2.75	.688
	FINE			
3	COARSE			
	FINE	20	2.72	.542
4	COARSE			
	FINE	25	2.72	.680
5	COARSE			
	FINE	15	2.65	.398
TOTALS				2.720

Dwg. Nº 626

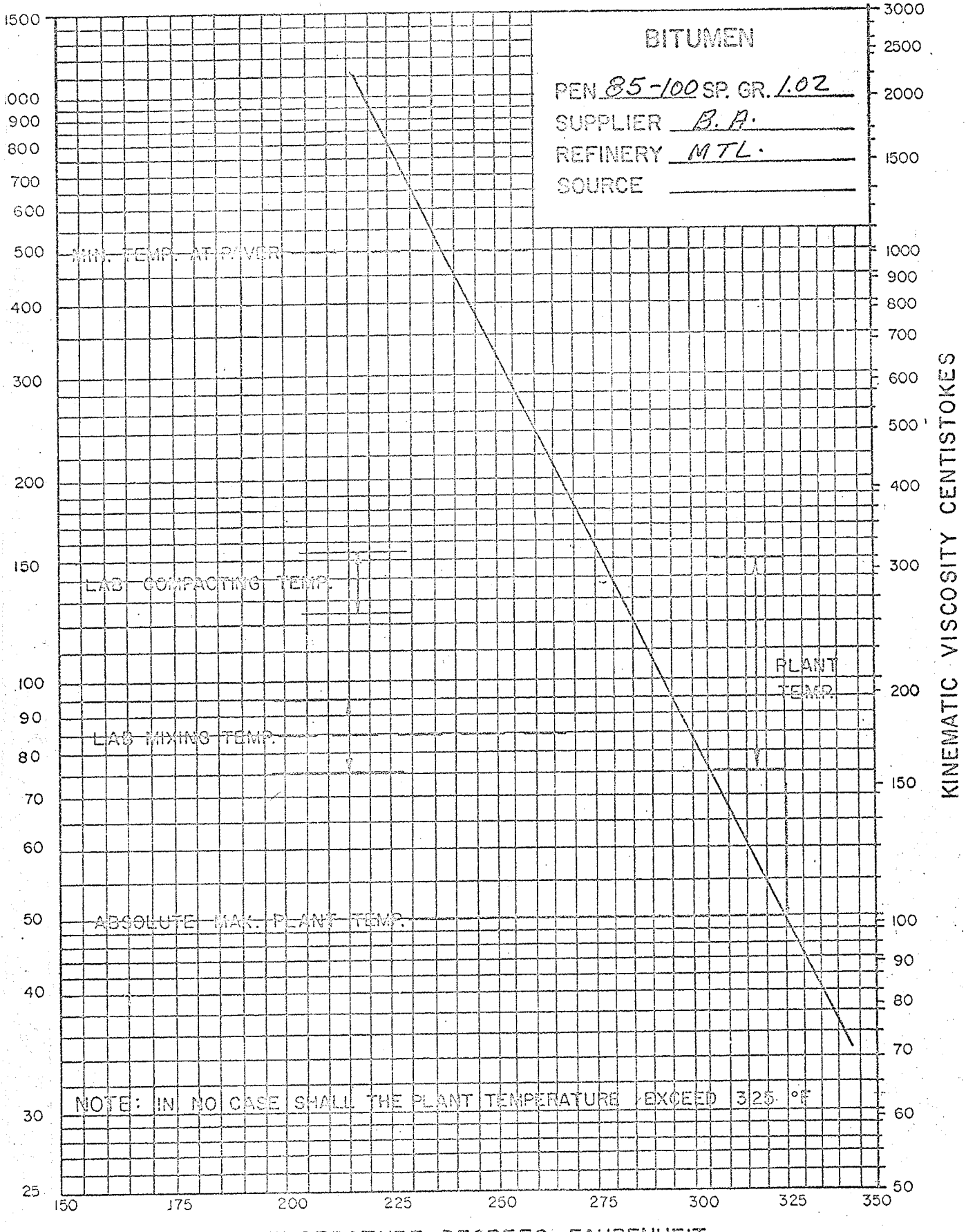
AGGREGATE FOR BRIQUETTE

AGG. Nº	GRADING PASS	GRADING RET	%OF TOTAL	AGG. WT.	CUM. WT.	
1	1	1/2				
	1/2	#3/8	15	180		
	#3/8	#4	25	300		
	10	PAN				
2	1	1/2				
	1/2	4				
	4	10	20	240		
	10	PAN	25	300		
3	1	1/2				
	1/2	4				
	4	10				
	10	PAN	15	180		
4	1	1/2				
	1/2	4				
	4	10				
	10	PAN				
5	1	1/2				
	1/2	4				
	4	10				
	10	PAN				
TOTALS				1200		

DESIGN BITUMEN CONTENT 5 LBS PER 100 LBS AGG.

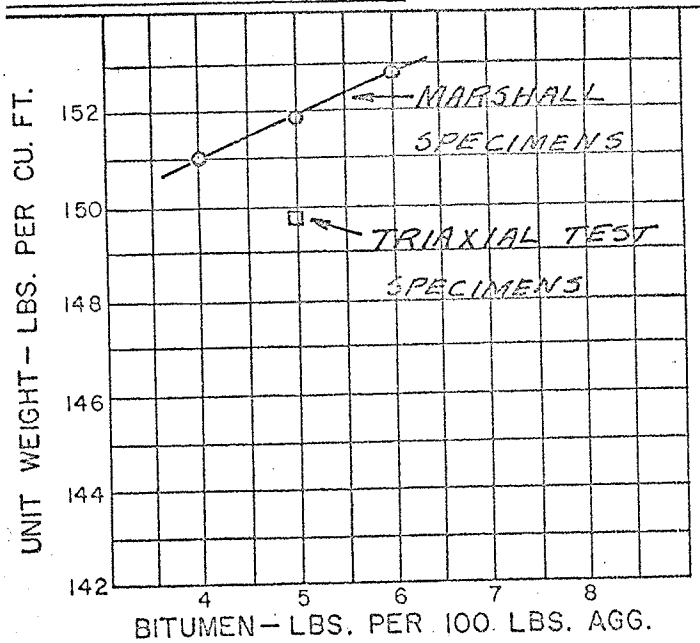
CONTRACT Nº _____ MIX B SHEET _____ OF _____

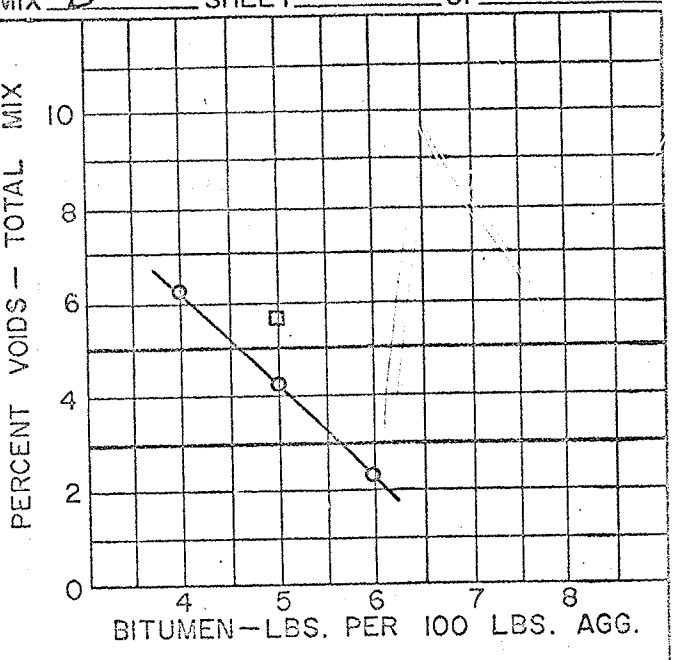
VISCOSITY VS. TEMPERATURE FOR ASPHALTS

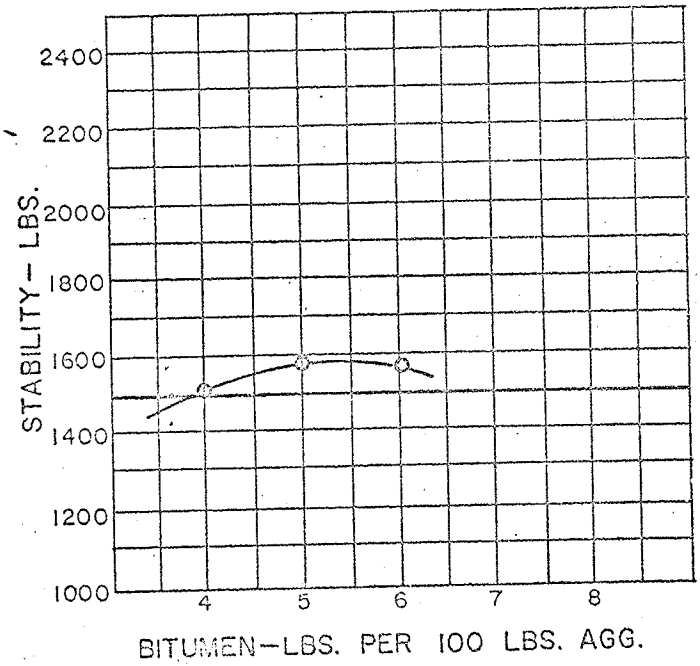


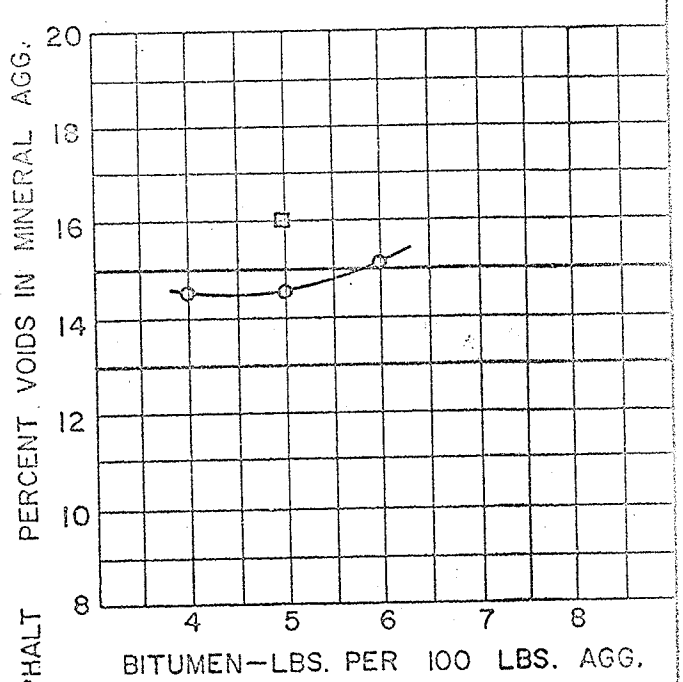
WG. Nº 627

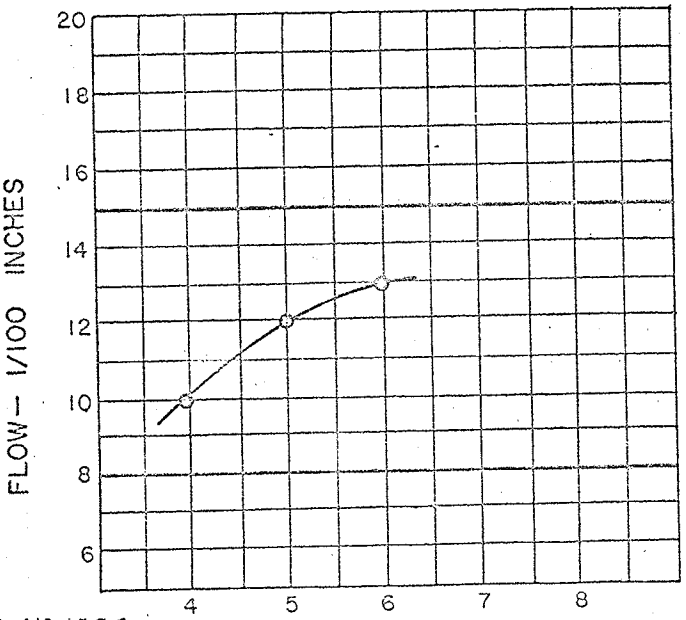
CONTRACT Nº _____ MIX B SHEET _____ OF _____

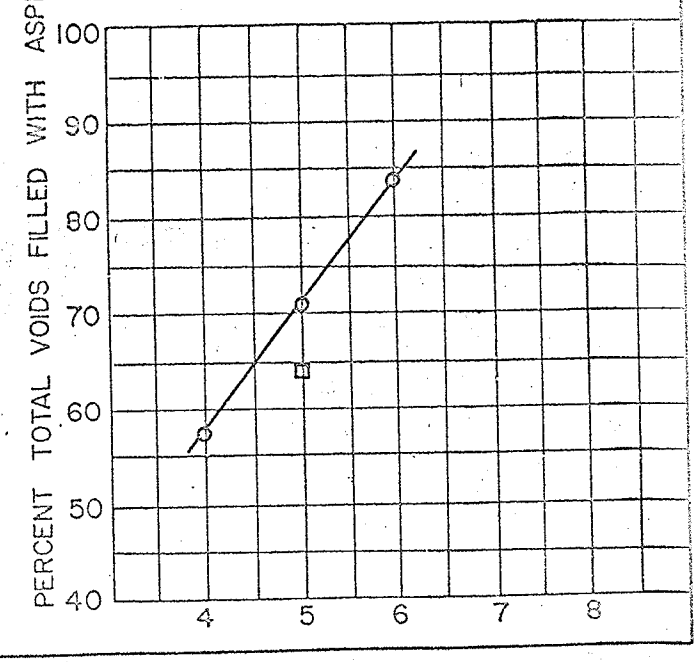












WG. Nº 629