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ALTERNATIVE MODIFIED BINDERS FOR AIRFIELD PAVEMENTS

Dr A F Stock

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The technical object of this research was to investigate materials, to modify, augment, extend and/or replace conventional asphalt cement binders for flexible airfield pavements, capable to sustain aircraft tire pressures of 350/400 psi. This study looked at a number of alternate materials and modified materials to determine their acceptability for producing the mixtures. There was a thorough review of the published literature concerning additive types, their effect on the properties of binders and mixers. Selection of a series of test procedures and development of a testing program to screen additives for their suitability for combination with bitumen, determine mix design procedures, and to measure the structural and mechanical properties of mixes was done.

It may be concluded that aircraft fitted with vectored thrust can cause additional structural damage to pavements as a result of heating effects. It is also concluded that erosion is possible as a result of the blast from the vectored thrust. (over)

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It is recommended that the operating parameters of aircraft using vectored thrust be investigated as this has considerable significance in relation to the damage potential. The analysis in this report provides sufficient data for a preliminary assessment of the probability of damage, therefore permitting a decision in relation to further investigation.

ALTERNATIVE MODIFIED BINDERS FOR AIRFIELD

PAVEMENTS

Dr A F Stock

Final Report

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The research reported in this Department was made possible through the support and sponsorship of the US Government through its European Research office of the US Army. ~~This report is intended only for the internal management of the contractor and the US Government.~~

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GENERAL INTRODUCTION

This report has been prepared to meet the requirements of the contract No.DAJA45 - 86 - C - 0043 issued by the U.S. Army Research, Development and Standardization Group - U.K.

It is divided into three parts, each devoted to separate topics. Since the topics are separate each may be regarded as an individual entity and so each section is introduced separately, and includes its own set of conclusions.

Part 1 of the report describes the analysis of creep data generated from tests on fourteen modifiers at the Materials Laboratory in the Pavements Division of the Waterways Experiment Station in Vicksburg, Mississippi. As will be described this analysis includes several different approaches to the assessment of the data.

Part 2 of the report consists of a collection of "factsheets" each of which contains a summary of the data available on a particular additive.

Part 3 gives the results of an investigation into the probable effects of operating aircraft fitted with "vectored thrust" type propulsion units.

Part of this contract was to develop a test plan to evaluate asphalt mixes containing modifiers. This test plan was described in the first periodic report and since this report deals with the results obtained from following the test plan it is not included in this document.

PART 1

ANALYSIS OF CREEP DATA

INTRODUCTION

The principal objective of this study is to asses the ability of additives to improve the resistance to permanent deformation of asphalt concrete. This aspect of the behaviour of a mix is often described as its "stability" but must not be confused with the failure load determined from a Marshall test. The Marshall Stability is derived from an empirical test and whilst it has been correlated with the performance of airfield pavements the results of tests on trial mixtures cannot be used to predict the performance of a pavement with a high degree of confidence. This is particularly true for mixes which depart significantly from what may be described as a conventional 'asphalt concrete'. By definition mixes containing special additives of the type under investigation in this study must be described as novel and therefore conclusions regarding the performance of the mixes based on Marshall Stability would be regarded as highly suspect.

This reasoning has lead to the adoption of the creep test as a means for assisting with the evaluation of the mixes. The method has the advantage of being a fundamental test which is widely used for evaluation of many types of material and has been applied successfully to bituminous materials. In addition it forms the basis of methods for predicting rut depths in pavements and therefore has the potential for providing a realistic parameter for evaluating the performance of mixes containing additives in pavements structures.

The creep tests carried out for this study were uniaxial constant-load compression tests. They were performed at two different temperatures and at a stress level which would not cause collapse of the specimens.

One of the parameters derived from creep tests for ranking mixes is the stiffness of the mix, determined after a suitable time under load. This parameter has limitations when considering the performance of mixes containing additives which modify the nature of the response of an asphalt mix to load. A conventional mix exhibits a restrained viscous behaviour under a constant load, the rate of deformation decreasing with time. (Assuming the material is not so highly stressed that it collapses.) The recovery of the material upon release from load also takes this same restrained viscous form, but it never fully recovers. Some of the additives in this study have the potential to modify this behaviour, specifically to increase the magnitude of the recovery, without necessarily changing the initial response of the mix to load. It was therefore considered necessary to measure the recovery of test specimens after the load had been removed and include this data in the assessment of the mixes.

In order to conform with standard mix design practice for airfields the binder content for the creep specimens was chosen at the 4% void content level determined from a series of Marshall tests. This also provides a practical point for comparison of the mixes which is highly desirable. However it has the unfortunate consequence of a different binder content for each mix IN ADDITION TO a different AC-20 content for each mix. Therefore any difference in the behaviour of the mixes under constant load could be due to a different AC-20 content, a different binder content, the effects of the modifier or some combination of these factors. In the first instance the relative performance of the individual mixes will be analysed. An attempt to isolate the effects of the individual additives will be described later.

AN INTRODUCTION TO THE INTERPRETATION OF CREEP DATA

It is generally accepted that asphalt cement can be treated as a thermorheologically simple material when investigating the behaviour of composites which use it as a binder. This means that the effects of time under load, on deformation, can be investigated by changing temperature. In other words a master creep curve describing the deformation with time of an asphalt cement can be developed from a series of tests at different temperatures, carried out over a convenient short time period, the results of the test at each individual temperature being adjusted by means of a shift factor.

Van de Loo(3) postulated that since asphalt cement is the only thermorheological component in an asphalt mix there should be a relationship between the shift factor for a mix and that of pure bitumen. This hypothesis was proved by examining the creep data published by several authors (4,5,6) and further confirmed by subjecting the results of flexure tests to the same analysis(7), thus study demonstrating that the shift factors for a mix and for the pure asphalt cement, used as the binder in the mix, were equal.

This discovery obviated the need to determine shift factors by experiment, they can be obtained from Van der Poel's nomograph(1) provided that the bitumen properties are known. Thus creep tests could be performed at convenient temperatures and the results presented as a master curve with deformation or strain being plotted as a function of reduced time. The numbers on the reduced time axis will depend upon the reference temperature selected and this is an inconvenience when results from several different sources are being compared. This problem can be overcome by plotting the results of the creep test as a function of the stiffness of the asphalt cement which can be determined quite readily from Van der Poel's nomograph(1).

Figures 1 - 4 have been reproduced from Van der Loo(3) to illustrate this procedure. Figure 1 shows the results of two creep tests, one at 50 degrees Farenheit (10 C) the other at 86 degrees Farenheit (30 C), strain being plotted as a function of loading time. Figure 2 shows the same results plotted but as the stiffness of the mix as a function of loading time. (The stiffness of the mix is defined as the ratio of the applied stress - a constant to the strain at any particular time). As can be seen from these two figures the time-temperature shift factors for are effectively equal for the two cases. Figure 3 shows the master creep curve, in which a reference temperature of 50 degrees Farenheit has been chosen, and the data plotted in terms of strain as a function of reduced time. Finally in figure 4 the data is plotted once more with the mix stiffness now being shown as a function of the stiffness of the bitumen. Selection of mix stiffness as the dependant variable has the added advantage of being independent of the stress applied during testing, thus permitting easier comparison of results from different sources and making it easier to plan test programmes.

There are further advantages to be obtained from this approach. Provided that mix composition does not change, the results of tests on samples with different binders can be presented on one single curve. This offers a powerful approach when evaluating the effects of additives, provided that the mix composition is carefully controlled.

When presented in the form of mix stiffness as a function of the stiffness of the bitumen the shape of the creep curve depends on the composition of the mix and its internal structure. The quality of the material can be judged by the slope of the curve and its position. The form of the creep curve is a material characteristic and is independent of test variables.

DETERMINATION OF THE STIFFNESS OF THE ASPHALT CEMENT

Introduction.

As indicated above, the creep data can be plotted in a manner which renders it independent from the test conditions, that is the applied stress and the test temperature. This is accomplished by plotting the stiffness of the mix (Smix) as a function of the stiffness of the asphalt cement (Sbit), both parameters being determined at convenient time intervals during the creep tests. The creep test programme carried out for this part of the study of the effects of selected additives did not include creep tests on the asphalt cement because such tests require a totally different procedure to that adopted for the asphalt concrete mixes. This section will describe how the stiffness of the asphalt cement was determined analytically and then discuss the results of the test programme.

Determination of the Stiffness-Time relationship for the asphalt cements.

Van der Poel's nomograph(1) was designed expressly for the purpose of computing the stiffness of asphalt cement at temperatures and loading times as required by the user. In addition to these parameters some data concerning the properties of the asphalt cement is required, namely the Penetration Index (P.I)(1) and the Softening Point as determined by the ring and ball test(2). Unfortunately the data supplied with the creep test results did not include the softening point temperature. The results of a penetration test at a temperature other than 77 F. would have facilitated the computation of the P.I. but this data was not available. These two parameters were estimated as described below. Whilst estimation of these parameters is not the most satisfactory procedure, any errors introduced will be identical in the assessment of all the additives because the same asphalt cement was used throughout the study. There is one comparison which may be unreliable as a result of the need to estimate these properties, and that relates to the mix produced with AC-40 for which a similar procedure was performed. If the AC-40 asphalt cement is of a significantly different rheological type to the AC-20 upon which the study is based, then the assumption of a general viscosity - temperature relationship which was made in order to estimate values for softening point will be invalid, and hence the comparison will be unreliable.

Figure 5 shows the generalised viscosity/temperature relationship that was used to estimate the asphalt cement properties for the stiffness nomograph. The procedure used is as follows;

1) Plot the viscosity at 140 F (60 C) on figure 5.
(The results of the tests on asphalt cement are reproduced in appendix A)
2) Draw a line parallel to the lines describing the general viscosity - temperature relationship through the point marked in step 1.
3) Check the validity of this line by plotting the result of the penetratio.. test on the figure.
4) Determine the softening point temperature from the temperature scale by reading the temperature at which the viscosity is 10,000 poise.

The check performed in step 3 above indicated that the relationship between temperature and viscosity constructed in thi: way was reasonably a .urate.

Having determined a softening point for both the AC-20 and AC-40 asphalt cements the penetration index was derived from the nomograph reproduced in figure 6. Table 1 contains the values determined for the two grades of asphalt cement.

The stiffness-time relationship derived from Van der Poel's nomograph for the two asphalt cements are shown in figure 7.

<u>The relationship between the mix stiffness and the stiffness of the asphalt cement</u>.

Plots of mix stiffness as a function of the stiffness of the un-modified binder are presented in appendix B. These plots show that in general the transformation of data into this form does permit the combination of data obtained at different temperatures into one master curve as anticipated. However the results for additive P (fig.B2-14) are not brought to a master curve by this approach, suggesting that the modifier has changed the fundamental behaviour of the binder.

The more convenient representation of the creep data can be obtained by plotting the stiffness data to logarithmic scales is shown in the next section.

INTERPRETATION OF CREEP DATA

Interpretation of the shape of the creep curves

Figures 8 - 21 are plots of mix stiffness as a function of the stiffness of the asphalt cement for the mixes in this test programme. Figure 9 shows the data obtained with the un-modified AC-20 (code B) binder and is therefore the basis for comparison for the mixes. These Figures show the results from the individual tests unlike those in appendix B which are for averaged data.

As noted above the quality of a mix can be judged from the slope and position of the creep curve. The analysis described below is derived from this premise, mixes with a higher stiffness at a given asphalt cement stiffness being judged to be of higher quality.

Preliminary analysis of the creep data in the averaged form presented in the appendix revealed that the curvature in this data was significant in relation to interpreting the results. For example plotting the equations produced by linear regressions to the averaged data, produced lines for the different mixes which crossed when the actual data sets did not. Also when the measured creep curves did cross each other the linear regression equations shifted the point of intersection along the Sbit axis. Since this axis can be correlated with an approximation to the rut depth, the shift changes the point at which one formulation becomes superior to its competitor. The final problem posed by this curvature in the Smix - Sbit relationship is that the judgement that a mix with a flat slope has superior performance to one with a steep slope cannot be applied, since there is no unique slope. It is more appropriate to consider the performance of the mixes for specific conditions, since the choice of which one is superior may depend upon the environment in which it is to function and the service required from it.

In order to overcome this deficiency in analysing the data a curve fitting routine using a set of orthogonal polynomials was used to provide a representation of the data. A description of the routine is given in appendix C., together with the derived coefficients and the root mean square value of the deviation between the experimental points and the best fit curve.

Curves were fitted to the full data set for each mix. The data was also separated according to test temperature and the data sets for the individual temperatures was analysed. In virtually all cases a second order polynomial provided the most satisfactory fit to the data.

The polynomials were evaluated at asphalt cement stiffnesses of 1.8, 0.145, and 0.04 psi. The middle value of 0.145 psi is representative of a rut depth of about 10% for a typical asphalt concrete mix (3). The other two values were determined to provide an indication of the behaviour of the mix in a "deep rut" condition which would be associated with a low stiffness for the asphalt cement (0.04 psi), and a "shallow rut" which would be associated with a high stiffness for the asphalt cement (1.8 psi).

Table 2. shows the values of mix stiffness at the various bitumen stiffnesses the data having been sorted in descending order so that the ranking of the mixes according to this parameter is also evident. Whilst table 2 gives a definite order for the mixes, close examination of the data shows that it is more appropriate to consider the mixes in groups. At the reference asphalt cement stiffness of 0.145 psi, mix P stands well clear of

all others at the head of the table, and mix C is a clear second. mixes K,D,and L are separated by very small differences in stiffness and so effectively form a group. The next group is formed from mixes I and E, with F being intermediate between this group and the following J,G,H,B, and A. Mix O is significantly below this last group. This process has also been applied to the results at the other values of asphalt cement stiffness and the results are shown in table 3.

Mixes P and C stand out consistently at the head of the table and O is consistently lower than all others. Mix J is consistently ranked in the same group as the control mix B A, H and F are either ranked with the control or one group up or down suggesting that they do not offer much gain (or loss) in performance. Mix G only offers a significant improvement at high bitumen stiffnesses, a condition which is unlikely to represent a problem area. This leaves mixes D,E,I,K,and L which generally show significant improvement. Of these I and L appear to offer little benefit at the high bitumen stiffness and so the all round benefits of D,E, and K make them the more desirable mixes. Thus the final ranking, starting with the mix showing the greatest benefit is as follows :-

1. Mix P.
2. Mix C.
3. Mixes D,E,K.
4. Mixes I,L.
5. Mixes J,H,F,G,A and B (Control)
6. Mix O.

It is appropriate to consider this ranking in conjunction with the classification of the additive which each one contains. Group 1, mix P(Chemkrete), is the only Oxidant in the study. Group 2, mix C(Trinidad), is the only hydrocarbon. Group 3, mixes D(Sulpher), E(Carbon black), and K(Polybilt-E.V.A.) include two of the three fillers and a plastic. Group 4, mixes I(Kraton), and L(Novophalt) contains a rubber and a plastic. Group 5, mixes J(Neoprene), H(Downright), F(Lime), G(Asphalt rubber), A(AC-40), and Control includes three types of rubber, the remaining filler, a hydrocarbon and of course the control. Group 6, mix O (Polyester fibers - Hercules) is the only fiber in the study. It is not possible to draw universal conclusions on the basis of these results concerning the efficacy of any particular group of additives, however the oxidant does appear to offer a significant improvement. Also the hydrocarbon appears to offer significant benefits, but it does contain a significant quantity of very fine minerals and so it is possible that a combined filler - hydrocarbon effect could be taking place, a view supported by the presence of two fillers in group three.

<u>Assessment of the departure from thermorheologically simple behaviour</u>.

The basis of the interpretation of the data above is that mixes are regarded as being thermorheologically simple. However several of the additives included in this study could influence the degree to which the various mixes approach this ideal. It can be seen that even the unmodified mixes do not conform totally to this ideal (See figures B1 and B2). It was therefore considered appropriate to examine the degree with which the various mixes either approached the ideal or departed from it. This is shown in Figures 22, 23, and 24 which plot the departure from the mean mix stiffness, of the mix stiffness measured at 77 and 104 Farenheit at asphalt cement stiffnesses of 1.8, 0.145, and 0.04 psi. The values of the departures are computed by taking the value calculated from the curve fitted to all the data from the value calculated from the relations derived for the 77 or 104 degree data. Thus the departures at specific temperatures are not the same in the positive and negative directions since the curve derived from the full set of data is not necessarily an average.

The first observation which can be made is that deviations as large as 30% from the mean can occur in materials which have been shown to conform with the premise of thermorheological simplicity. This deviation must therefore be representative of the experimental scatter.

There is significant similarity between the effects of the modifiers at asphalt cement stiffnesses of 0.145 and 0.04 psi. However the effect of many of the additives at the high binder stiffness is less significant. Mix O, which contains the oxidant is probably the most notable example of this since at an asphalt cement stiffness of 1.8 psi. it shows one of the smallest deviations whilst at a value of 0.145 psi. it is the largest.

The results in figures 22,23, and 24 have been grouped according to the classification recommended in report 1. This shows general conformity of the 'modification effect' for each of the three extenders, the four rubbers and the two plastics. However it does highlight the fact that there are considerable differences in the effects of the different additives within each of these groups. This should not be particularly surprising since the titles "rubber" and "plastic" are very general, each describing families of materials which range widely in terms of molecular structure and physical properties. The extender group also contain materials which are, or may be chemically active within the asphalt cement - mineral composite. Thus it is unwise to anticipate that any specific rubber or plastic, or even filler, will have an effect similar to that of another material of the same group without knowledge of its molecular structure and chemical reactivity. It is, of course, always most desirable to measure the response of a mixture containing the additive in question in a manner appropriate to its intended application.

ASSESSMENT OF RESISTANCE TO DEFORMATION

Introduction.

As stated above the principal objective of this study is to determine the validity of the hypothesis that additives can improve the resistance to deformation of asphalt mixes. It was therefore considered to be appropriate to use a mechanistic procedure for predicting rut depth as a part of the evaluation.

There are several procedures described in the literature but the one which is most convenient for use in relation to the data gathered during this study is described in the Shell pavement design manual (8,9). This method is based upon a significant volume of research and includes correlation between the development of rutting in laboratory wheel tracking experiments, that which develops in - service pavements, and creep test data. Figure 25 shows a flow chart of the procedure (9).

This procedure was developed for highway pavements. Thus the traffic data required has to be estimated and the rut depths computed are unlikely to be representative of those found on airfield pavements. However the relative magnitude of the deformation calculated for each mix compared with that of the control will represent the relative improvement which can be achieved. Hence the results are presented as a rutting index, as described below.

The procedure for calculating rut depth.

The Shell pavement design manual(8) is based upon a series of charts and is intended for use, by hand, in the field. Since rut depth predictions were required at various asphalt layer thicknesses and for different climatic regions a computer program was written to reduce some of the burden of calculation. A listing of this program, which is written in BASIC is provided in Appendix D. The following is a list of the input data and major steps in the program, supplemented by comments to indicate how the various difficulties were overcome.

1). Correction factor for dynamic effects. This factor is included in the procedure in recognition of the difference between the static load condition of the creep test and the dynamic loading to which pavements are subjected. Values are tabulated in the manual, and have been reproduced within the computer program.

2). Traffic volume data. This has been estimated.

3). The Penetration Index of the asphalt cement. See Appendix A.

4). Thickness of Sublayers. The procedure requires that the asphalt layer be subdivided to take account of temperature gradients. The design manual recommendation of three sub-layers, the upper two being 1.57 inches thick (40mm) the third making up the balance of the thickness were adopted.

5). Data on traffic weight. This has been estimated. 6). The effective mean annual air temperature. This is obtained from a table which is reproduced in the program. The values used for this study are for New York, 66 degrees Farenheit (19 C) and for Houston, 77 degrees Farenheit (25 C).

7). The Softening Point of the asphalt cement. See appendix A.

8). The slope of the plot of the logarithm of the stiffness of the mix against the logarithm of the stiffness of the bitumen. (Logarithms are to the base 10). This was obtained from a linear regression of all creep data after it had been transformed to the required format.

9). The value of the mix stiffness at a bitumen stiffness of 1 psi. This was obtained from the regression analysis performed as part of step 8.

10). A proportionality factor "Z". This is obtained from a series of 96 tables in the manual. (Because of the volume of data in these tables time constraints and storage limitations this step was performed manually. The following data is necessary as input to the tables for the determination of Z.

1). The dynamic modulus of the subgrade. Estimates based on C.B.R. values are acceptable.(A C.B.R. value of 10% was used for the study.)

2). The total thickness of the combined base and subbase layers.

3). The thickness of the deepest of the three sublayers into which the asphalt layer had been subdivided.

4). The stiffness of the asphalt in the sublayer. Stiffness data derived from the dynamic stiffness test program was used for this determination together with a temperature derived from the manual which is described as "the effective annual air temperature" (Chart T).

5). The stiffness of the asphalt in sublayers 1 and 2 of the asphalt surfacing. The same data base was used for these layers as for layer 3 above. Appropriate temperatures were derived from chart T.

11). This completes the input of data to the program. The final step is to execute the program which provides a value of rut depth.

Discussion of Results

Rut depths were calculated for asphalt layer thicknesses of 4, 5, and 10 inch thick pavements. The first two thicknesses were derived from the computerised design method developed by the Corps of Engineers for Airfield pavements. A 10 inch thickness was selected to satisfy interest in thick asphalt pavements.

As indicated above the results have been transformed to a rutting index to focus attention on the relative merits of the different mixes. The baseline for the calculation of this index is mix B, for which the index has been set to unity. Since calculations were performed for mixes at two temperatures and three thicknesses the rut index has been calculated separately for each one. This eliminates the obvious trend of increasing rut depth as a function of increasing asphalt layer thickness, whilst showing up any differences which can be attributed to changes in the pavement structure.

The results of this study are shown in Table 4. The majority of mixes show definite improvements in resistance to permanent deformation over the control mix B. The exceptions are mix G, (one of the group classified as a rubber), and mix O. Predicted rut depths range from 2.26 to 3.05 times that of the control for G, and 4.04 to 5.15 for O. The changes in environmental conditions and pavement thickness do not affect the ranking order as determined by computed deformation significantly as the changes in temperature and reference stiffness affect the ranking by creep data. However the results do fall into groups according to the magnitude of the difference from the reference. The ranking by group is shown in Table 5. Mix L consistently shows the best performance by a significant margin. Mixes I,D, and P have very similar effects followed by F and K each in an individual group. Group 5 comprising mixes H,E,C, and J form a group within which the order changes with layer thickness and environment. However since these mixes all have similar performance the change in order is probably not significant.

As with the creep data the results indicate that classification by type is not an indicator of probable performance. This part of the analysis indicates that one of the plastics provides the best performance, the other representative of that group offering relatively small improvements. Group 2 contains one of the rubbers, one of the extenders and the oxidant. The mixes in group 5 offer only marginal improvement over the control, the group including two rubbers one extender and one hydrocarbon. This reinforces the observation made above that performance is not necessarily related to the general description of the modifier.

ANALYSIS OF THE REBOUND DATA

Introduction

The data analyses presented in the preceding sections has, to a large degree, been based upon the creep stiffness of the mix. Thus mixes with higher stiffness after a given period under sustained load would tend to achieve a higher position in the ranking order. This could however be quite misleading in relation to the possible value of an additive in relation to its ability to improve the resistance of a mix to the development of permanent deformation. To illustrate this point consider the case of a layer of perfectly elastic material resting on a rigid support. Since this layer is perfectly elastic, upon release of any applied load it would recover completely. This would be the case regardless of the elastic modulus of the material in this perfectly elastic layer. Thus a material could have a very low modulus of elasticity but not be subject to buildup of permanent deformation.

When the test programme for this project was being prepared it was felt that some of the additives included in the study could modify the behaviour of the mix to make it behave more like an elastic material, thus improving its recovery characteristics without increasing its stiffness. Hence a decision was taken to measure the recovery of samples for a period of one hour after the release the load applied in the creep test. This section is devoted to a discussion of the results from this part of the test program.

Discussion of results.

The results of the individual specimens were collected together according to test temperature and averaged. No attempt was made to utilize the techniques described in previous sections of this report to combine the data obtained at different temperatures.

The data was smoothed using the same curve fitting technique as for the creep data. (See appendix C.) The smoothed data was used to compute rates of recovery for each mix, at each temperature, 30, 60, and 3600 seconds after release of the load. Close examination of the recovery data suggested that in some cases the readings taken immediately upon release of the load could be unreliable and so the datum for the calculations was the deformation of the specimens after one second of recovery.

The percentage recovery after 3600 seconds was also determined from the smoothed data and as a percentage of the total deformation in the specimen one second after the load had been released.

Tables 6 and 7 show the ranking of the mixes and the data used to compute it, at 77 and 104 degrees Farenheit respectively. Mixes are listed according to their rate of recovery, high rates, which mean that the mix will recover more in a given time, appear towards the top of the table. It should be noted that mix K does not appear in Table 6. This is because the data did not produce results that were realistic.

Considering the results of the mixes tested at 77 degrees Farenheit alone, the greatest consistency with regard to ranking is shown at the bottom of the table. Mix P consistently shows the poorest performance, and mix H never climbs above three from the bottom. Amongst the other mixes there is considerable movement up and down the scale. As with the data discussed above the mixes have been collected into groups which are considered to have similar performance. This is shown in table 8 for the rebound at 77 degrees Farenheit. This approach highlights mixes O and L as always being in the top or second group. It also shows that the mixes are most clearly differentiated by their rate of recovery 30 seconds after release from load. If an extended period of time is available for recovery then there is little to choose between the majority of the mixes.

Applying a similar approach to the mixes tested at 104 degrees Farenheit it is noticeable that there is generally much more consistency in the ranking of the mixes and greater differentiation at all points of comparison. Table 9 shows the grouping of the results and highlights mix B as having the best performance and mixes L and O as consistently second equal.

Comparing the ranking of the mixes at the two temperatures indicates that there are significant changes between the relative performance of some mixes at different temperatures. Mix L ranked at number 2 is the only mix to retain its ranking regardless of temperature. Since this is a high ranking this mix rates as the one with the best all round recovery characteristics. Mixes B, H, G, I, C, and P all improve there ranking at the higher temperature, which could be considered an advantage since the problem of permanent deformation is always accentuated at higher temperatures.

Rankings for the mixes at 77 and 104 degrees Farenheit have been determined by assigning a score to each mix according to its position as shown in Tables 6, and 7. An overall ranking has been obtained by combining the scores of the mixes at both temperatures. This is shown in Table 9. The final ranking, arrived at by grouping mixes with similar overall ranking scores, is shown in Table 10. It should be noted that the control mix, B, is in the highest ranking group derived from this analysis.

Considering the ranking by group as shown in table 10 in relation to the classification of the individual modifiers it is clear that the type of additive used is not an indication of its likely performance. As noted above the control mix is in the group with the best performance. Also in this group are a plastic and a fiber. Since the rest of the mixes show inferior performance further discussion of this point is perhaps academic, but is included so that a full picture can be presented. The second performance group contains a filler, the third a hydrocarbon and two of the rubbers. The forth group is another of the rubbers, and the fifth group a hydrocarbon a filler and a rubber. The last group contains a filler and the oxidant.

RANKING THE ADDITIVES

As indicated in the introduction the binder contents of the mixes used in this study were determined on the basis of a void content of 4%. This means that a valid comparison of mixes has been obtained. However this has lead to mixes having different binder contents and different asphalt cement contents. These differences could possibly be the reason for some, though not all, of the performance differences which have been measured. In recognition of this fact an attempt was made to develop adjustment factors to normalise the data from each mix to a common binder content for the purpose of isolating the effects of the additives. Preliminary calculations made to investigate the feasibility of this approach indicated that considerable work would be necessary and that any conclusions reached would be suspect. Since a study of this sort was beyond the remit of the project it was not pursued.

RANKING THE MIXES

The creep - recovery data generated in this study has been analysed in several different ways. These include the creep stiffness of the mix, measures of the degree of modification of the behaviour of the mix, estimated deformation in the mixes, and the recovery upon release of the load. Each of these evaluations has been carried out at different temperatures and, where appropriate, for different pavement structures. Whilst some of these analyses relate to similar aspects of the performance of the mixes in pavements it is not the case for all of them. Thus strengths and weaknesses of various mixes in different environments have, to some extent been identified. An all-round ranking can be generated from this data, and such an approach is attractive from a traditional view of pavement engineering. However this view may lead to inefficient utilization of the advantages to be gained from specific formulations.

For example the recovery characteristics of a mix are only of significance if it deforms under load. If the mix is inherently resistant to deformation, or is included in a pavement structure in such a manner that it is not subject to deformation, then the recovery characteristics are not a primary factor in decisions relating to its use. Also a formulation which shows potential performance advantages in a hot environment at the expense of low temperature performance should not be rejected simply because it does not have all round performance. Additives offer the potential to tailor mixes to meet particular performance requirements and when combined with the mechanistic approach to pavement design offer greater opportunities than have been available in the past to exploit a full cost - performance optimization for pavement design and rehabilitation.

An overall ranking has been obtained by combining the "ranking scores" of each mix in each of the ranking exercises. This is presented in Table 12, in which mixes of similar overall performance have been collected together.

CONCLUSIONS

1) Mixes containing additives L,I,H,F,D,P,and C all exhibit superior overall performance to the control mix B. The mix with additive E has the same performance.

2) The mix containing additive L, shows the most significant overall improvement with mix I taking second place. In terms of overall performance there is no significant difference in the gain that can be achieved from mixes containing additives D, F, H, and P.

3) Consideration should be given to specific advantages which may accrue from using a particular additive even though its overall ranking is not particularly high.

4) There is an urgent need to integrate mix design with the structural design of the pavement in order that efficient use can be made of the significant performance advantages available from some of the additives. This approach would also assist in overcoming the deficiencies in some of the mixes. It is suggested that most of the technology required for this integrated approach is already in existence.

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TABLE 1 Computed softening point and Penetration Index (P.I.)

Asphalt Cement (degrees C)	Softening Point	Penetration Index
AC-20	45.5	-1.4
AC-40	56.4	-0.6

TABLE 2 Comparison of Mix Stiffness at a range of bitumen stiffnesses

Sbit = 1.8 psi		Sbit = 1.45 psi		Sbit = 0.04 psi	
Mix Code	Smix (psi)	Mix Code	Smix (psi)	Mix Code	Smix (psi)
P	235659	P	139432	P	104926
C	136160	C	75008	C	57588
K	107739	K	62621	D	52619
D	100731	D	62427	L	51986
E	94312	L	59341	K	49204
G	89290	E	54963	I	46184
I	84025	I	54258	E	42808
H	81961	F	49106	F	40532
L	81150	J	45480	J	35937
J	76666	G	45149	H	35827
F	74402	H	44943	A	34354
B	72929	B	43626	B	33646
A	68008	A	41006	G	33109
O	58700	O	28477	O	21743

TABLE 3 Mixes ranking by groups of similar performance

S bit = 0.145 psi	S bit = 1.8 psi	S bit = 0.04 psi
P	P	P
C	C	C
K,D	K,D	D,L,K
I,E	E,G	I
F	I,H,L	E,F
J,G,H,B,A	J,F,B	J,H,A,B,G

TABLE 4 Ranking by 'Rut Index'

4 inch Pavement				5 inch Pavement				10 inch Pavement			
Low Temp.		High Temp.		Low Temp.		High Temp.		Low Temp.		High Temp.	
Mix Code	Rut Index	Mix Code	Rut Index	Mix Code	Rut Index	Mix Code	Rut Index	Mix Code	Rut Index	Mix Code	Rut Index
L	.2	L	.15	L	.19	L	.14	L	.16	L	.14
I	.3	I	.23	I	.27	I	.22	I	.22	I	.21
D	.35	D	.26	D	.31	D	.24	D	.24	D	.23
P	.35	P	.28	P	.35	P	.27	P	.31	P	.23
F	.5	F	.36	F	.46	F	.35	F	.37	F	.37
K	.7	K	.54	K	.62	K	.51	K	.47	K	.48
H	.85	C	.67	C	.69	H	.65	H	.59	H	.63
E	.85	H	.69	H	.77	E	.67	J	.65	E	.64
C	.85	E	.78	J	.77	J	.67	C	.65	J	.64
J	.85	J	.78	E	.81	C	.69	E	.82	C	.74
B	1	B	1	B	1	B	1	A	.86	A	.93
A	1.05	A	1.08	A	1	A	1.02	B	1	B	1
G	3.05	G	2.79	G	3.0	G	2.57	G	2.9	G	2.26
O	4.85	O	5.15	O	4.62	O	5.13	O	4.04	O	4.94

TABLE 5 Peformance groups based on Rut Index

Mix
L
I,D,P
F
K
H,E,C,J
B,A
G
O

TABLE 6 Rebound parameters at 77 degrees Farhenheit

Recovery Rate							
30 sec		60 sec		3600 sec		% Recovery	
O	20.0	O	16.7	J	7.8	F	46.0
L	20.0	L	16.7	L	1.6	B	45.1
F	16.7	A	11.7	F	1.6	E	36.0
A	13.3	F	10.0	O	1.5	G	34.9
J	13.3	J	10.0	G	1.1	L	33.5
D	13.3	D	8.3	E	1.1	D	32.7
C	10.0	B	6.7	A	0.9	J	24.4
I	6.7	G	5.0	I	0.7	C	22.7
H	3.3	E	5.0	H	0.6	I	22.2
G	1.7	H	3.3	C	0.5	H	19.8
P	0	P	0	P	0.5	P	17.1

TABLE 7 Rebound parameters at 104 degrees Farenheit

Recovery Rate							
30 sec		60 sec		3600 sec		% Recovery	
B	73.3	B	48.3	O	1.5	B	58.5
L	57.0	L	40.0	B	1.5	L	45.8
O	56.7	O	40.0	L	1.5	O	45.8
F	40.0	G	26.7	G	1.2	H	39.4
G	33.3	F	25.0	H	0.7	A	35.9
H	30.0	A	20.0	F	0.7	P	33.3
E	26.7	H	18.3	C	0.6	I	29.4
A	26.7	I	15.3	P	0.6	C	28.8
I	23.3	C	13.3	I	0.6	F	26.6
C	20.0	K	11.7	E	0.6	G	26.5
K	16.7	J	11.7	K	0.5	K	23.7
D	16.7	P	10.0	A	0.5	E	22.8
J	16.7	D	10.0	J	0.4	J	19.2
P	16.7	E	1.8	D	0.3	D	15.0

TABLE 8 Group ranking from 77°F rebound tests

Recovery rate			
30 sec	60 sec	3600 sec	% Rebound
O,1	O,L	J	F,B
F	A	L,F,O	E,G,L,O,D
A,J,D	F,J	G,E,B,D,A	A,J,C,I
B,C,E	D,I	I	H
I	B,C	H	P
H	G,E	C	
G	H	P	
P	P		

TABLE 9 Group ranking from 77°F rebound tests

30 sec	60 sec	3600 sec	% Rebound
B	B	O,B,L	B
L,O	L,O	G	L,O
F	G,F	H,F	H
G,H	A,H	C,P,I,E	A,P
E,A	I	K,A	I,C
I	C	J	F,G
C	K,J	D	K,E
K,D,J,P	P,D		J
	E		

TABLE 10 Overall ranking from rebound rests (excluding % recovery)

77°F test	104°F tests	Combined
O	B	L
L	L	O
F	O	B
J	H	F
A	F	A
D	G	H
B	A	G
E	I	I
I	C	C
C	E	E
G	K	J
H	J	D
P	P	P
	D	

TABLE 11 Overall ranking by group, from the rebound data

Mix
L,O,B
F
A,H,G
I
C,E,J
D,P

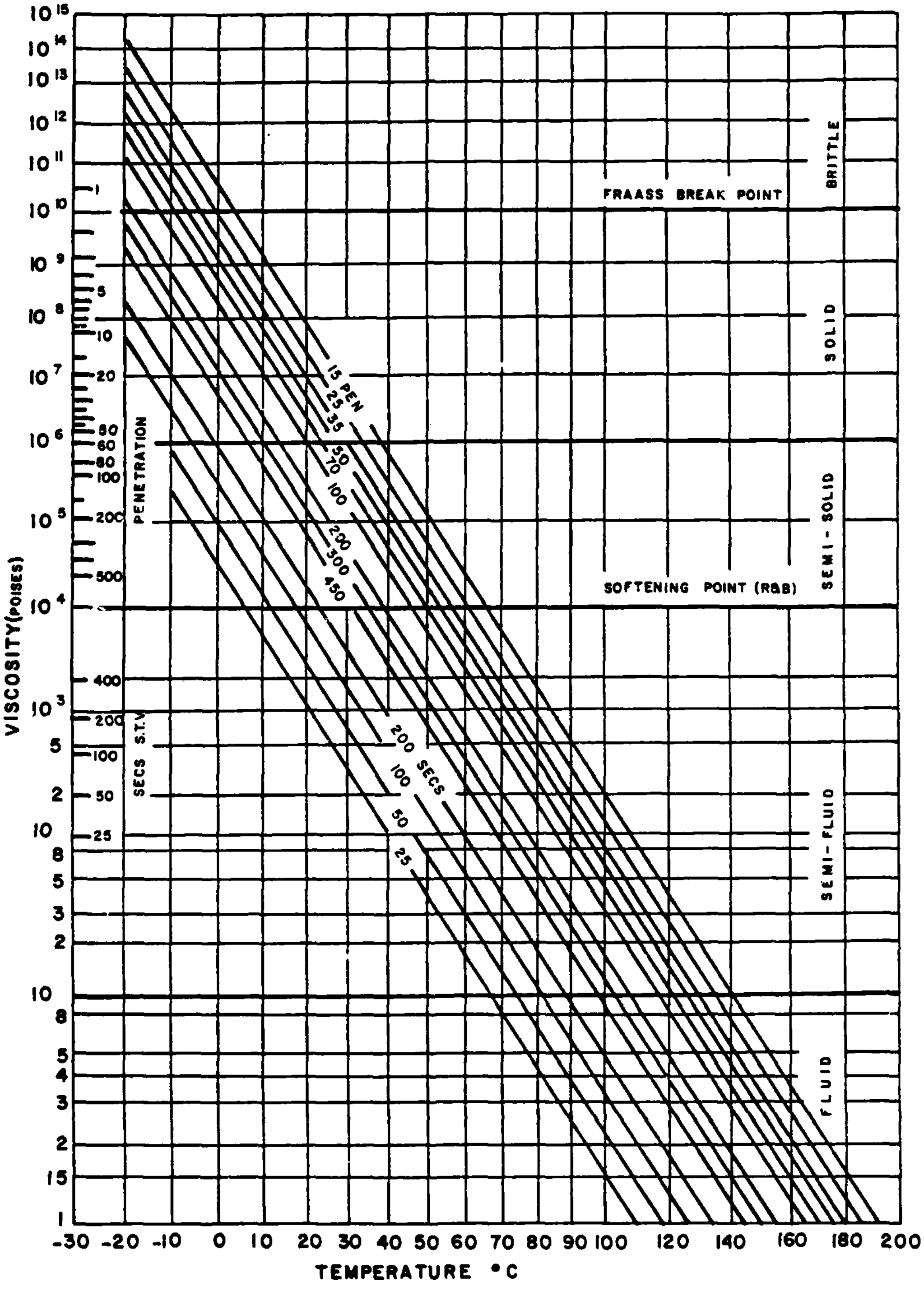

FIGURE 1. General viscosity—temperature relationship

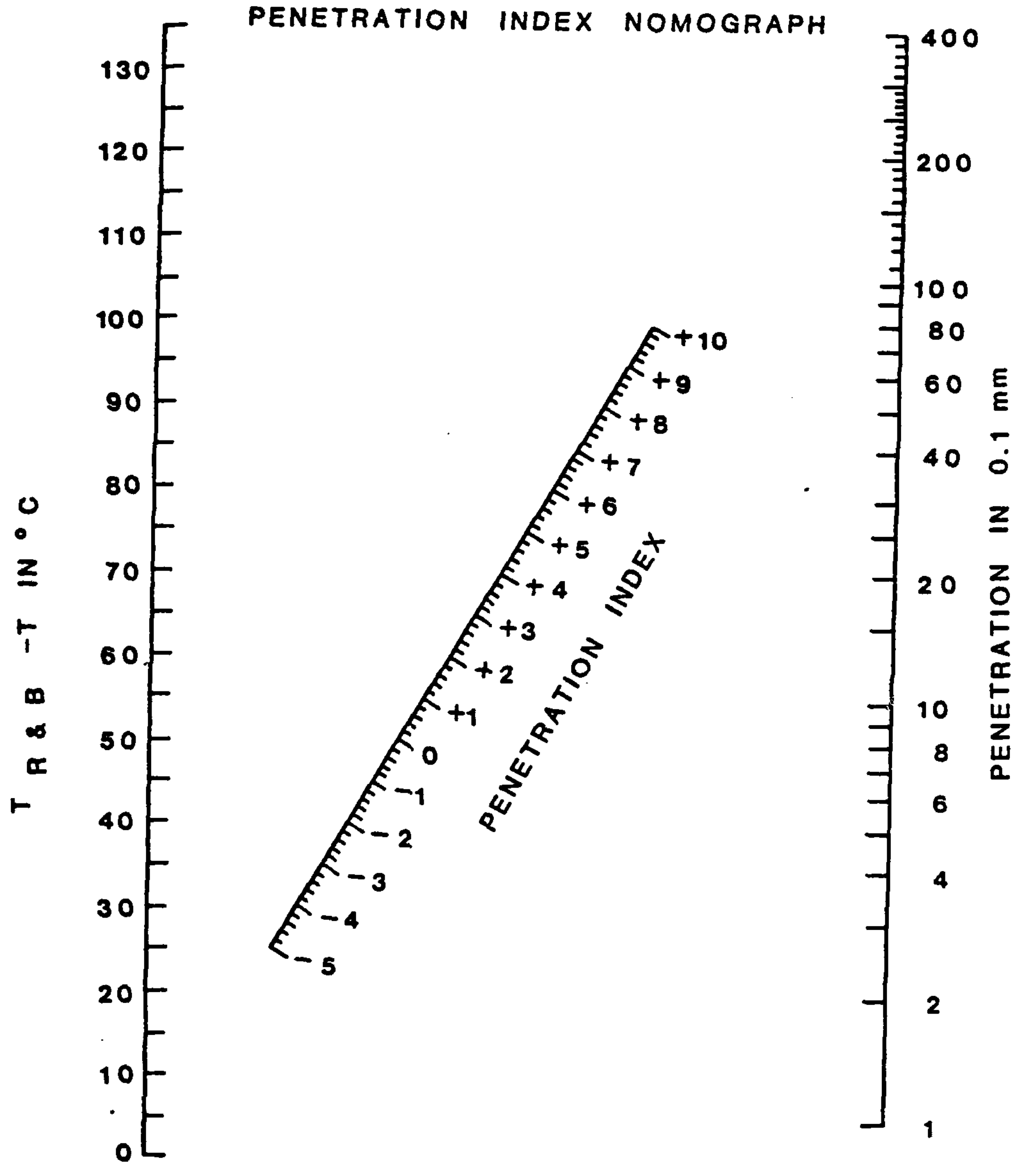

FIGURE 2. Penetration index nomograph

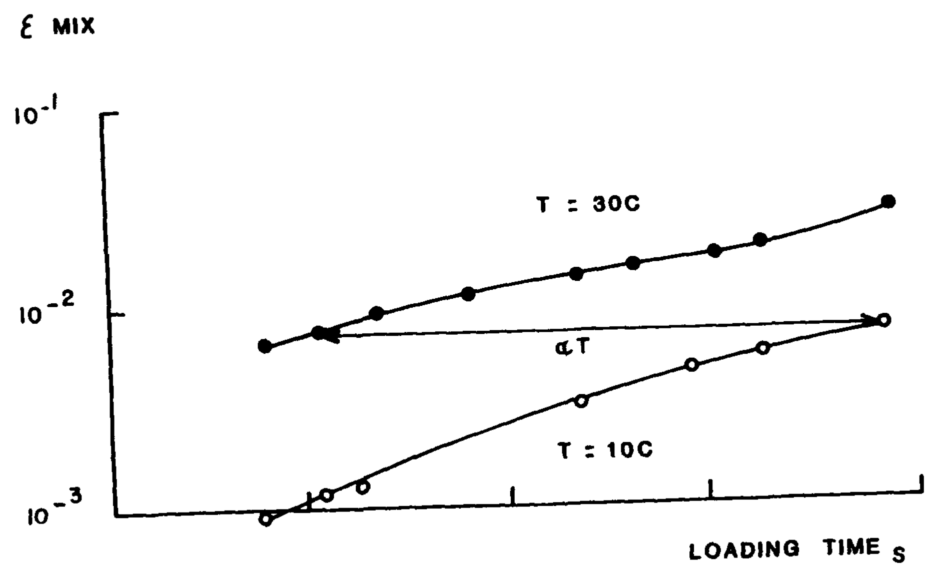

FIGURE 3. Strain vs time at two temperatures

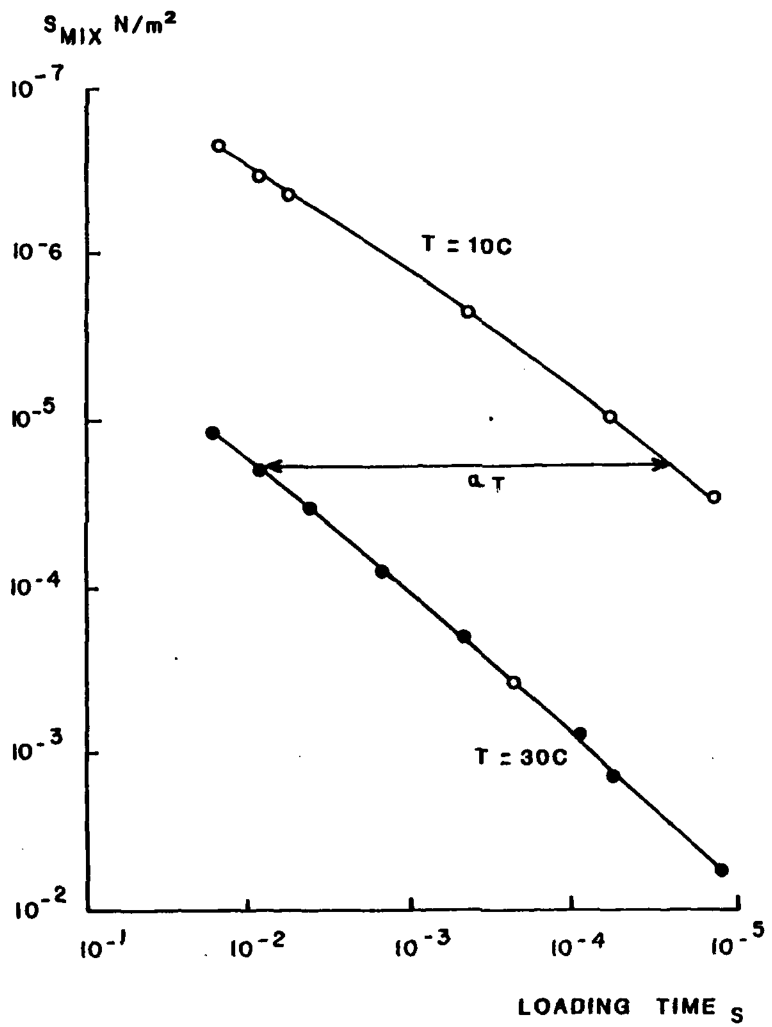

FIGURE 4. Smix vs time at two temperatures

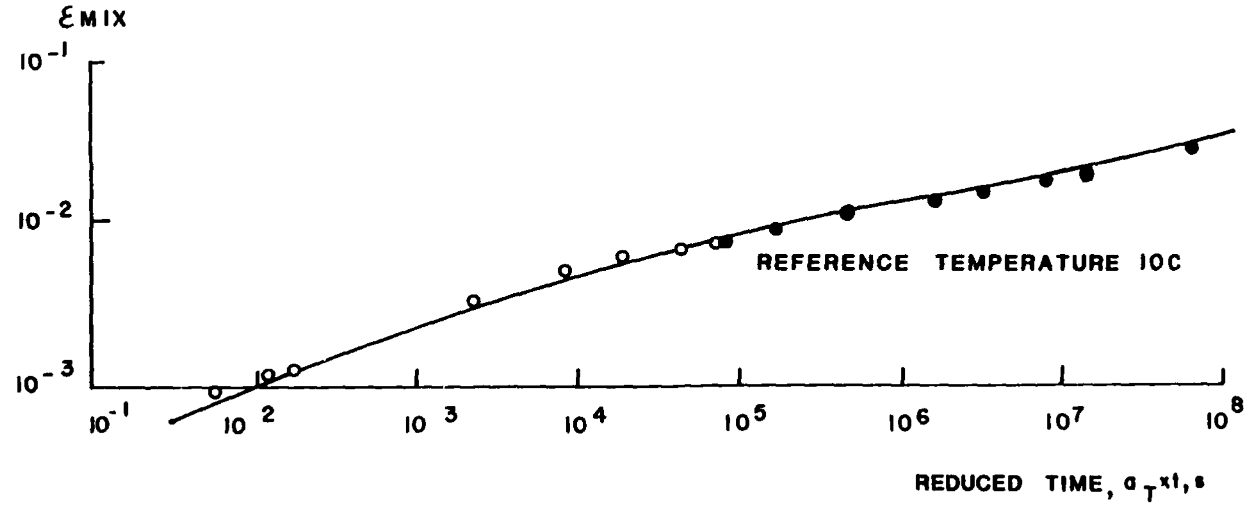

FIGURE 5. Strain in the mix as a function of reduced time

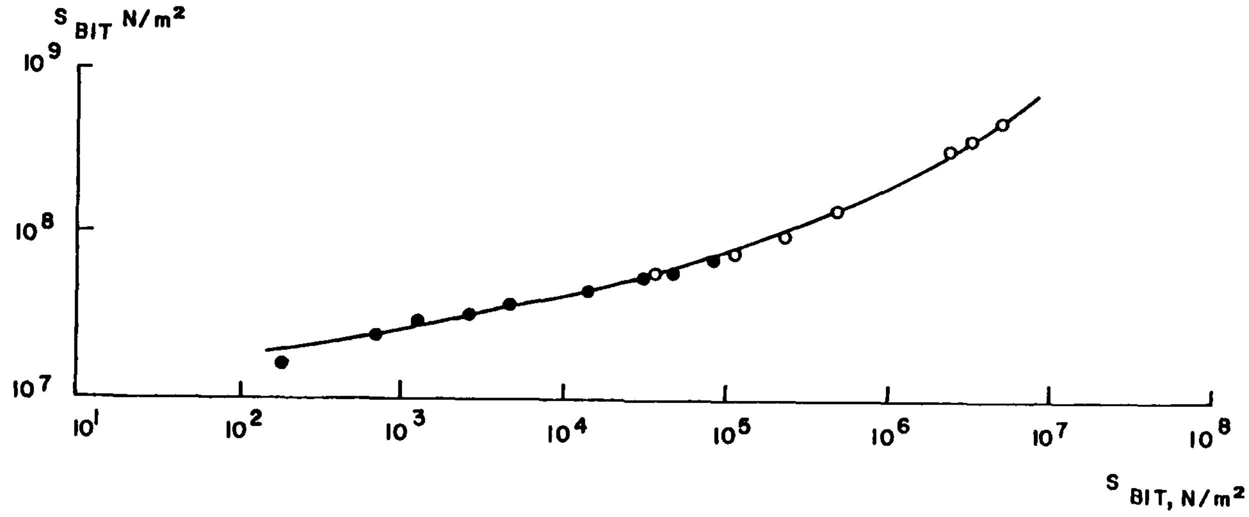

FIGURE 6. Stiffness of the mix as a function of stiffness of the bitumen

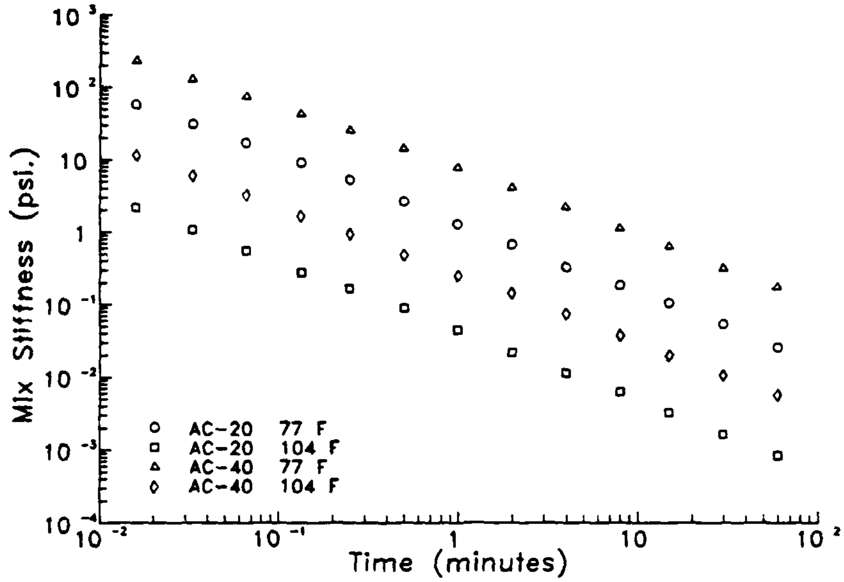

FIGURE 7. Calculated stiffness – time relationships

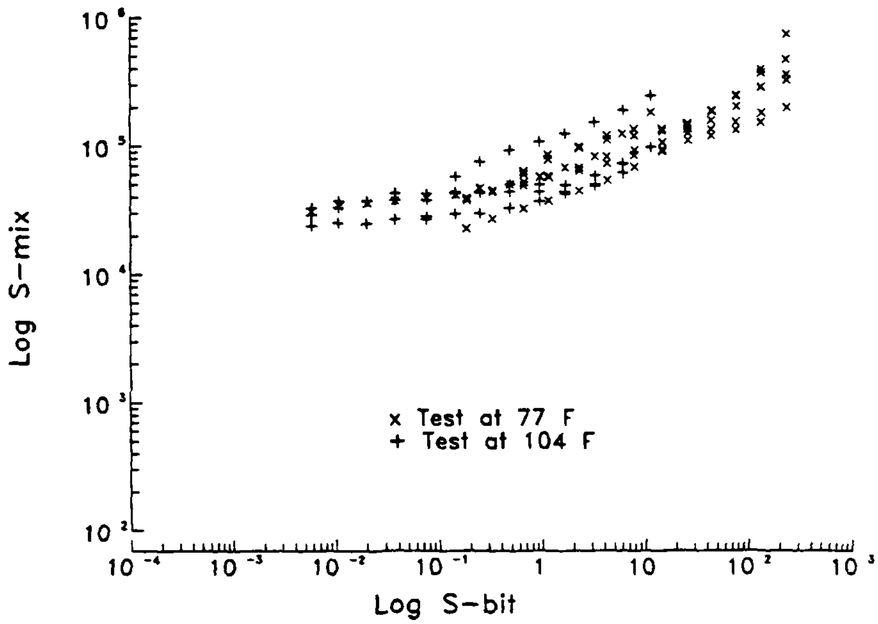

FIGURE 8. Creep data for mix A

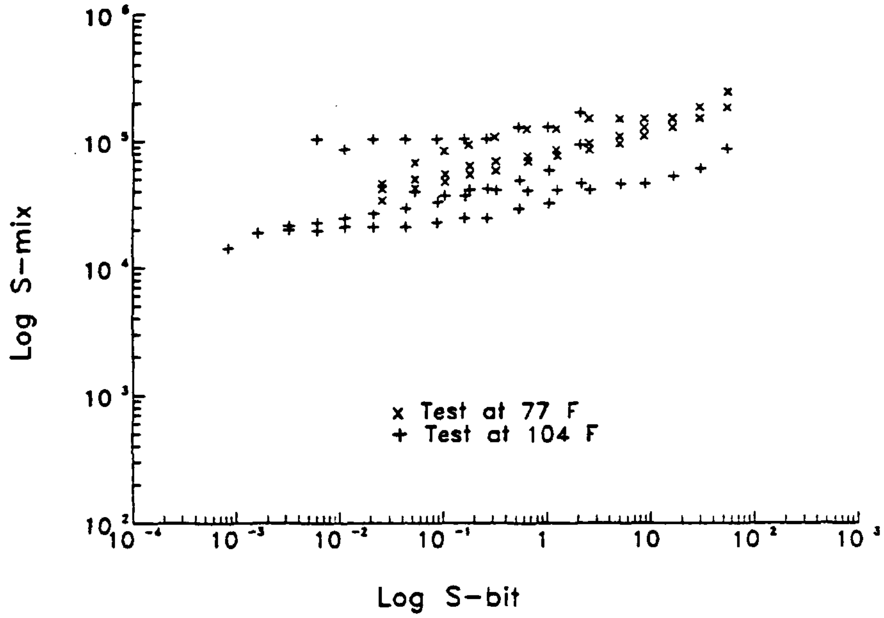

FIGURE 9. Creep data for mix B

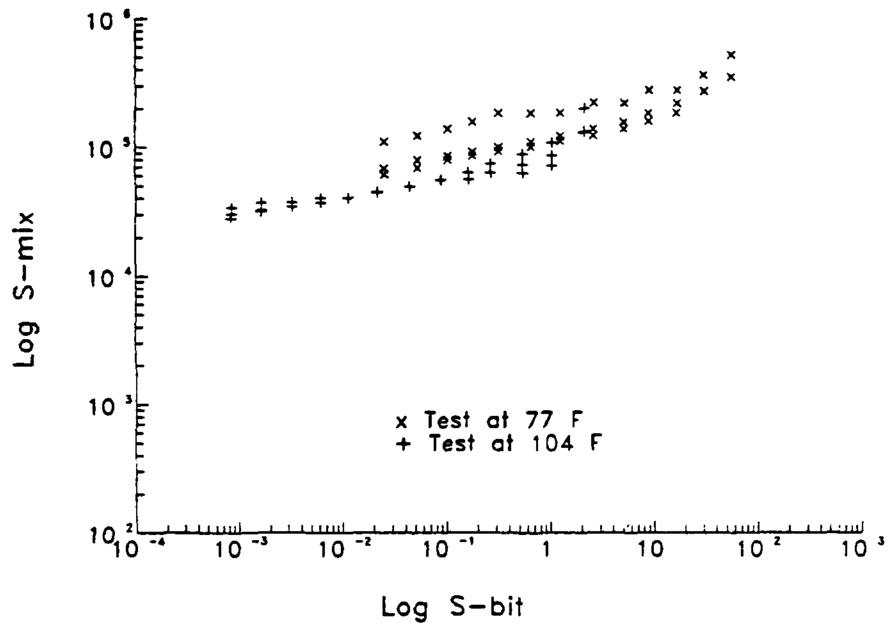

FIGURE 10. Creep data for mix C

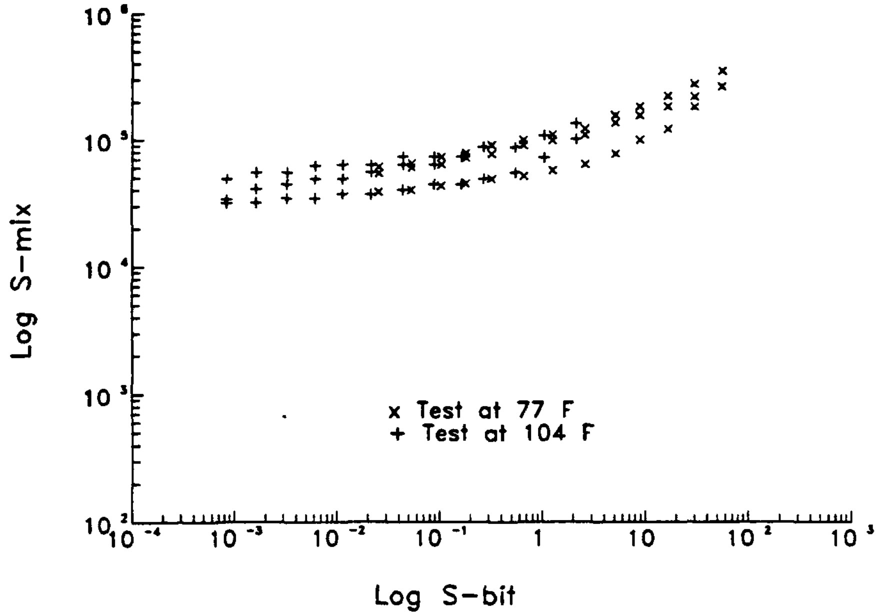

FIGURE 11. Creep data for mix D

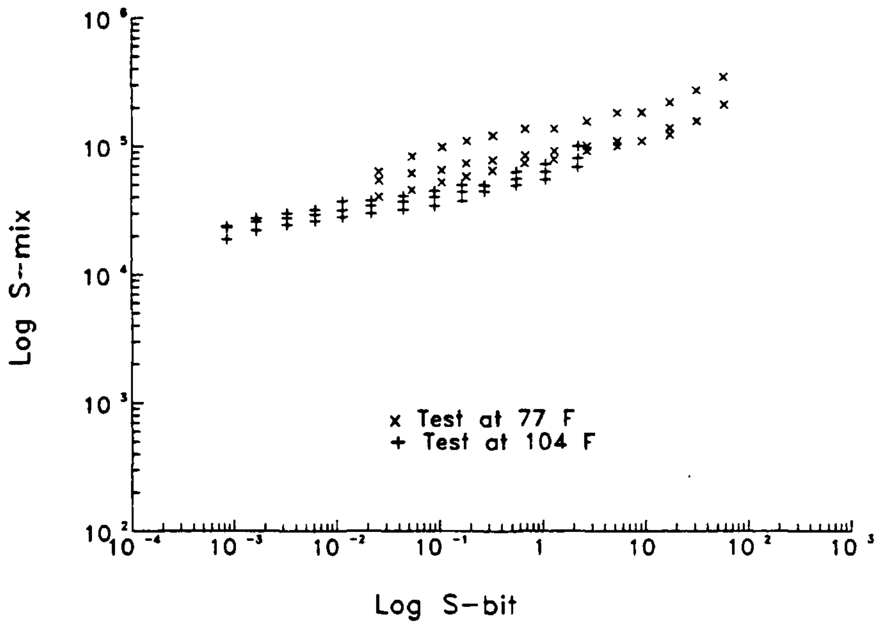

FIGURE 12. Creep data for mix E

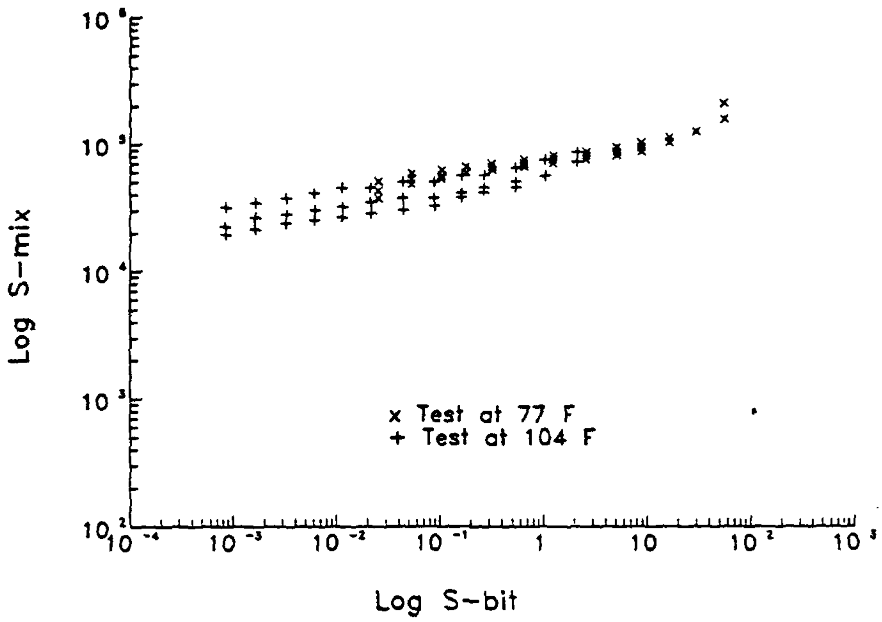

FIGURE 13. Creep data for mix F

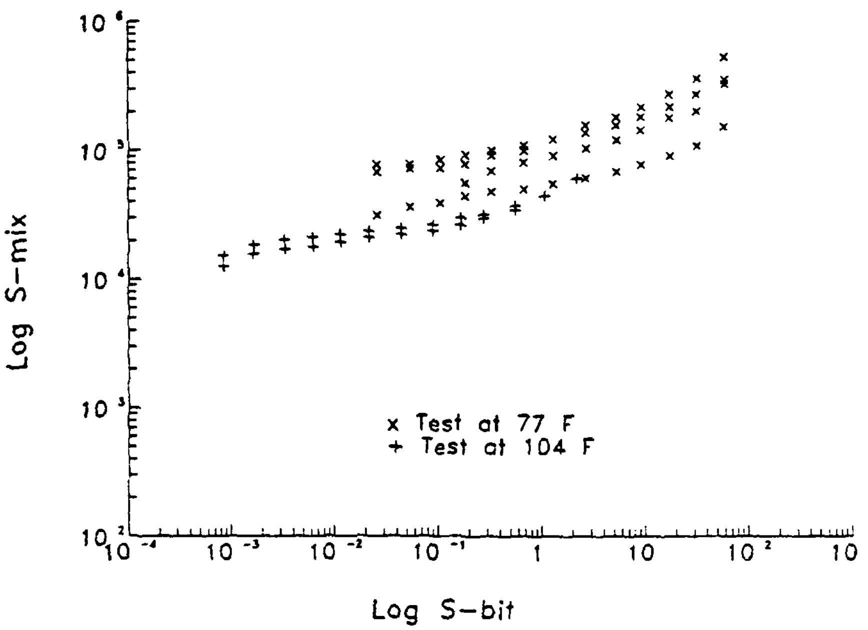

FIGURE 14. Creep data for mix G

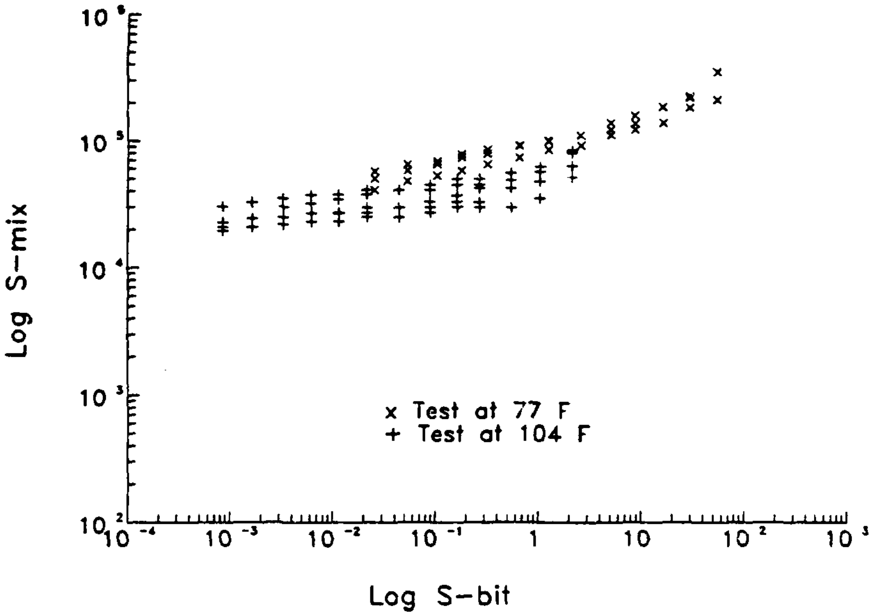

FIGURE 15. Creep data for mix H

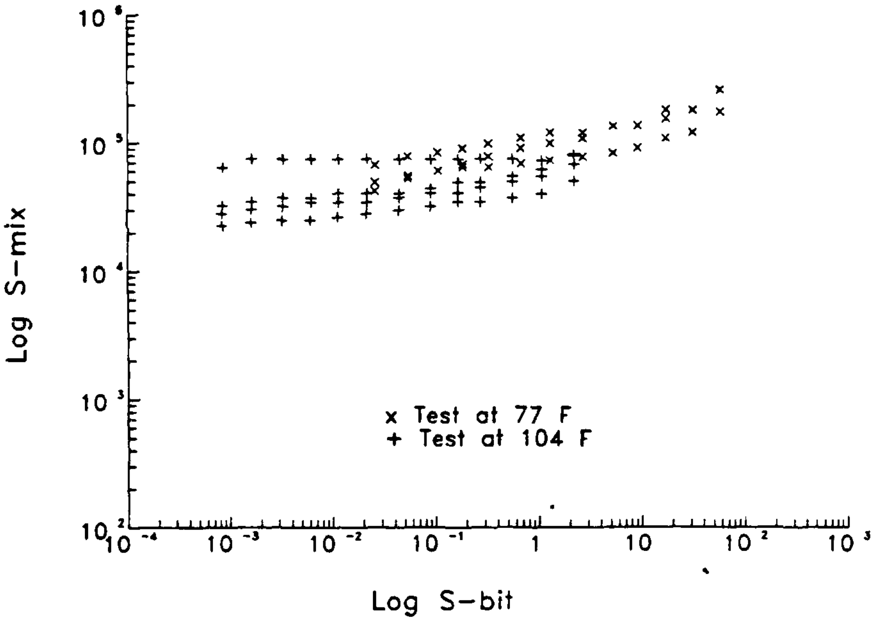

FIGURE 16. Creep data for mix I

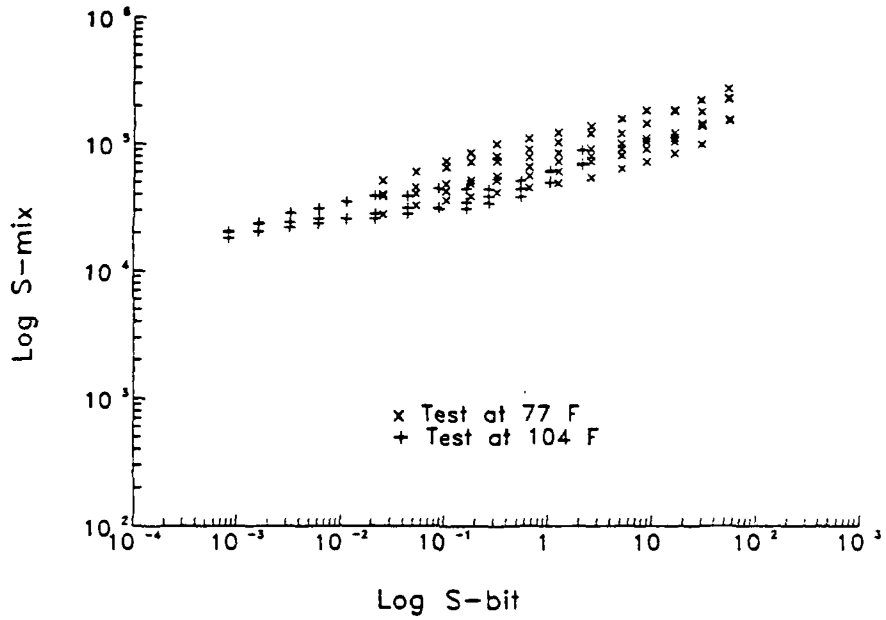

FIGURE 17. Creep data for mix J

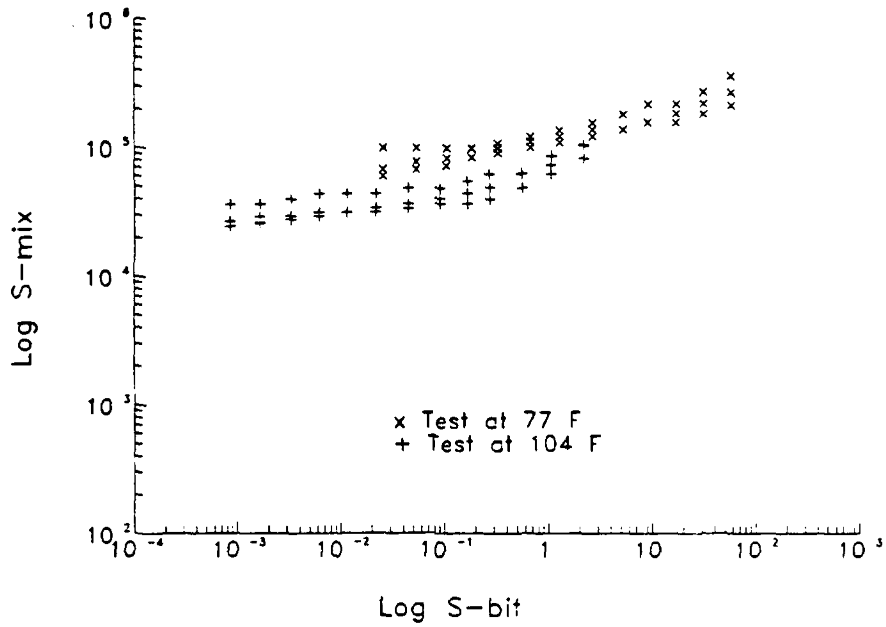

FIGURE 18. Creep data for mix K

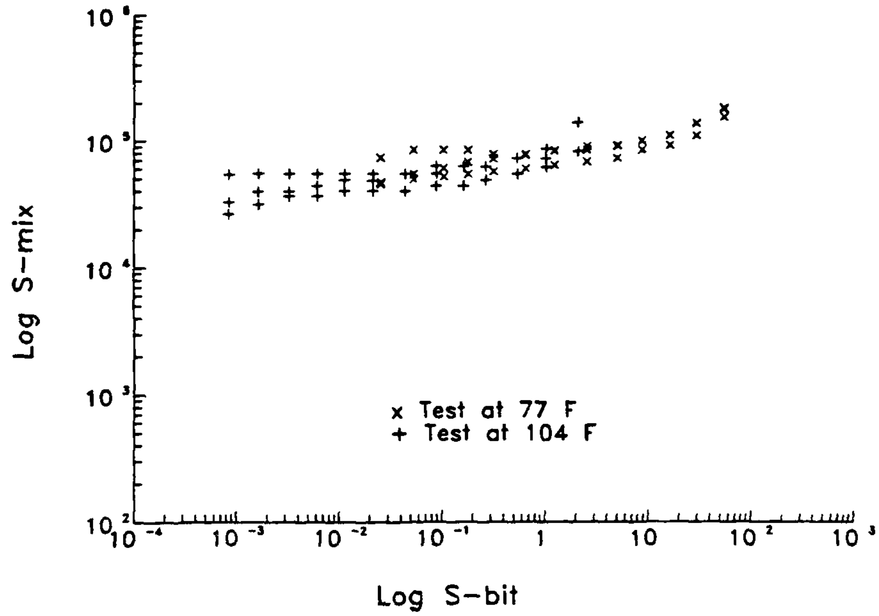

FIGURE 19. Creep data for mix L

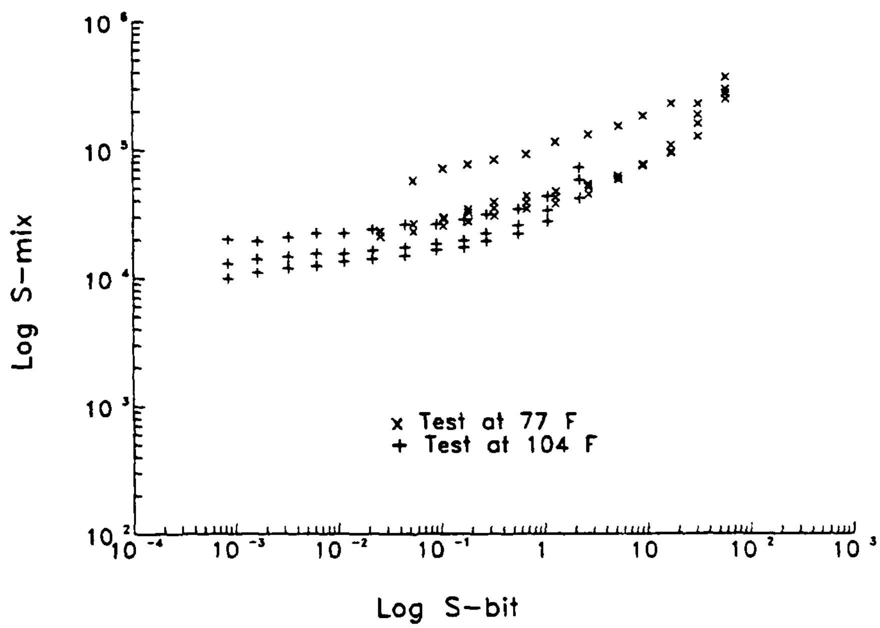

FIGURE 20. Creep data for mix O

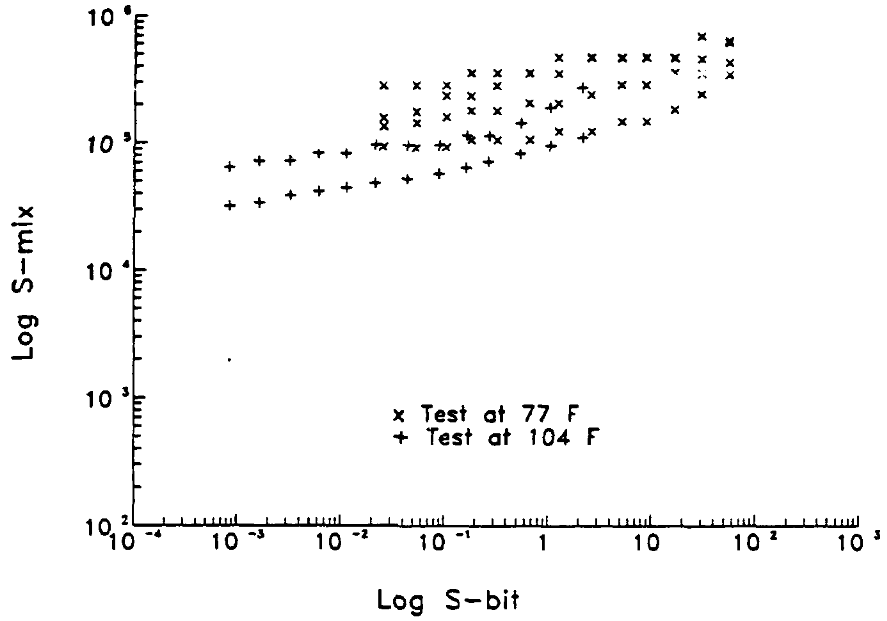

FIGURE 21. Creep data for mix P

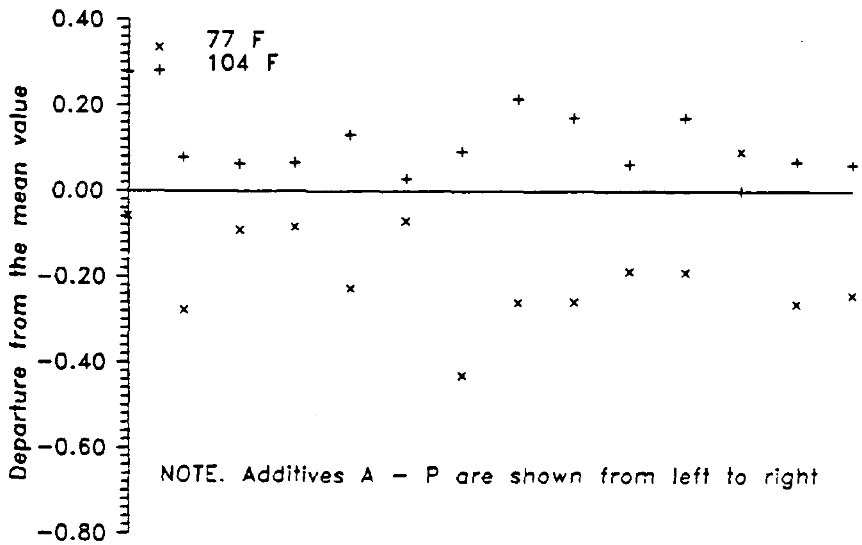

FIGURE 22. Departure from the mean value of mix stiffness at an asphalt cement stiffness of 1.8 psi.

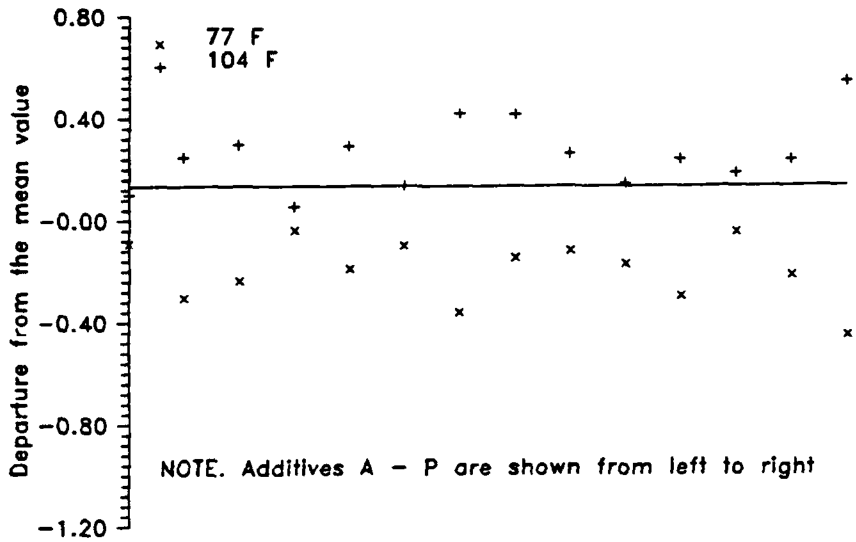

FIGURE 23. Departure from the mean value of mix stiffness at an asphalt cement stiffness of 0.145 psi.

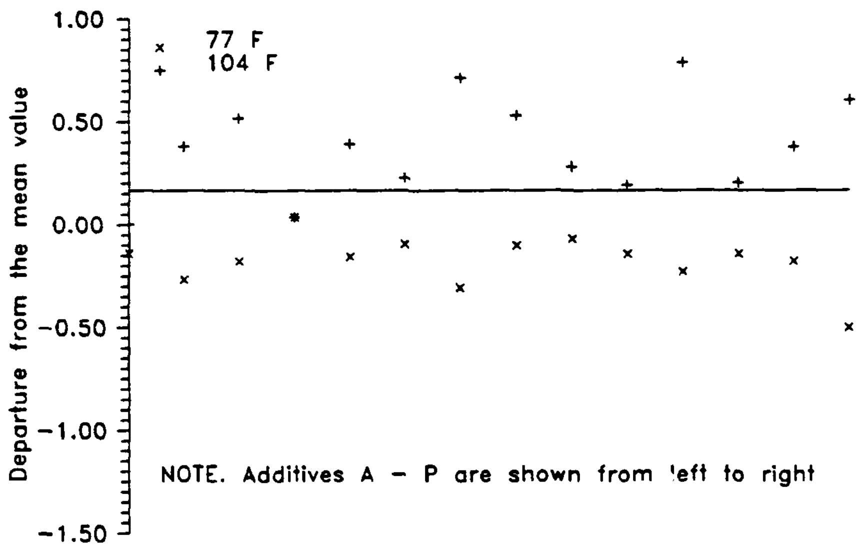

FIGURE 24. Departure from the mean value of mix stiffness at an asphalt cement stiffness of 0.04 psi.

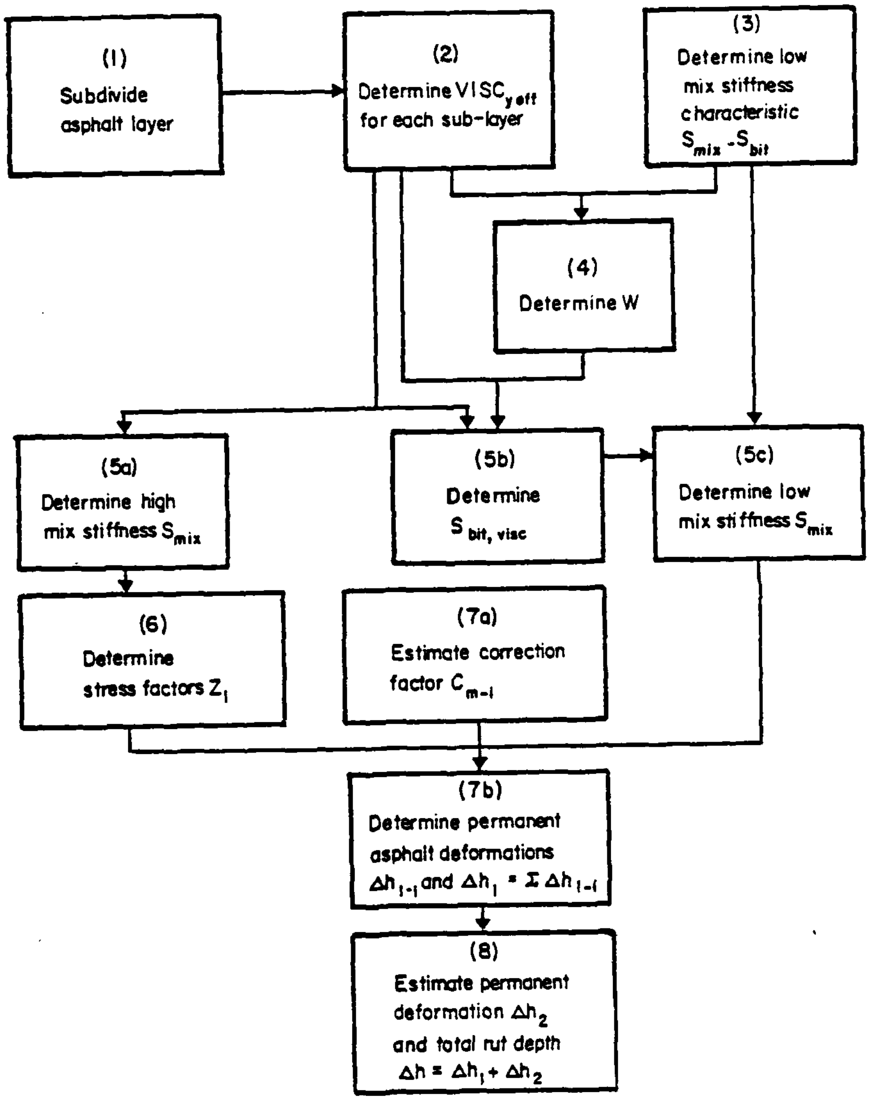

FIGURE 25. Flow chart for the computation of permanent deformation

APPENDIX A.

ASPHALT CEMENT TEST DATA

TEST	AC-20	AC-40
Viscosity 140 F (poise)	2138	3256
Viscosity 275 F (cst.)	478	334
Penetration 77 F,100g,5sec.	85	39
Flash point (Cleveland open cup)	450+	450+
Solubility in trichloroethylene %	99.95	99.98
Spot test	negative	negative
THIN FILM OVEN RESIDUE		
Viscosity 140 F (poise)	4651	6562
Ductility 77 F,5cm/min.	150+	150+ L.

APPENDIX B.

PLOTS OF AVERAGED CREEP DATA

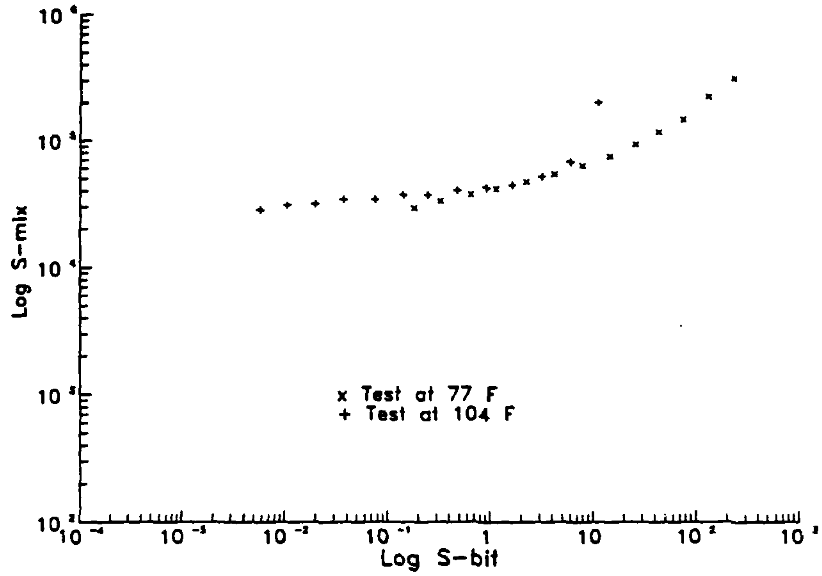

FIGURE B1. Averaged creep data for mix A at 77 and 104 degrees F.

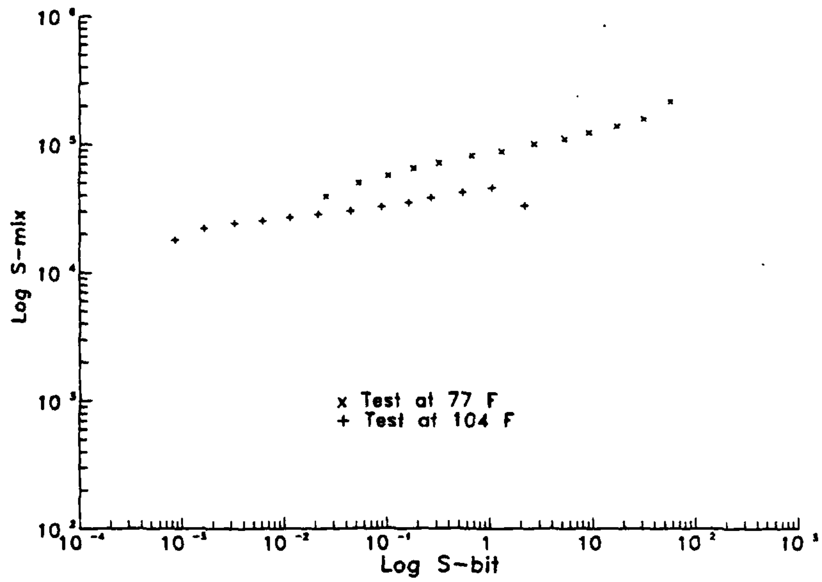

FIGURE B2. Averaged creep data for mix B at 77 and 104 degrees F.

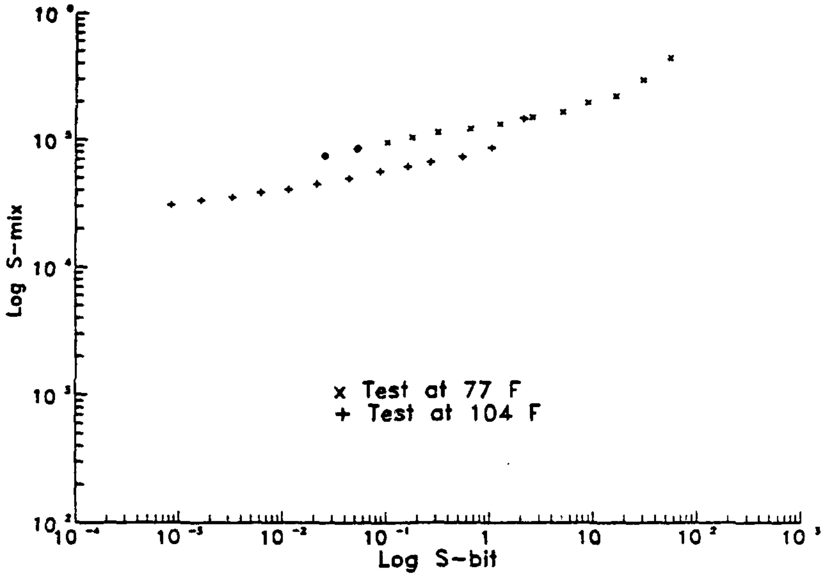

FIGURE B3. Averaged creep data for mix C at 77 and 104 degrees F.

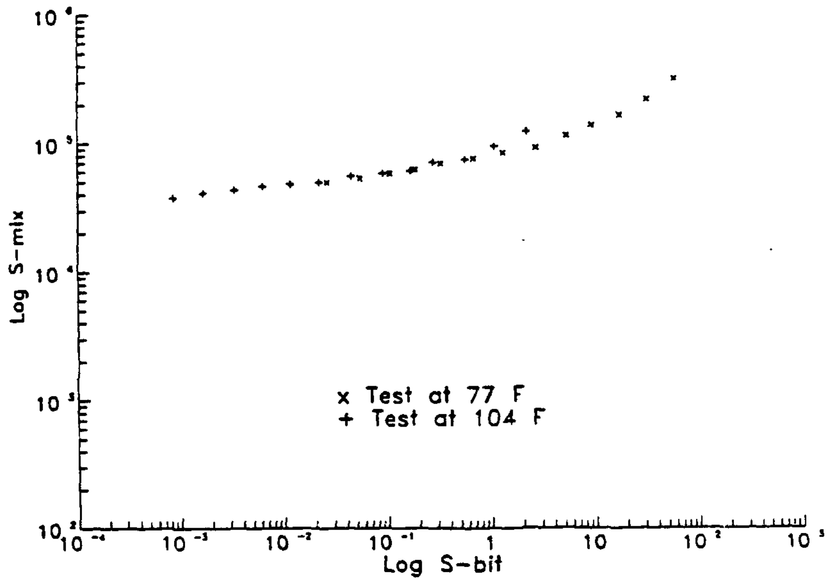

FIGURE B4. Averaged creep data for mix D at 77 and 104 degrees F.

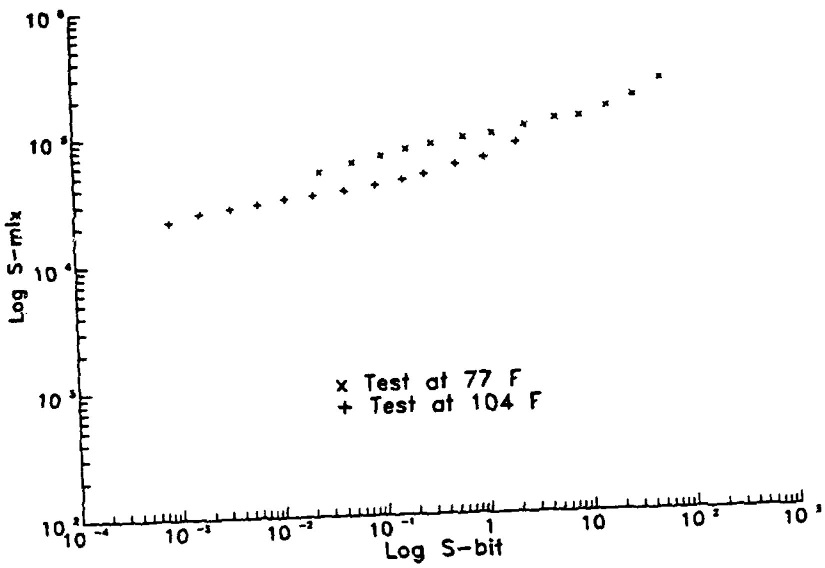

FIGURE B5. Averaged creep data for mix E at 77 and 104 degrees F.

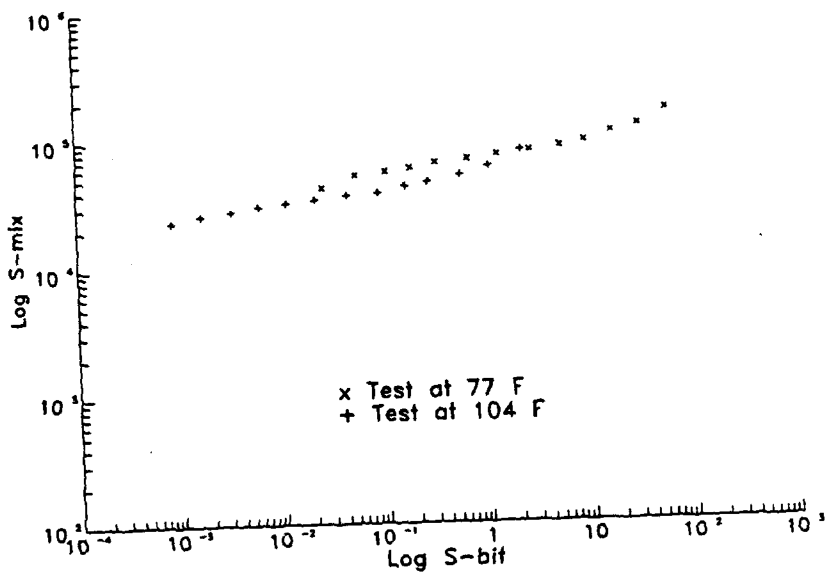

FIGURE B6. Averaged creep data for mix F at 77 and 104 degrees F.

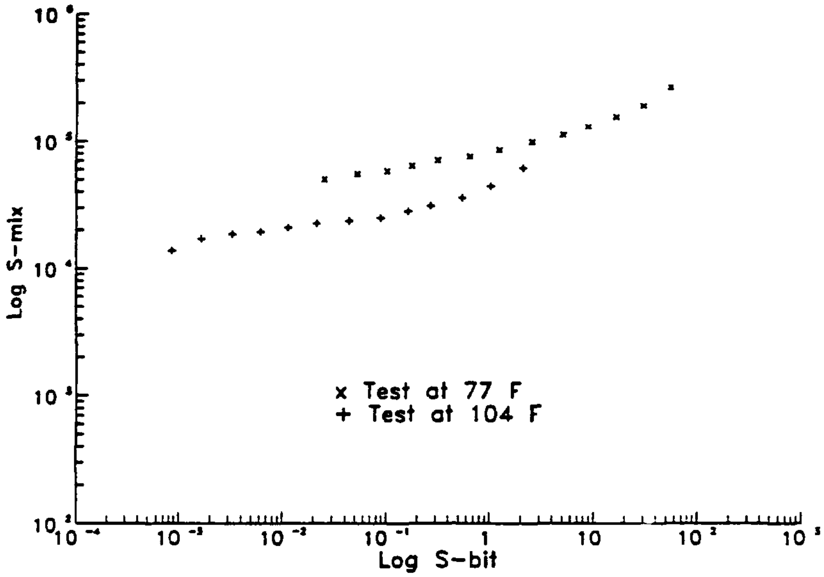

FIGURE B7. Averaged creep data for mix G at 77 and 104 degrees F.

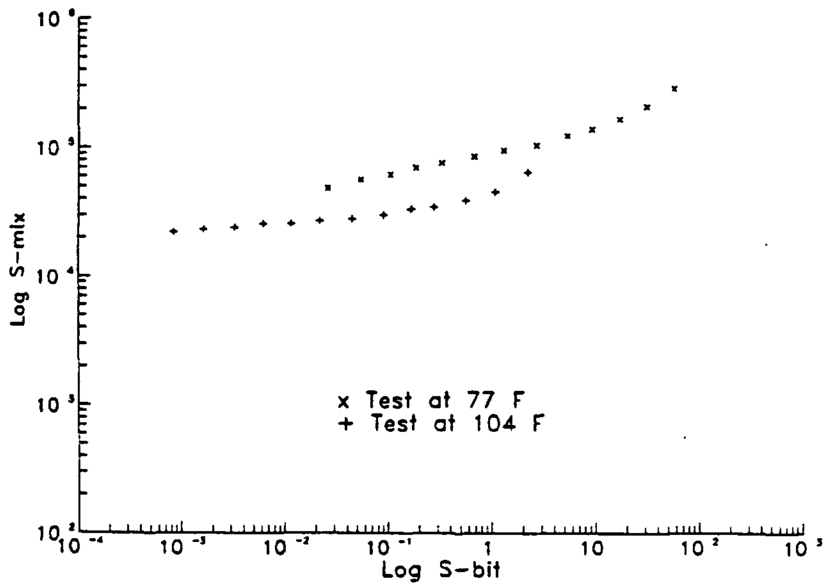

FIGURE B8. Averaged creep data for mix H at 77 and 104 degrees F.

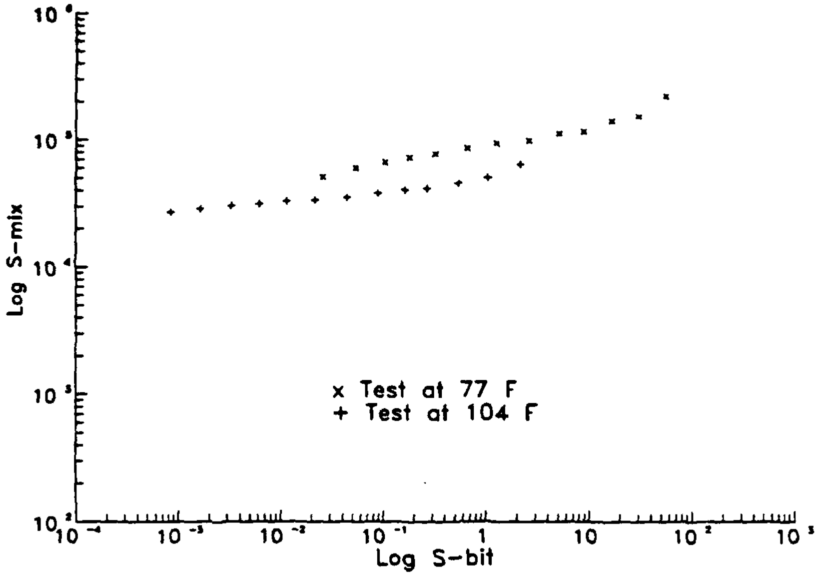

FIGURE B9. Averaged creep data for mix I at 77 and 104 degrees F.

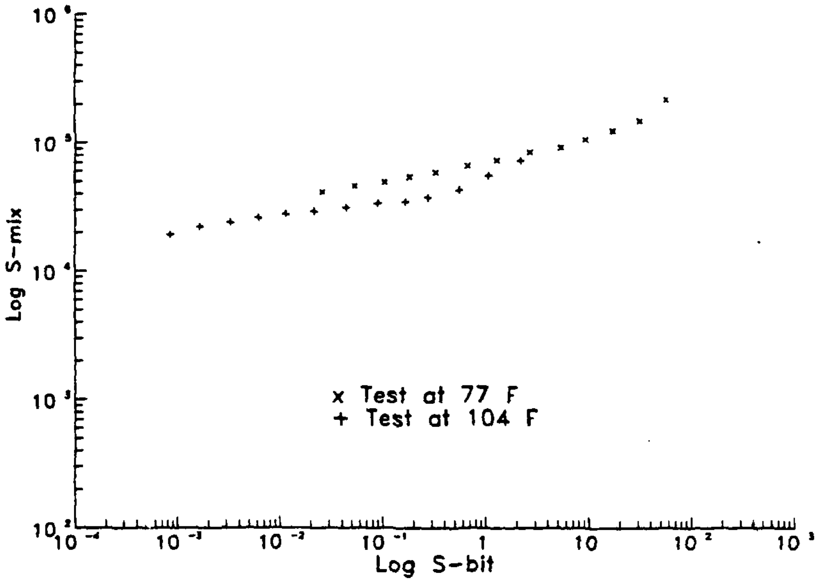

FIGURE B10. Averaged creep data for mix J at 77 and 104 degrees F.

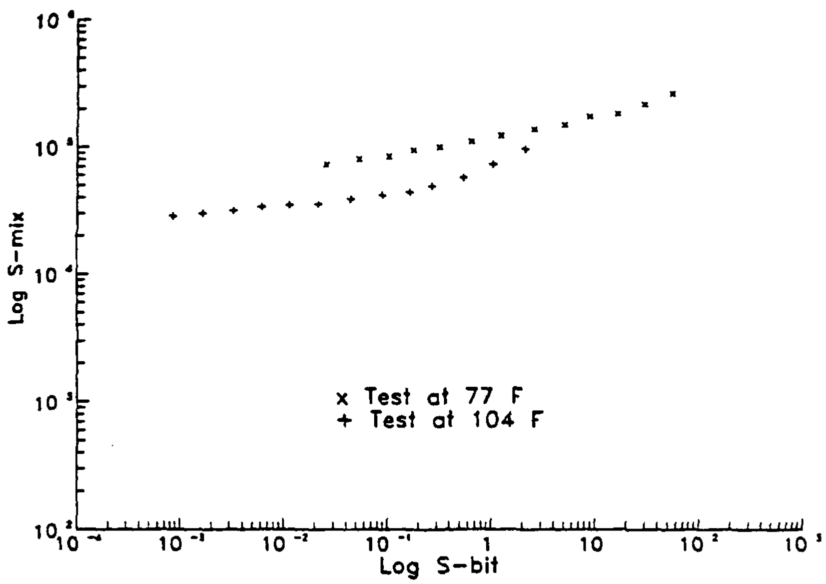

FIGURE B11. Averaged creep data for mix K at 77 and 104 degrees F.

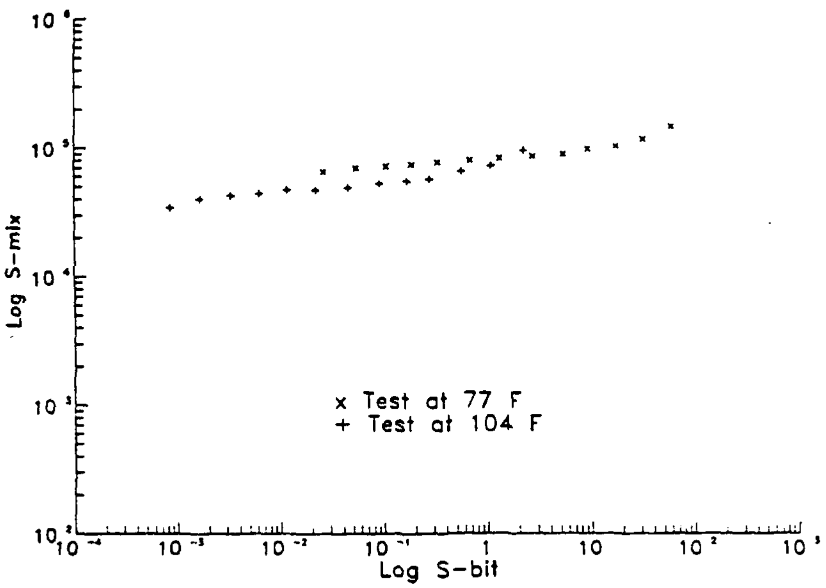

FIGURE B12. Averaged creep data for mix L at 77 and 104 degrees F.

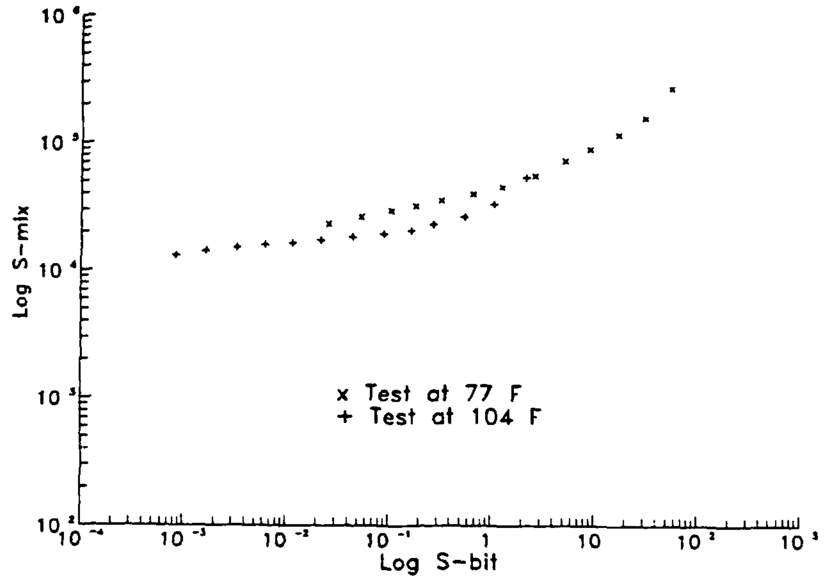

FIGURE B13. Averaged creep data for mix O at 77 and 104 degrees F.

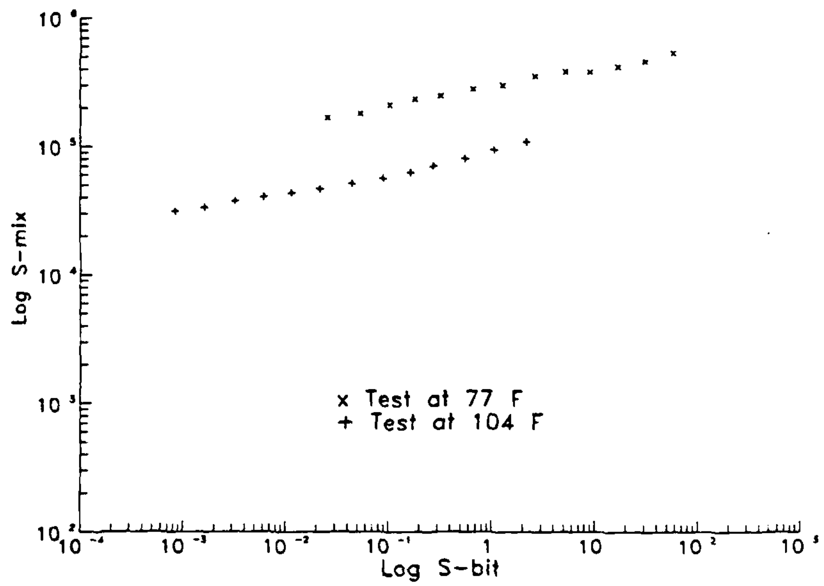

FIGURE B14. Averaged creep data for mix P at 77 and 104 degrees F.

APPENDIX C.

CURVE FITTING PROCEDURES

Some of the data sets analysed in this report contained considerable scatter. For example the deformation - time plots for a number of nominally identical specimens tested under supposedly identical conditions were frequently separated by a very wide margin. In order to analyse these results for the parameters required it was considered to be necessary to determine a mathematical function which passed satisfactorily close to the data points. It is also important that the function chosen does not impose a form to the relationship that it does not truly possess. For example a second order polynomial should not be used in an attempt to follow data which has a logarithmic form.

Based on previous experience it was anticipated that Chebyshev Polynomials would provide a satisfactory solution and a suite of computer routines were developed, in Fortran, and using the "least squares" technique, to run on a personal computer from those published in reference C1. Chebyshev polynomials have been found to be particularly successful for fitting this kind of experimental data and have the advantage of providing equations which are well conditioned for solution. These routines are listed at the end of this appendix. Readers are directed to reference C2 for a discussion of the use of these functions for curve fitting.

The strategy adopted in fitting the curves to the data was to compute the Chebyshev coefficients for polynomials up to the order 10. The root mean square value of the residual is also computed by the program and this parameter examined in order to determine which polynomial provides the best fit. In most cases this parameter settles to a fairly constant value after some initial large values. The lowest order of polynomial at which this constant value is achieved is the one which provides the most satisfactory fit. It should be noted that the R.M.S. residual will, in some cases start to decrease again at high order polynomials. This is because at high orders the polynomial approximation is being forced to follow the fluctuations in the data rather than smooth them out. (The R.M.S. residual at the desired order of fit also provides an indication of the characteristic error in the data.) Having selected the order of the polynomial which best represents the data this polynomial was evaluated at the data points, and at a point midway between each pair of data points. This curve was then plotted to ensure that it provided a satisfactory representation of the data, and did not include undesirable fluctuations. If it was still judged to be satisfactory it was used to generate the data required for the analysis.

```
      INTEGER CASE, F TYPE, M, K, IWGHT, R, I, J, IFAIL,FLAG, AD,ADD
      REAL F, XMID, XCAP, X1, XM, D
      COMMON X(0:500), Y(0:500), W(0:500), A(0:30,0:30), S(0:30)
      DIMENSION AK(0:30)
C     COMMON X,Y,W,A,S
 9000 FORMAT (I2)
 9001 FORMAT (I3)
 9002 FORMAT (I1)
 9003 FORMAT (2F19.7)
 9004 FORMAT (F10.6)
      NIN = 5
      NOUT = 6
      READ (NIN,9000) AD
      ADD = AD + 10
      READ (NIN,9002) FLAG
      READ(NIN,9000) NCASE
      CASE = 0
      DO 9999, CASE = 1,NCASE
      WRITE (NOUT,9006)
 9006 FORMAT (4X,'CURVE FIT USING CHEBYSHEV POLYNOMIALS'//10X,'INPUT DAT
     *A')
C
C     POLYNOMIAL FIT TO ARBITRARY DATA POINTS
C
C     M IS THE NUMBER OF PAIRS OF DATA POINTS (FORMAT I3)
C
C     K IS THE MAXIMUM DEGREE REQUIRED (FORMAT I2)
C
C     IWGHT IS RESPECTIVELY 1 OR 2 ACCORDING TO WHETHER THE INDEPENDENT
C     VARIABLE AND THE WEIGHT, RESPECTIVELY. W(R) IS SUPPLIED ONLY IF
C     IWGHT = 2
C
      READ(NIN,9001) M
      READ(NIN,9000) K
      READ(NIN,9002) IWGHT
      DO 10, R = 1,M
      READ(NIN,9003) X(R), Y(R)
      IF (IWGHT .EQ. 1) THEN
      W(R) = 1
      GOTO 9
      ELSE
      READ(NIN,9004) W(R)
      END IF
    9 CONTINUE
   10 CONTINUE
      WRITE(NOUT,9007)
 9007 FORMAT(2X,'CHEBYSHEV POLYNOMIAL FIT TO ARBITRARY DATA POINTS'/)
      WRITE (NOUT,9008) M
 9008 FORMAT(2X,'NUMBER OF DATA POINTS = ',I3)
      WRITE (NOUT,9009) K
 9009 FORMAT(2X,'MAXIMUM DEGREE = ',I2)
      IF (IWGHT .EQ. 1) THEN
      WRITE(NOUT,9010)
 9010 FORMAT(2X,'UNIT WEIGHTING FACTORS'//5X,'R',5X,'ABSCISSA X(R)',2X,
     *'ORDINATE Y(R)'///)
      ELSE
      WRITE(NOUT,9011)
      END IF
 9011 FORMAT(2X,'USER SUPPLIED WEIGHTING FACTORS'//5X,'R',5X,'ABSCISSA
     *X(R)',2X,'ORDINATE Y(R)',2X,'WEIGHT W(R)')
```

```
      IF (FLAG .NE. 0) GOTO 21
      DO 20 R = 1,M
      IF (IWGHT .EQ. 1) THEN
      WRITE(NOUT,9012) R,X(R),Y(R)
      ELSE
      WRITE(NOUT,9013) R,X(R),Y(R),W(R)
      END IF
   20 CONTINUE
   21 CONTINUE
 9012 FORMAT(4X,I3,7X,F15.7,4X,F15.7)
 9013 FORMAT(4X,I3,7X,F15.7,4X,F15.7,2X,F10.6)
C
      CALL POLY FIT(M, K, X, Y, W, A, S, IFAIL)
C
      IF (IFAIL .NE. 0) GOTO 9999
      WRITE(NOUT,9014)
 9014 FORMAT(///,20X,'RESULTS'/20X,'-------')
      DO 30 I = 0,K
      WRITE(NOUT,9015) I
 9015 FORMAT(/,5X,'DEGREE = ',2X,I2)
      WRITE(NOUT,9016)
 9016 FORMAT(//,3X,'J',3X,'CHEBYSHEV COEFFICIENT A(J)')
      DO 40 J = 0,I
      WRITE(NOUT,9017) J,A(I,J)
 9017 FORMAT(2X,I2,10X,E15.6)
   40 CONTINUE
      WRITE(NOUT,9018) S(I)
 9018 FORMAT(/,5X,'R.M.S. RESIDUAL = ',E15.6)
   30 CONTINUE
      DO 50 I = 0,K
      AK(I) = A(K,I)
   50 CONTINUE
      X1 = X(1)
      XM = X(M)
      D = XM - X1
      IF (FLAG .NE. 1) GO TO 9998
      WRITE(NOUT,9019) K
 9019 FORMAT(//,'POLYNOMIAL APPROXIMATIONS AND RESIDUALS FOR DEGREE',I2
     *)
      WRITE(NOUT,9020)
 9020 FORMAT(2X,'R',2X,'ABSCISSA  ORDINATE   APPROXIMATION  RESIDUAL')
      F = CHEBSER(K, AK, -1.0, IFAIL)
      FF = F - Y(1)
      R = 1
      WRITE(NOUT,9021) R, X(1), Y(1), F, FF
      DO 60 R = 2,M
      XMID = 0.5 * (X(R-1) + X(R))
      XCAP = ((XMID - X1) - (XM - XMID)) /D
      F = CHEBSER(K, AK, XCAP, IFAIL)
      WRITE(NOUT,9022) XMID,F
 9021 FORMAT(2X,I3,4F15.7)
 9022 FORMAT(6X,2F15.7)
      XCAP = ((X(R) - X1) - (XM - X(R))) / D
      F = CHEBSER(K, AK, XCAP, IFAIL)
      FF = F - Y(R)
      WRITE(NOUT,9021) R, X(R), Y(R), F, FF
   60 CONTINUE
      IF (FLAG .EQ. 1) WRITE(ADD,9023) (AK(II), II = 0,K)
 9023 FORMAT (E15.6)
 9998 CONTINUE
 9999 CONTINUE
```

```
      STOP
      END


      SUBROUTINE POLY FIT(M, K, XX, YY, WW, AA, SS, IFAIL)
      COMMON X(0:500), Y(0:500), W(0:500), A(0:30,0:30), S(0:30)
C
C     THIS PROCEDURE DETERMINES LEAST-SQUARES POLYNOMIAL APPROXIMATIONS
C     OF DEGREES 0,1,....K TO THE SET OF DATA POINTS (X(R), Y(R)) WITH
C     WEIGHTS W(R)  (R = 1,2,......,M), WHERE
C
C               EPS(R) = W(R) * (Y(R) - F(R))
C
C     AND F(R) IS THE VALUE OF THE POLYNOMIAL OF DEGREE I AT THE R TH
C     DATA POINT.
C
C     EACH POLYNOMIAL IS REPRESENTED IN CHEBYSHEV - SERIES FORM WITH
C     NORMALISED ARGUEMENT XCAP. THIS ARGUEMENT LIES IN THR RANGE -1
C     TO +1 AND IS RELATED TO THE ORIGONAL VARIABLE X BY THE LINEAR
C     TRANSFORMATION -
C
C               XCAP = (2 * X - XMAX - XMIN)/(XMAX - XMIN)
C
C     HERE XMAX AND XMIN ARE RESPECTIVELY THE LARGEST AND SMALLEST
C     VALUES OF X(R). THE POLYNOMIAL APPROXIMATION OF DEGREE I IS
C     REPRESENTED AS
C
C               0.5 * A(I,0) * T0(XCAP) + A(I,1) * T1(XCAP)
C           + A(I,2) * T2(XCAP) + ... + A(I,I) * TI(XCAP)
C
C     WHERE TJ(XCAP) IS THE CHEBYSHEV POLYNOMIAL OF THE FIRST KIND OF
C     DEGREE J IN XCAP.
C
C     FOR EACH VALUE OF I (I = 0,1,...,K) THE PROCEDURE PRODUCES THE
C     VALUES OF A(I,J) (J = 0,1,...,I), TOGETHER WITH THE VALUES OF
C     THE ROOT MEAN SQUARE RESIDUAL S(I) DEFINED BY SQRT(SIGMA(I)/(M -
C     I - 1). IN THE CASE M = I + 1 THE PROCEDURE ARBRITRARILY SETS THE
C     VALUE OF S(I) TO ZERO.
C
C     RESTRICTIONS ON THE PROCEDURE ARE :-
C
C               (1) THE WEIGHTS MUST BE STRICTLY POSITIVE, NON-DECREAS-
C                   ING,
C               (2) THE NUMBER OF DISTINCT VALUES OF X(R) MUST EXCEED
C                   THE MAXIMUM DEGREE K.
C
C     THESE THREE RESTRICTIONS ARE TESTED BEFORE THE START OF THE MAIN
C     COMPUTATION IN ROUTINE "CHECK DATA".
C
C     ON A SATISFACTORY EXIT FROM PROCEDURE POLY FIT THE INTEGER IFAIL
C     IS SET TO ZERO, OTHERWISE IFAIL TAKES THE VALUR 1, 2, OR 3 ACCOR-
C     IFD IT IS KNOWN IN ADVANCE THAT THE DATA SATISFIES THE ABOVE CON-
C     DITIONS, THEN THE DECLARATION AND CALL OF "CHECK DATA" CAN BE
C     OMITTED.
C     THE METHOD EMPLOYED IS DUE TO FORSYTHE, G.E. (GENERATION AND USE
C     OF ORTHOGONAL POLYNOMIALS FOR DATA FITTING WITH A DIGITAL COMPUT-
C     OR, J. SIAM, VOL. 56, 74 - 88, 1957) AND IS BASED UPON THE GENER-
C     ATION OF A SET OF POLYNOMIALS ORTHOGONAL WITH RESPECT TO SUMATION
C     OVER THE NORMALIZED DATA SET. THE EXTENSIONS DUE TO CLENSHAW, C.W
C     (CURVE FITTING WITH A DIGITAL COMPUTOR, COMPUT. J., VOL. 2, 170-
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```
C     173, 1960) TO REPRESENT THESE POLYNOMIALS AS WELL AS THE APPROXI-
C     MATING POLYNOMIALS IN THEIR CHEBYSHEV - SERIES FORMS ARE INCORP-
C     ORATED. THE MODIFICATIONS SUGGESTED BY REINSCH AND GENTLEMAN
C     (SEE GENTLEMAN, W. M., AN ERROR ANALYSIS OF GOERTZELS (WATTS)
C     METHOD FOR COMPUTING FOURIER SERIES, COMPUT. J., VOL. 12, 160-
C     165, 1969) TO THE METHOD ORIGONALLY EMPLOYED BY CLENSHAW FOR
C     EVALUATING THE ORTHOGONAL POLYNOMIALS FROM THEIR CHEBYSHEV -
C     SERIES REPRESENTATIONS ARE USED TO GIVE GREATER NUMERICAL STABIL-
C     ITY;
C
      REAL D,ALPHA I PLUS1,BETA I,CI,XCAPR,FACTOR,DJ,BJ,BJ PLUS 1,
     *BJ PLUS 2,WRPR,WRPR SQUARED,EPS R,SIGMA I,PIJ,DI,DI MINUS 1,X1,XM
      INTEGER R,I,I PLUS 1,I MINUS 1,J,J PLUS 1
      DIMENSION EPS(0:500),XCAP(0:500),WRP(0:500),PI(0:30),
     *PI MINUS 1(0:30)
      IFAIL = 0
      CALL CHECKDAT(IFAIL,M)
      IF (IFAIL .NE. 0) GO TO 2000
      X1 = X(1)
      XM = X(M)
      D = XM - X1
C
C     THE INITIAL VALUES EPS(R) (R = 1,2,...,M) OF THE WEIGHTED RESID-
C     UALS AND THE VALUES XCAP(R) (R = 1,2,...,M) OF THE NORMALISED
C     INDEPENDANT VARIABLE ARE COMPUTED. NOTE THAT XCAP(R) IS COMPUTED
C     FROM THE EXPRESSION BELOW, RATHER THAN THE MORE MATURAL FORM
C     (2.0 * X(R) - X1 - XM)/D, SINCE THE FORMER GUARANTEES THE COMPU-
C     TED VALUE TO DIFFER FROM THE TRUE VALUE BY AT MOST 4.0 * MACHINE
C     ACCURACY, WHEREAS THE LATTER HAS NO SUCH GUARANTEE.
C
      DO 10 R = 1,M
      EPS(R) = W(R) * Y(R)
      XCAP(R) = ((X(R) - X1) - (XM - X(R)))/D
   10 CONTINUE
      I MINUS 1 = 0
      BETA I = 0
      DO 1000 I = 0,K
C
C     SET STARTING VALUES FOR DEGREE I
C
      I PLUS 1 = I + 1
      IF (I .GE. K) GO TO 12
      DO 11 J = I PLUS 1,K
      A(I,J) = 0
      PI(I PLUS 1) = 0
      PI MINUS 1(I PLUS 1) = 0
   11 CONTINUE
   12 CONTINUE
C
      ALPHA I PLUS 1 = 0
      CI = 0
      DI = 0
      A(I MINUS 1,I) = 0
      PI(I) = 1.0
      PI MINUS 1(0) = PI(1)
      DO 1500 R = 1,M
      XCAPR = XCAP(R)
C
C     THE WEIGHTED VALUE WRP(R) OF THE ORTHOGONAL POLYNOMIAL OF DEGREE
C     I AT X = X(R) IS COMPUTED BY RECURRENCE FROM ITS CHEBYSHEV SERIES
C     REPRESENTATION
```

```
C
      IF (XCAPR .LT. -0.5) THEN
C
C     GENTLEMAN'S MODIFDIED RECURRENCE
C
      FACTOR = 2.0 * (1.0 + XCAPR)
      DJ = 0
      BJ = 0
      DO 1510 J = I,1,-1
      DJ = PI(J) - DJ + FACTOR * BJ
      BJ = DJ - BJ
 1510 CONTINUE
      WRP(R) = W(R) * (0.5 * PI(0) - DJ + 0.5 * FACTOR * BJ)
      WRPR = WRP(R)
C
      ELSE IF (XCAPR .LE. 0.5) THEN
C
C     CLENSHAW'S ORIGONAL RECURRENCE
C
      FACTOR = 2.0 * XCAPR
      BJ = 0
      BJ PLUS 1 = 0
      DO 1520 J = I,1,-1
      BJ PLUS 2 = BJ PLUS 1
      BJ PLUS 1 = BJ
      BJ = PI(J) - BJ PLUS 2 + FACTOR * BJ PLUS 1
 1520 CONTINUE
      WRP(R) = W(R) * (0.5 * PI(0) - BJ PLUS 1 + 0.5 * FACTOR * BJ)
      WRPR = WRP(R)
C
      ELSE
C
C     REINSCH'S MODIFIED RECURRENCE
C
      FACTOR = 2.0 * (1.0 - XCAPR)
      DJ = 0
      BJ = 0
      DO 1530 J = I,1,-1
      DJ = PI(J) + DJ - FACTOR * BJ
      BJ = BJ + DJ
 1530 CONTINUE
      WRP(R) = W(R) * (0.5 * PI(0) + DJ - 0.5 * FACTOR * BJ)
      WRPR = WRP(R)
      END IF
C
C     THE COEFFICIENT CI OF THE I'TH ORTHOGONAL POLYNOMIAL AND THE
C     COEFFICIENTS ALPHA I PLUS 1 AND BETA I IN THE THREE TERM RECURRE-
C     NCE RELATION FOR THE ORTHOGONAL POLYNOMIALS ARE COMPUTED
C
      WRPR SQUARED = WRPR * WRPR
      DI = DI + WRPR SQUARED
      CI = CI + WRPR * EPS(R)
      ALPHA I PLUS 1 = ALPHA I PLUS 1 + WRPR SQUARED * XCAPR
 1500 CONTINUE
      CI = CI / DI
      IF (I .GT. 0) BETA I = DI / DI MINUS 1
      ALPHA I PLUS 1 = 2.0 * ALPHA I PLUS 1 / DI
C
C     THE WEIGHTED RESIDUALS EPS(R) (R = 1,2,...,M) FOR THE DEGREE I
C     ARE COMPUTED, TOGETHER WITH THEIR SUM OF SQUARES, SIGMA I
C
```

```
      SIGMA I = 0
      DO 20 R = 1,M
      EPS R = EPS(R) - CI * WRP(R)
      EPS(R) = EPS R
      SIGMA I = SIGMA I + EPS R * EPS R
   20 CONTINUE
C
C     THE ROOT MEAN SQUARE RESIDUAL S(I) FOR DEGREE I IS THEORETICALLY
C     UNDEFINED IF M = I + 1 (THE CONDITION FOR THE POLYNOMIAL TO PASS
C     EXACTLY THROUGH THE POINTS). SHOULD THIS CASE ARRISE THE R.M.S.
C     RESIDUAL IS SET ARBRITRARILY TO ZERO
C
      IF (I PLUS 1 .LT. M) THEN
      S(I) = SQRT(SIGMA I / (M - I PLUS 1))
      ELSE
      S(I) = 0
      END IF
C
C     THE CHEBYSHEV COEFFICIENTS A(I,0),A(I,1),...,A(I,I) IN THE POLYN-
C     OMIAL APPROXIMATION OF DEGREE I, TOGETHER WITH THE COEFFICIENTS
C     PI(0),PI(1),...,PI(I) IN THE CHEBYSHEV-SERIES REPRESENTATION OF
C     THE I'TH ORTHOGONAL POLYNOMIAL ARE COMPUTED
C
      DO 30 J = 0,I
      J PLUS 1 = J + 1
      PIJ = PI(J)
      A(I,J) = A(I MINUS 1,J) + CI * PIJ
      IF (J PLUS 1 .GT. K) GO TO 2000
      PI(J) = PI(J PLUS 1) + PI MINUS 1(J) - ALPHA I PLUS 1 * PIJ -
     *BETA I * PI MINUS 1(J PLUS 1)
      PI MINUS 1(J PLUS 1) = PIJ
   30 CONTINUE
      DI MINUS 1 = DI
      I MINUS 1 = I
 1000 CONTINUE
 2000 CONTINUE
      END


      SUBROUTINE CHECKDAT (IFAIL,M)
C
      INTEGER M DISTINCT,R
      REAL XR, XR MINUS 1 S
      DIMENSION X(0:500),Y(0:500),W(0:500)
      COMMON X,Y,W,A,S
C
C     CHECK THAT THE WEIGHTS ARE SRTICTLY POSITIVE
C
      IFAIL = 1
      DO 1000, R = 1,M
      IF (W(R) .LE. 0) GO TO 1010
 1000 CONTINUE
C
C     CHECK THAT THE VALUES OF X(R) ARE NON-DECREASING AND DETERMINE
C     THE NUMBER OF DISTINCT VALUES OF X(R)
C
      IFAIL = 2
      M DISTINCT = 1
      XR MINUS 1 = X(1)
      DO 2000, R = 2,M
```

```
      XR = X(R)
      IF (XR .GT. XR MINUS 1) THEN
      M DISTINCT = M DISTINCT + 1
      ELSE IF (XR .LT. XR MINUS 1) THEN
      GO TO 1010
      END IF
      XR MINUS 1 = XR
 2000 CONTINUE
C
C     IF THE MUNBER OF DISTINCT VALUES OF X(R) FAILS TO EXCEED THE MAX-
C     IMUM DEGREE K THERE IS NO UNIQUE POLYNOMIAL APPROXIMATION TO THAT
C     DEGREE
C
      IFAIL = 3
      IF (M DISTINCT .LE. K) GO TO 1010
      IFAIL = 0
 1010 CONTINUE
      END


      FUNCTION CHEBSER(N, A, XCAP, IFAIL)
      INTEGER N, IFAIL, K
      REAL XCAP,ETA, FACTOR, DK, BK, BK PLUS 1, BK PLUS 2
      DIMENSION A(0:30)
C
C     THIS PROCEDURE EVALUATES THE POLYNOMIAL
C        0.5 * A(O) * TO(XCAP) + A(1) * T1(XCAP) + A(2) * T2(XCAP)+...
C              ...+ A(N) * T2(XCAP)
C
C     FOR ANY VALUE OF XCAP IN THE RANGE -1 .LE. XCAP .GE. 1. HERE
C     TJ(XCAP) DENOTES THE CHEBYSHEV POLYNOMIAL OF THE FIRST KIND OF
C     DEGREE J IN XCAP.
C     IN PRACTICE, THE VARIABLE XCAP WILL USUALLY HAVE BEEN OBTAINED
C     FROM AN ORIGONAL VARIABLE X, WHERE
C
C         XCAP = ((X - XMIN) - (XMAX - X)) / (XMAX - XMIN)
C
C     AND XMAX AND XMIN DENOTE RESPECTIVELY THE LARGEST AND SMALLEST
C     VALUES OF X. NOTE THAT THIS FORM OF THE TRANSFORMATION SHOULD BE
C     USED COMPUTATIONALLY RATHER THAN THE MORE NATURAL MATHEMATICAL
C     EQUIVALENT
C
C         XCAP = (2 * X -XMIN - XMAX) / ( XMAX - XMIN)
C
C     SINCE THE FORMER GUARANTEES THAT THE COMPUTED VALUE DIFFERS FROM
C     ITS TRUE VALUE BY AT MOST 4.0 * ETA, WHERE ETA IS THE LARGEST
C     FLOATING - POINT NUMBER SUCH THAT 1.0 + ETA IS COMPUTED AS UNITY
C     WHEREAS THE LATTER HAS NO SUCH GUARANTEE.
C
C     ON A NORMAL EXIT IFAIL = 0. IF ABS(XCAP) > 1.0 + 4.0 * ETA THEN
C     NO EVALUATION IS ATTEMPTED AND IFAIL IS SET TO UNITY.
C
C     THE METHOD EMPLOYED IS BASED UPON THE THREE - TERM RECURRENCE
C     RELATION DUE TO CLENSHAW, C.W. (A NOTE ON THE SUMMATION OF CHEBY-
C     SHEV SERIES, M.T.A.C., VOL., 9, 118 - 120, 1955), WITH MODIFICATI
C     ONS TO GIVE GREATER MUMERICAL STABILITY DUE TO REINSCH AND GENTL-
C     EMAN, W.M., AN ERROR ANALYSIS OF GOERTZELS (WATTS) METHOD FOR
C     COMPUTING FOURIER SERIES, COMPUT. J., VOL. 12, 160 - 165, 1969)
C
C
```

```
C     TO ENSURE THAT THE VALUE OF XCAP, COMPUTED AS RECCOMENDED ABOVE
C     SHALL BE ACCEPTED BY THE PROCEDURE, THE VALUE ON THE RIGHT HAND
C     SIDE OF THE FOLLOWING STATEMENT SHOULD BE REPLACED BY THE VALUE
C     OF ETA AS DEFINED ABOVE.
C
      ETA = 0
      IF (ABS(XCAP) .GT. 1.0 + 4.0 * ETA) THEN
      IFAIL = 1
      ELSE IF (XCAP .LT. - 0.5) THEN
C
C     GENTLEMAN'S MODIFIED RECURRENCE
C
      FACTOR = 2.0 * (1.0 + XCAP)
      DK = 0
      BK = 0
      DO 10 K  = N,1,-1
      DK = A(K) - DK + FACTOR * BK
      BK = DK - BK
   10 CONTINUE
      CHEBSER = 0.5 * A(0) - DK + 0.5 * FACTOR * BK
C
      ELSE IF (XCAP .LE. 0.5) THEN
C
C     CLENSHAW'S ORIGONAL RECURRENCE
C
      FACTOR = 2.0 * XCAP
      BK = 0
      BK PLUS 1 = 0
      DO 20 K  = N,1,-1
      BK PLUS 2 = BK PLUS 1
      BK PLUS 1 = BK
      BK = A(K) - BK PLUS 2 + FACTOR * BK PLUS 1
   20 CONTINUE
      CHEBSER = 0.5 * A(0) - BK PLUS 1 + 0.5 * FACTOR * BK
      ELSE
C
C     REINSCH'S MODIFIED RECURRENCE
C
      FACTOR = 2.0 * (1.0 - XCAP)
      DK = 0
      BK = 0
      DO 30 K = N,1,-1
      DK = A(K) + DK - FACTOR * BK
      BK = BK + DK
   30 CONTINUE
      CHEBSER = 0.5 * A(0) + DK - 0.5 * FACTOR * BK
      END IF
      IFAIL = 0
      END
```

Program to evaluate the Chebyshev Series for any value of the independant variable X within the range of X for which the function was origonally derived.

```
      REAL X, XCAP, XMAX, XMIN, Y, XX, YY
      INTEGER I, K, NX, NCURVE
      DIMENSION A(0:30)
```

```
      NIN = 5
      NOUT = 6
 1000 FORMAT (F10.6)
 1002 FORMAT (I1)
 2000 FORMAT (/,2X,'MIX STIFFNESS (SBIT = ',F10.5,' =',E15.6)
 1001 FORMAT (E15.4)
      READ (NIN,1002) NCURVE
      DO 10 J = 1, NCURVE
      READ (NIN,1000) XMAX
      READ (NIN,1000) XMIN
      READ (NIN,1002) NX
      READ (NIN,1002) K
      READ (NIN,1001) (A(I), I = 0,K)
      DO 11 JJ = 1, NX
      READ (NIN,1000) XX
      X = ALOG10(XX)
      XCAP = ((X - XMIN) - (XMAX - X)) / (XMAX - XMIN)
      YY = CHEBSER(K, A, XCAP, 1)
      Y = 10.0**YY
      WRITE (NOUT, 2000) XX,Y
   11 CONTINUE
   10 CONTINUE
      STOP
      END
```

APPENDIX D.

COMPUTER PROGRAM FOR THE SHELL METHOD FOR CALCULATING RUT DEPTHS.

```
'*************************************************************************
'*                                                                       *
'*                                                                       *
'*   PROGRAM NAME : SHELL.BAS                                            *
'*                                                                       *
'*   DESCRIPTION  : PROGRAM TO DETERMINE PERMANENT DEFORMATION           *
'*                              (SHELL ANALYSIS)                         *
'*                                                                       *
'*                                                                       *
'*                                                                       *
'*************************************************************************

DECLARE SUB FACTORg (SG!)
DECLARE SUB TyeffH2 (XV, C, SP, Q, PI, MAA, H2, D2, W, CM, ZF)
DECLARE SUB TyeffH1 (XV, C, SP, Q, PI, MAA, H1, D1, W, CM, ZF)
DECLARE SUB TyeffH31 (XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF)
DECLARE SUB TyeffH32 (XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF)
DECLARE SUB TyeffH33 (XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF)
DECLARE SUB TyeffH34 (XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF)
DECLARE SUB TyeffH35 (XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF)
DECLARE SUB VISCyeff (XV, PI!, VISCOSITY!)
DECLARE SUB GETCM (CM!)
DECLARE SUB THICK (H1, H2, H3, H11, H12, H13)
DECLARE SUB FACTORA (Q, AF)
DECLARE SUB MAATeff (MAA)
CLS
LOCATE 1, 2: PRINT "*************************************************************
******************"
LOCATE 2, 22: PRINT "PERMANENT DEFORMATION  (Shell Analysis) "
LOCATE 3, 2: PRINT "*************************************************************
******************"

CALL GETCM(CM)
CLS

CALL FACTORg(SG)
CLS

LOCATE 10, 20
PRINT "  ENTER THE PENETRATION INDEX OF BITUMEN  <PI>    "
LOCATE 11, 20
INPUT "         ( -2 <= PI >=2 )                          = "; PI
CLS

LOCATE 11, 25
INPUT "ENTER THE MIX CODE : "; C$
CLS


CALL THICK(H1, H2, H3, H11, H12, H13)
CLS


LOCATE 8, 12
INPUT " ENTER NUMBER OF COMMERCIAL AXLES PER LANE PER DAY   <WD>  = "; WD
CLS
```

```
CALL MAATeff(MAA)
CLS


LOCATE 8, 20
INPUT "  ENTER THE SOFTENING POINT OF THE BITUMEN  (oC)  = "; SP
CLS

LOCATE 10, 8
PRINT " ENTER THE VALUE OF THE SLOPE (q) OF MIX  v.  BITUMEN STIFFNESS "
LOCATE 11, 8
INPUT " PLOT DERIVED FROM THE RESULTS OF THE CREEP TEST.  =          "; Q
LOCATE 15, 5
INPUT "ENTER THE INTERCEPT OF PLOT MIX v. BITUMEN STIFFNESS WITH X-AXIS. ="; C
CLS


CALL FACTORA(Q, AF)
CLS

W = WD * 365 * SG * 1.4 * AF


IF H11 = 40 THEN CALL TyeffH1(XV, C, SP, Q, PI, MAA, H1, D1, W, CM, ZF)
IF H2 = 0 THEN D2 = 0: D3 = 0: GOTO TOTALDEPTH

IF H12 = 40 THEN CALL TyeffH2(XV, C, SP, Q, PI, MAA, H2, D2, W, CM, ZF)
IF H3 = 0 THEN D3 = 0: GOTO TOTALDEPTH

IF H13 = 50 THEN CALL TyeffH31(XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF)
IF H13 = 100 THEN CALL TyeffH32(XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF)
IF H13 = 200 THEN CALL TyeffH33(XV, C, SP, Q, PI, MAA, H3, D3, W, CM. ZF)
IF H13 = 350 THEN CALL TyeffH34(XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF)
IF H13 = 520 THEN CALL TyeffH35(XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF)

TOTALDEPTH:
D = D1 + D2 + D3
CLS
LOCATE 6, 20
PRINT "DEFORMATION SUBLAYER 1  (D1)   "; D1
LOCATE 7, 20
PRINT "DEFORMATION SUBLAYER 2  (D2)   "; D2
LOCATE 8, 20
PRINT "DEFORMATION SUBLAYER 3  (D3)   "; D3
LOCATE 12, 15
PRINT "             PERMANENT DEFORMATION    (mm)    = "; D
LPRINT "MIX CODE : "; C$
LPRINT "WD,SP,H1,H2,H3,Q,C,MAA"; WD; SP; H1; H2; H3; Q; C; MAA
LPRINT "D1,D2,D3  "; D1; D2; D3
LPRINT "             PERMANENT DEFORMATION    (mm)    = "; D

3500 DATA 5,5,5,6,6,6,6,6,7,7
3510 DATA 11,11,12,12,13,14,15,16,17,17
3520 DATA 16,18,19,21,23,25,27,29,32,35
3530 DATA 22,25,28,31,35,39,44,49,56,63
3540 DATA 28,33,38,43,50,58,68,79,92,108
3550 DATA 35,41,49,58,70,84,101,122,149,181
3560 DATA 42,51,62,76,93,118,148,186,235,298
3570 DATA 49,62,78,99,127,164,214,280,365,487
```

```
SUB FACTORA (Q, AF) STATIC
FACTORA:
XQ = LOG(Q) / LOG(10)

IF Q >= .06 OR Q <= .1 THEN
        A = 15.91
        B = 26.28
        C = 11.61
ELSEIF Q >= .11 OR Q <= .2 THEN
        A = 12.5
        B = 17.08
        C = 6.14
 ELSEIF Q >= .21 OR Q <= 1! THEN
        A = .5
        B = -.131
        C = -.017
END IF

LY = A * XQ ^ 2 + B * XQ + C
AF = 10 ^ LY
END SUB

SUB FACTORg (SG) STATIC
FACTORg:
3000 LOCATE 1, 27: PRINT "TRAFFIC SUMMATION FACTORS"
3010 FOR N = 1 TO 15
3020 ATEN$ = ATEN$ + CHR$(196)
3030 NEXT
3031 '
3040 PRINT CHR$(218) + ATEN$ + CHR$(196);
3050 FOR N = 1 TO 10
3060 PRINT CHR$(194) + CHR$(196) + CHR$(196) + CHR$(196) + CHR$(196) + CHR$(196)
;
3070 NEXT
3080 PRINT CHR$(191)
3081 '
3090 MIDLE$ = CHR$(179) + SPACE$(16) + CHR$(179)
3100 FOR N = 1 TO 10
3110 MIDLE$ = MIDLE$ + SPACE$(5) + CHR$(179)
3120 NEXT
3130 PRINT MIDLE$
3132 '
3140 PRINT CHR$(195) + ATEN$ + CHR$(196) + CHR$(197);
3150 PRINT CHR$(196) + CHR$(196) + CHR$(196) + CHR$(196) + CHR$(196);
3160 FOR N = 1 TO 9
3170 PRINT CHR$(193) + CHR$(196) + CHR$(196) + CHR$(196) + CHR$(196) + CHR$(196)
;
3180 NEXT
3190 PRINT CHR$(180)
3191  '
3200 PRINT CHR$(179) + SPACE$(16) + CHR$(179) + SPACE$(59) + CHR$(179)
3201 '
3210 PRINT CHR$(195) + ATEN$ + CHR$(196) + CHR$(197);
3220 PRINT CHR$(196) + CHR$(196) + CHR$(196) + CHR$(196) + CHR$(196);
3230 FOR N = 1 TO 9
3240 PRINT CHR$(194) + CHR$(196) + CHR$(196) + CHR$(196) + CHR$(196) + CHR$(196)
;
3250 NEXT
3260 PRINT CHR$(180)
3261 '
3270 FOR N = 1 TO 15
```

```
3280 PRINT MIDLE$
3290 NEXT
3300 PRINT CHR$(192) + ATEN$ + CHR$(196);
3310 FOR N = 1 TO 10
3320 PRINT CHR$(193) + CHR$(196) + CHR$(196) + CHR$(196) + CHR$(196) + CHR$(1_3
;
3330 NEXT
3340 PRINT CHR$(217)
3341 '
3342 '
3350 LOCATE 5, 48: PRINT "g"
3360 LOCATE 3, 2: PRINT "Growth rate b,%"
3370 LOCATE 5, 2: PRINT "Design life,yrs"
3380 '
3390 FOR N = 1 TO 10
3400 LOCATE 3, 13 + N * 6 - 1 * (N < 10): PRINT N
3410 NEXT
3420 FOR N = 1 TO 8
3430 LOCATE (5 + N * 2), 9: PRINT N * 5
3440 NEXT N
3441 '
3450 FOR N = 7 TO 21 STEP 2
3460 FOR m = 18 TO 72 STEP 6
3470 READ x: LOCATE N, m - 1 * (N < 10) - 1 * (N < 100): PRINT x
3480 NEXT m
3490 NEXT N
3491 '
3492
3571 '
LOCATE 23, 10
INPUT "     ENTER THE SUMMATION FACTOR  <g>   (Table above) = "; SG
END SUB

SUB GETCM (CM) STATIC
GETCM:
CLS
LOCATE 5, 27: PRINT " CORRECTION FACTOR FOR DYNAMIC EFFECTS  "
LOCATE 8, 32: PRINT "Mix Type                        Cmi "
LOCATE 9, 32: PRINT "--------                        --- ": PRINT
LOCATE 10, 22: PRINT "Sand sheet and lean sand mixes"
LOCATE 11, 22: PRINT "Lean open asphaltic concrete          1.6-2.0 "
LOCATE 13, 22: PRINT "lean bitumen macadam                  1.5-1.8 "
PRINT
LOCATE 15, 22: PRINT "Asphaltic concrete, Gravel sand "
LOCATE 16, 22: PRINT "Gravel sand asphalt                   1.2-1.6  "
LOCATE 17, 22: PRINT "Dense bitumen macadam "
LOCATE 19, 22: PRINT "Mastic types, Gu" + CHR$(225) + "asphalt,"
LOCATE 20, 22: PRINT "HOT ROLLED ASPHALT                    1.0-1.3 "
LOCATE 22, 8: INPUT " ENTER CORRECTION FACTOR FOR DYNAMIC FACTOR  <CMi>  (Table
above) ="; CM

END SUB

SUB MAATeff (MAA) STATIC
MAATeff:
FOR N = 1 TO 15
ATEN$ = ATEN$ + CHR$(196)
NEXT
LOCATE 1, 27
PRINT CHR$(218) + ATEN$ + CHR$(196) + CHR$(194) + ATEN$ + CHR$(196) + CHR$(191,
MIDLE1$ = CHR$(179) + SPACE$(16) + CHR$(179) + SPACE$(16) + CHR$(179)
```

```
LOCATE 2, 27
PRINT MIDLE1$
LOCATE 3, 27
PRINT CHR$(195) + ATEN$ + CHR$(196) + CHR$(197) + ATEN$ + CHR$(196) + CHR$(180)
FOR N = 1 TO 17
LOCATE 3 + N, 27
PRINT MIDLE1$
NEXT N
LOCATE 21, 27
PRINT CHR$(192) + ATEN$ + CHR$(196) + CHR$(193) + ATEN$ + CHR$(196) + CHR$(217)
LOCATE 2, 32: PRINT "LOCATION"
LOCATE 2, 48: PRINT "MAATeff oC"
LOCATE 4, 32: PRINT "STOCKHOLM": LOCATE 4, 52: PRINT "14"
LOCATE 6, 32: PRINT "CHICAGO": LOCATE 6, 52: PRINT "10"
LOCATE 8, 32: PRINT "FRANKFURT": LOCATE 8, 52: PRINT "15"
LOCATE 10, 32: PRINT "HOUSTON": LOCATE 10, 52: PRINT "25"
LOCATE 12, 32: PRINT "LAGOS": LOCATE 12, 52: PRINT "27"
LOCATE 14, 32: PRINT "LONDON": LOCATE 14, 52: PRINT "14"
LOCATE 16, 32: PRINT "MELBOURNE": LOCATE 16, 52: PRINT "16"
LOCATE 18, 32: PRINT "NEW YORK": LOCATE 18, 52: PRINT "19"
LOCATE 20, 32: PRINT "ROME": LOCATE 20, 52: PRINT "21"
LOCATE 23, 4: INPUT " ENTER THE EFFECTIVE MEAN ANNUAL AIR TEMP.  <MAATeff>  (Tab
le above)  = "; MAA
END SUB

SUB THICK (H1, H2, H3, H11, H12, H13) STATIC
LOCATE 9, 2
PRINT " THE ASPHALT THICKNESS MUST BE SUBDIVIDED SO THAT THE TEMPERATURE AT DIFF
ERENT"
LOCATE 10, 2
PRINT " DEPTHS CAN BE TAKEN INTO ACCOUNT.  (Not more than three layers)"
LOCATE 12, 5
INPUT "      ENTER    <RET>    TO CONTINUE : "; y$
CLS
40 LOCATE 7, 1: PRINT "          ENTER THE THICKENESS OF SUBLAYER 1    (H1 < or
=40mm) "; : INPUT H1
IF H1 <= 40 THEN H11 = 40
IF H1 > 40 THEN
        BEEP
        LOCATE 7, 1
        PRINT SPACE$(70)
        GOTO 40
END IF
50 LOCATE 10, 1: PRINT "          ENTER THE THICKENESS OF SUBLAYER 2    (H2 < or
 =40mm) "; : INPUT H2
IF H2 <= 40 THEN H12 = 40
IF H2 > 40 THEN
        BEEP
        LOCATE 10, 1
        PRINT SPACE$(70)
        GOTO 50
END IF
60 LOCATE 13, 1: PRINT "          ENTER THE THICKENESS OF SUBLAYER 3  (H3 <600m
m) "; : INPUT H3
SELECT CASE H3
        CASE IS < 75
                H13 = 50
        CASE 76 TO 150
                H13 = 100
        CASE 151 TO 275
                H13 = 200
```

```
        CASE 276 TO 430
                H13 = 350
        CASE 431 TO 600
                H13 = 520
        CASE IS > 600
                BEEP
                LOCATE 13, 1
                PRINT SPACE$(70)
                GOTO 60
END SELECT

END SUB


SUB TyeffH1 (XV, C, SP, Q, PI, MAA, H1, D1, W, CM, ZF) STATIC
TyeffH1:
TH1 = .0082 * (MAA) * (MAA) + 1.37 * (MAA)
T1 = TH1 - SP
XV = T1
CALL VISCyeff(XV, PI, VISCOSITY)
SBIT1 = (3 * VISCOSITY) / (.02 * W)
CLS
LOCATE 8, 32: PRINT "< SUBLAYER 1 >"
'LOCATE 9, 10: INPUT " ENTER THE EFFECTIVE MIX STIFFNESS  (SM) . THIS VALUE SHOU
LD BE"
'LOCATE 10, 10: PRINT " READ FROM THE Smix V. Sbit PLOT FOR   Sbit =    "; SBIT'
'LOCATE 11, 10: INPUT "                                                  "; SM1
SB1 = SBIT1 * .000145038#
LSB1 = LOG(SB1) / LOG(10)
LY1 = (Q * LSB1) + C
Y1 = 10 ^ LY1
SM1 = Y1 * 6894.76
LOCATE 15, 12
INPUT "  ENTER THE PROPORTIONALITY FACTOR.  <Z>   (Table Z)  =  "; ZF

D1 = (CM * H1 * ZF * 6 * 100000!) / SM1
END SUB

SUB TyeffH2 (XV, C, SP, Q, PI, MAA, H2, D2, W, CM, ZF) STATIC
TyeffH2.
TH2 = .0099 * (MAA) * (MAA) + 1.2 * (MAA)
T2 = TH2 - SP
XV = T2
CALL VISCyeff(XV, PI, VISCOSITY)
SBIT2 = (3 * VISCOSITY) / (.02 * W)
CLS
LOCATE 9, 32: PRINT "< SUBLAYER 2 >"
'LOCATE 10, 10: PRINT " ENTER THE EFFECTIVE MIX STIFFNESS  (SM) . THIS VALUE SHO
ULD BE"
'LOCATE 11, 10: PRINT " READ FROM THE Smix V. Sbit PLOT FOR   Sbit =    "; SBIT
'LOCATE 12, 10: INPUT "                                                  "; SM2
SB2 = SBIT2 * .000145038#
LSB2 = LOG(SB2) / LOG(10)
LY2 = (Q * LSB2) + C
Y2 = 10 ^ LY2
SM2 = Y2 * 6894.76

LOCATE 16, 12
INPUT "  ENTER THE PROPORTIONALITY FACTOR.  <Z>   (Table Z)  =  "; ZF
```

```
D2 = (CM * H2 * ZF * 6 * 100000!) / SM2
END SUB

SUB TyeffH31 (XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF) STATIC
TyeffH31:
TH3 = .0073 * (MAA) * (MAA) + 1.17 * (MAA) - .017
T3 = TH3 - SP
XV = T3
CALL VISCyeff(XV, PI, VISCOSITY)
SBIT3 = (3 * VISCOSITY) / (.02 * W)
CLS
LOCATE 8, 32: PRINT "< SUBLAYER 3 >"
'LOCATE 9, 10: PRINT " ENTER THE EFFECTIVE MIX STIFFNESS  (SM) . THIS VALUE SHOU
LD BE"
'LOCATE 10, 10: PRINT " READ FROM THE Smix V. Sbit PLOT FOR   Sbit =   "; SBIT3
'LOCATE 11, 10: INPUT "                                                   "; SM3
SB3 = SBIT3 * .000145038£
LSB3 = LOG(SB3) / LOG(10)
LY3 = (Q * LSB3) + C
Y3 = 10 ^ LY3
SM3 = Y3 * 6894.76

LOCATE 15, 12
INPUT "  ENTER THE PROPORTIONALITY FACTOR.  <Z>   (Table 2)  =  "; ZF

D3 = (CM * H3 * ZF * 6 * 100000!) / SM3
END SUB

SUB TyeffH32 (XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF) STATIC
TyeffH32:
TH3 = .0061 * (MAA) * (MAA) + 1.18 * (MAA) - .036
T3 = TH3 - SP
XV = T3
CALL VISCyeff(XV, PI, VISCOSITY)
SBIT3 = (3 * VISCOSITY) / (.02 * W)
CLS
LOCATE 8, 32: PRINT "< SUBLAYER 3 >"
'LOCATE 9, 10: PRINT " ENTER THE EFFECTIVE MIX STIFFNESS  (SM) . THIS VALUE SHOU
LD BE"
'LOCATE 10, 10: PRINT " READ FROM THE Smix V. Sbit PLOT FOR   Sbit =   "; SBIT3
'LOCATE 11, 10: INPUT "                                                   "; SM3
SB3 = SBIT3 * .000145038£
LSB3 = LOG(SB3) / LOG(10)
LY3 = (Q * LSB3) + C
Y3 = 10 ^ LY3
SM3 = Y3 * 6894.76

LOCATE 15, 12
INPUT "  ENTER THE PROPORTIONALITY FACTOR.  <Z>   (Table 2)  =  "; ZF

SM3 = Q * SBIT3
D3 = (CM * H3 * ZF * 6 * 100000!) / SM3
END SUB

SUB TyeffH33 (XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF) STATIC
TyeffH33:
TH3 = .0053 * (MAA) * (MAA) + 1.16 * (MAA) - .047
T3 = TH3 - SP
XV = T3
CALL VISCyeff(XV, PI, VISCOSITY)
SBIT3 = (3 * VISCOSITY) / (.02 * W)
CLS
```

```
LOCATE 8, 32: PRINT "< SUBLAYER 3 >"
'LOCATE 9, 10: PRINT " ENTER THE EFFECTIVE MIX STIFFNESS  (SM) . THIS VALUE SHOU
LD BE"
'LOCATE 10, 10: PRINT " READ FROM THE Smix V. Sbit PLOT FOR   Sbit =   "; SBIT3
'LOCATE 11, 10: INPUT "                                                  "; SM3
SB3 = SBIT3 * .000145038#
LSB3 = LOG(SB3) / LOG(10)
LY3 = (Q * LSB3) + C
Y3 = 10 ^ LY3
SM3 = Y3 * 6894.76

LOCATE 15, 12
INPUT "  ENTER THE PROPORTIONALITY FACTOR.  <Z>   (Table Z)  =  "; ZF
D3 = (CM * H3 * ZF * 6 * 100000!) / SM3
END SUB

SUB TyeffH34 (XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF) STATIC
TyeffH34:
TH3 = .0047 * (MAA) * (MAA) + 1.11 * (MAA) - .057
T3 = TH3 - SP
XV = T3
CALL VISCyeff(XV, PI, VISCOSITY)
SBIT3 = (3 * VISCOSITY) / (.02 * W)
CLS
LOCATE 8, 32: PRINT "< SUBLAYER 3 >"
'LOCATE 9, 10: PRINT " ENTER THE EFFECTIVE MIX STIFFNESS  (SM) . THIS VALUE SHOU
LD BE"
'LOCATE 10, 10: PRINT " READ FROM THE Smix V. Sbit PLOT FOR   Sbit =   "; SBIT3
'LOCATE 11, 10: INPUT "                                                  "; SM3
SB3 = SBIT3 * .000145038#
LSB3 = LOG(SB3) / LOG(10)
LY3 = (Q * LSB3) + C
Y3 = 10 ^ LY3
SM3 = Y3 * 6894.76

LOCATE 15, 12
INPUT "  ENTER THE PROPORTIONALITY FACTOR.  <Z>   (Table Z)  =  "; ZF
D3 = (CM * H3 * ZF * 6 * 100000!) / SM3
END SUB

SUB TyeffH35 (XV, C, SP, Q, PI, MAA, H3, D3, W, CM, ZF) STATIC
TyeffH35:
TH3 = .0047 * (MAA) * (MAA) + 1.06 * (MAA) - .033
T3 = TH3 - SP
XV = T3
CALL VISCyeff(XV, PI, VISCOSITY)
SBIT3 = (3 * VISCOSITY) / (.02 * W)
CLS
LOCATE 8, 32: PRINT "< SUBLAYER 3 >"
'LOCATE 9, 10: PRINT " ENTER THE EFFECTIVE MIX STIFFNESS  (SM) . THIS VALUE SHOU
LD BE"
'LOCATE 10, 10: PRINT " READ FROM THE Smix V. Sbit PLOT FOR   Sbit =   "; SBIT3
'LOCATE 11, 10: INPUT "                                                  "; SM3
SB3 = SBIT3 * .000145038#
LSB3 = LOG(SB3) / LOG(10)
LY3 = (Q * LSB3) + C
Y3 = 10 ^ LY3
SM3 = Y3 * 6894.76

LOCATE 15, 12
INPUT "  ENTER THE PROPORTIONALITY FACTOR.  <Z>   (Table Z)  =  "; ZF
```

```
D3 = (CM * H3 * ZF * 6 * 100000!) / SM3
END SUB

SUB VISCyeff (XV, PI, VISCOSITY) STATIC
VISCyeff:
IF PI = -2 THEN
        A = .000524
        B = -.0903
        C = 3.3
ELSEIF PI = -1 THEN
        A = .00048
        B = -.0812
        C = 3.43
ELSEIF PI = 0 THEN
        A = .0006146
        B = -.07011
        C = 3.457
ELSEIF PI = 1 THEN
        A = .0004954
        B = -.0655
        C = 3.589
ELSEIF PI = 2 THEN
        A = .0003288
        B = -.0792
        C = 3.23
END IF
LY = A * XV * XV + B * XV + C
VISCOSITY = 10 ^ LY
END SUB
```

PART 2

FACT SHEETS

INTRODUCTION

Computerized data bases were interrogated in an attempt to obtain sufficient technical information to prepare fact sheets on the following additives. Plastics: Polybilt; Novophalt; Novalastic; 3M-Asphadur; Solar-Lagugel; Accorex; Europrene; Bilulastic. rubber: Phopave; Olexobit; Neoflex; Ralumac; Sealgum; Neolastic; Cariflex/krater; hydrocarbon; Trinidad Lake Asphalt. Others: Ogra-Shield; Dutchlaid.

The search yielded sufficient data for the following sheets, which are reproduced in this section. Olexobit; Cariflex; Ralumac; Sealgum; Neolastic; Neoflex.

This disappointing result is probably due to the fact that there is considerable delay in the process of publication of technical information - in many cases of the order of 2 or more years (eg Transportation Research Records). To this must be added the time taken to collect the information into the technical data bases. These may be 2 years behind the current date.

Since much of the interest in additives is relatively recent and the names appear in trader magazines, the technical data, if indeed there is any, may be some years behind the introduction of the product.

MATERIAL Olexobit

SUPPLIER

Deutch B.P.
(British Petroleum, GERMANY)

DESCRIPTION

Olexobit is a blend of asphalt cement and a polymer based on an Ethyl-Propo-Diene monomer (E.P.D.M). It is supplied as a ready made binder, and may be described, generically, as a rubberised asphalt. The quantity of additive in the bitumen is regarded as proprietary information by the supplier.

USES(AS RECOMMENDED BY THE PRODUCER)

As the binder for high grade paving applications in West Germany. It's most common use is as a binder in Gussasphalt mixes which are subject to heavy traffic. Alternative formulations of Olexobit are also produced for roofing applications and for emulsification for use in surface treatments.

HANDLING AND MIXING

No detailed information is available, but it is probable that Olexobit is handled in a manner which is similar to conventional materials.

DISCUSSION AND RECOMMENDATION

Olexobit has been in use in Germany since about 1970 and since it is still in use it would appear to be reasonable to assume that it is successful. However its use does not appear to have spread into other European countries, let alone into other continents. It has been used in comparative trials in the United Kingdom. These trials have been based on Hot Rolled Asphalt, the mix most commonly used for surfacing heavily trafficked roads in the United Kingdom.As yet no results are available.

SUMMARY

The manufacturers do not attempt to give this product a high profile. However the fact that it is still in use some 18 years after its initial introduction supports a view that it provides the type of service required from it.

MATERIAL Cariflex

SUPPLIER
Shell Elastomers
Shell Centre
London

DESCRIPTION

Cariflex is described as a Thermoplastic Rubber (TR). The title is general and describes a family of block copolymers based on styrene and either butadiene or isoprene which are produced for a wide range of industrial applications as well as for use in blending with bitumen. The products promoted for use in paving applications are as follows:
Cariflex TR-1101 - A clear linear block copolymer based on styrene and butadiene, with a styrene content of 30% by mass, and a viscosity of 4.0 Pa.s measured on a 25% by mass solution in toluene at 25 C in a Brookfield viscometer. Cariflex TR-1184 - A clear branched block copolymer based on styrene and butadiene, with a styrene content of 30% by mass, and a viscosity of 20.0 Pa.s measured on a 25% by mass solution in toluene at 25 C in a Brookfield viscometer. Cariflex TR-KX71 - Similar to TR-1184 but containing 50 phr of oil for the purpose of decreasing the mixing time. The oil content is 33.3% by weight of the total. The viscosity, measured as above is 2.3 Pa.s

USES (AS RECOMMENDED BY THE PRODUCER)

Blends of Cariflex and bitumen are recommended for a very wide range of uses in the paving industry. It is claimed that Cariflex will reduce permanent deformation, and increase fatigue life, characteristics which make it ideal for use in wearing courses and thin overlays. Improved durability and reduced post construction compaction suggest its use in porous friction course material. As a stress absorbing membrane it can absorb horizontal crack mouth movements of several millimeters,maintain elastic characteristics over a wide range of temperatures, adhere efficiently to the old surface, and placed successfully in thin layers. Surface treatments are enhanced by better initial chip retention and tensile properties and an extended range of use. The three Cariflex binders described above are usually supplied in pellet form. The pellets are baged and supplied in quantities of approximately one tonne on a shrink film wrapped pallet.

HANDLING AND MIXING

The manufacturers of Cariflex indicate that the product does not present any unacceptable hazard when used in accordance with normal safe handling procedures adopted in the industry. The following specific recommendations are made by the supplier with regard to safety during processing; 1)Avoid inhalation of fumes and vapours from the hot rubber/compound.

2) Prevent skin contact with hot rubber/compound surfaces.

3) Observe the safety regulations for the chemicals used in rubber

processing. Care is necessary with regard to the selection of mixing equipment. The mixing temperature should not exceed 185 C and the blending time should be as short as possible consistent with their being time to dissolve the TR as completely as possible in the bitumen. Mixing is easiest if the pellets are preground into a fine powder. The modest shearing action of a paddle mixer may be adequate depending on the type of bitumen. Immersion mixers with serrated rotors and stators give the best results because of their high rotation speed and the cutting action of the teeth. Addition of Cariflex is usually recommended in quantities of 12-14% by mass of the total binder.

DISCUSSION AND RECOMMENDATIONS

Cariflex is claimed to improve nearly all aspects of the performance of bituminous paving mixes. There is a relatively large volume of supporting data derived from laboratory tests. However much of this work has been directed towards supporting the use of Cariflex as an additive in roofing mixes. To date no information is available concerning the performance of blends in highway applications other than in surface treatments. It is believed that Cariflex is very similar to if not identical with the Shell U.S.A. additive Kraton.

SUMMARY

The manufacturers claims are based on relatively extensive laboratory studies. However the lack of data from full scale trials in highway mixes is not particularly encouraging. Since Kraton is being included in the study and is almost certainly similar to Cariflex it is recommended that Cariflex be excluded from the study.

MATERIAL Ralumac

SUPPLIER

Raschig Corporation
5000 Osborne Tpke,
Richmond,
Va 23231

Parent Company

Raschig GmBH
Mundenheimer Strasse
100 D 6700
Ludwigshafen/Rhine

DESCRIPTION

Ralumac is an emulsified Latex modified 80 Penbinder. The residual binder has Penetration of 50-65 at 25 degrees Centigrade, a ring and ball softening point of 58-64 degrees Centigrade and a Frass breaking point of -13. The cold mix produced with this binder has a binder content of 5.0-9.0% by weight depending on the aggregate grading. The void content of a Marshall specimen of the mix should be between 2 and 6% by volume and the Marshall stability is greater than 10kN. Ralumac seal coats can be constructed with thicknesses ranging from 20lb/s.y to 45lb/s.y

USES (AS RECOMMENDED BY THE PRODUCER)

Ralumac is used as a surface treatment to restore profile and skid resistance. It also seals the existing surface and can be used as an overlay on cobblestone surfaces to reduce noise. Ralumac surface treatments can be applied without tack coats on all surfaces because of its superior adhesive properties.

HANDLING AND MIXING

The binder is handled as if it is a conventional asphalt emulsion. Special purpose built machinery is used for in-situ mixing, and is coupled directly with further purpose built construction equipment. When used for on heavily trafficked roads it high quality graded aggregate with a maximum size of between 0.2 and 0.3 inches is recommended for both rut filling and for overlays. When treating streets in residential areas the maximum recommended aggregate size is 0.1 to 0.2 inches, depending upon the traffic volume and the desired thickness. On seriously deformed surfaces profile improvement is provided by spot levelling prior to the final treatment. The cold mix may be applied at ambient temperatures as low as 40 degrees F, and it can carry traffic as soon as 20 minutes after construction.

DISCUSSION AND RECOMMENDATIONS

The particular advantages claimed for Ralumac are

A) It provides good immediate strength even when applied under adverse conditions.

B) It provides high resistance to polishing and good skid resistance.

C) It extends the conventional working season Ralumac was achieved greatest market penetration in West Germany but is used in other European countries. One example cited is of a treatment to Autobahn A 61 near Ludwigshafen. The treatment consisted of correcting rut depth of up to 1.5 inches and a final overlay of 0.3 inch mix. Good values of skid resistance were reported after three years of traffic.

SUMMARY

The manufacturers claims are supported by a limited number of trials carried out in Europe. Whilst it is likely that it would function successfully in the U.S.A. a strong recommendation should await further successful data. Since Ralumac is designed for use in relatively thin resurfacing type applications specifically to restore skid resistance and surface profile it is not recommended for use in this study.

MATERIAL Sealgum

SUPPLIER Pavement Technologies, Inc.
15042 NE 40th Street, Suite 201
Redmond,
Washington 98052
Tel. 206-883-6860
Telex: 323680(PaveTech)

DESCRIPTION

Sealgum is a cold laid, rough textured waterproof, latex modified binder-based micro-asphalt concrete. The binder is in the form of an emulsified latex-modified asphalt emulsion. The mix has a high filler content to maximize its waterproofing characteristics and minimize the risk of bleeding.

USES (AS RECOMMENDED BY THE PRODUCER)

It is recommended for use in Urban streets, in parking lots, industrial areas and school yards. It is also reccomended for surfacing emergency stopping lanes and parking areas, and as a new wearing course on asphalt stabilized base courses. Surfacing of damp, compacted sand/gravel base courses is possible, after curing. Airfield runways and taxiways can be resurfaced with Sealgum and it is suitable for the maintenance of rural pavements under rapid, medium and high density traffic.

HANDLING AND MIXING

The material is proportioned mixed and placed directly onsite by a single batch or continuous machine. A special mechanical spreader is incorporated in the machine which can operate on pavements of any width. The machine is claimed to be capable of covering up to 25,000 sq.yd. of surface per working day. Light compaction is recommended if the newly treated surface is to receive some traffic. Sealgum sets rapidly and so a treated pavement can be reopened to traffic very quickly.

DISCUSSION AND RECOMMENDATIONS

Sealgum is offered as an alternative to surface treatment by slurry seal and by thin hot mix overlays.

The advantages claimed over slurry seals are -

A) More durability;

B) Greater skid resistance;

C) Better levelling and finishing characteristics;

D) Thicker and more flexible surfacing; The advantages claimed over thin hot mix overlays are -

A) Simplification of detailing in the region of joints with shoulders etc.;

B) Localized treatment is possible e.g. in wheel track ruts;

C) Improved adhesion to existing pavement surface;

D) Since only light compaction is required the risk of disruption to underground utilities is minimised;

E) The equipment can readily adjust to the variable cross section of old surfaces.

SUMMARY

Sealgum appears to be a mix based on the latex modified binder Neoflex produced by the same company for use in simple surface treatments. In describing the material Remillon(1) postulates that for materials used in thin layers cohesion rather than internal friction is primarily responsible for the performance of the mix. No data is currently available to verify the advantages claimed for the mix. No improvement in the resistance to permanent deformation have been claimed for this material, therefore it is not recommended for inclusion in this study.

MATERIAL Neolastic

SUPPLIER Pavement Technologies, Inc.
15042 NE 40th Street,
Suite 201 Redmond,
Washington 98052
Tel. 206-883-6860
Telex: 323680(PaveTech)

DESCRIPTION

Neolastic is a cationic thermoplastic co-polymer modified bitumen-based emulsion. It is supplied as a ready made liquid binder.

USES (AS RECOMMENDED BY THE PRODUCER)

As the binder in single or double chip seal treatment on either flexible or rigid pavements carrying heavy traffic. Maintenance of primary and secondary road system pavements carrying medium or high densities of traffic. Preventative maintenance for heavily trafficked highways.

HANDLING AND MIXING

Neolastic, is handled in the same way as conventional asphalt emulsion.It is applied by spraybar also in a manner which is largely conventional. In the European trials it was usually applied at a rate of spread of about 2kg/sqm. though two trials at a rate of 1.6kg/sqm. have been completed successfully.

DISCUSSION AND RECOMMENDATIONS

The particular advantages claimed for Neolastic are

A) It provides good immediate strength even when applied under adverse conditions.

B) It does not require that either the underlying surface or the chippings added subsequently be dry in order to obtain a successful treatment.

C) It does not penetrate the asphalt substrate and so will not contribute to any potential fatting problems.
Several trials of Neolastic were carried out in Europe in 1980. They were recorded as performing satisfactorily in 1983. There is very little data in the literature relating to measurements of the performance of Neolastic under traffic. It is therefore impossible to be certain of its performance in a North American environment.

SUMMARY

The manufacturers claims are supported by a limited number of trials carried out in Europe. Whilst it is likely that it would function successfully in the U.S.A. a strong recommendation should await further successful data. Since Neolastic is designed for use in Chip Seal type applications it is not recommended for use in this study.

MATERIAL Neoflex

SUPPLIER Pavement Technologies, Inc.
15042 NE 40th Street, Suite 201
Redmond,
Washington 98052
Tel. 206-883-6860
Telex: 323680(PaveTech)

DESCRIPTION

Neoflex is a cationic latex modified bitumen-based emulsion.It is supplied as a ready made liquid binder.

USES (AS RECOMMENDED BY THE PRODUCER)

As the binder in single surface treatments to restore skid resistance and drainage in Urban streets and on the pavements of primary and secondary road systems. As the binder in double surface treatments when a high degree of wear resistance and surface drainage is required. For example, accident black spots, heavily trafficked pavements.

HANDLING AND MIXING

Neoflex, is handled in the same way as a conventional asphalt emulsion. It is applied by spray bar also in a manner which is largely conventional. In the European trials it was usually applied at a rate of spread of about 2kg/sqm. though two trials at a rate of 1.6kg/sqm. have been completed successfully.

DISCUSSION AND RECOMMENDATIONS

The particular advantages claimed for Neoflex are

A) It provides good immediate strength even when applied under adverse conditions.
B) It does not require that either the underlying surface or the chippings added subsequently be dry in order to obtain a successful treatment.
C) It does not penetrate the asphalt substrate and so will not contribute to any potential fatting problems.

Several trials of Neoflex were carried out in Europe in 1980. They were recorded as performing satisfactorily in 1983. There is very little data in the literature relating to measurements of the performance of Neoflex under traffic.It is therefore impossible to be certain of its performance in a North American environment.

SUMMARY

The manufacturers claims are supported by a limited number of trials carried out in Europe. Whilst it is likely that it would function successfully in the U.S.A. a strong recommendation should await further successful data. Since Neoflex is designed for use in Seal Coat type applications it is not recommended for use in this study.

PART 3

PRELIMINARY STUDIES OF THE EFFECTS OF VECTORED THRUST

A. INTRODUCTION

The purpose of this study is to provide a preliminary investigation of the effects of vectored thrust aircraft on the surface of asphalt pavements.

Three areas will be investigated as follows:-

1) The possibility of localised heating causing excessive hardening in the binder.
2) The possibility of a reduction in the strength in the pavement as a result of reduced stiffness of the asphalt layer through significant "in depth" heating.
3) The effect of the high speed air or " jet blast" directed on to the pavement surface.

As this is a preliminary investigation the study will utilize as far as possible existing techniques for the computations. These techniques will be described briefly and where appropriate their limitations will be mentioned.

DETERMINATION OF PAVEMENT TEMPERATURE

Calculation procedure.

For the purpose of this study the exhaust from a vectored thrust aircraft will be considered to be analogous to a pavement heater of the type used for hot planing, and also in some forms of insitu recycling.

Carmichael et al (1) reported an analysis designed to model the change in pavement temperature with depth resulting from the passage of a heater. This analysis treats the pavement as a semi-infinite solid at a fixed initial temperature, where the temperature above the surface is suddenly changed and maintained at a new and higher temperature. Carmichael et. al. (1) solved the partial differential equation for temperature distribution in the pavement as a function of time using a foreword difference numerical equation. The solution includes an empirical relationship to account for convection at the pavement surface, which is attributed to Clazie et. al. (2). This relationship is used to correct the surface temperature at the end of each time period used in the calculation.

The computer programme reported by Carmichael et. al. (1) was modified to suit the particular requirements of this study by increasing the number of steps available to the solution procedure and rearranging the input data to accept time of exposure directly.

Computation of pavement temperatures.

Data provided by Capt. G.E. Walrond, Project Officer for the Advanced Technology F-15 Pavement Interaction Study indicated that the temperature at the centre of the exhaust plume of the engine at the pavement surface was 1000 degrees Rankine (540 degrees Fahrenheit).

Temperature profiles were calculated after 1,2,5,and 10 minutes exposure to this temperature. Following a preliminary series of calculations the maximum depth for calculation was set to 3.75 inches. This ensured that the full depth of penetration of the heat from the exhaust was computed.

Initial pavement temperatures of 32, 70 and 100 degrees Fahrenheit were to investigate the effects of this parameter.

There are two significant limitations to this analysis. The first one is the assumption of a uniform temperature profile with depth, as a starting point. This condition is not likely to occur in practise and the true profile could be very different from this assumption. The second one concerns an observation made whilst examining the data produced by the programme. When comparing the results of the preliminary studies with the results of the main study it was there were some differences in the profiles obtained. The preliminary studies, carried out with relatively coarse increments of time for the foreword difference solution to the heat transfer equations indicated higher temperatures at and near the pavement surface. Carmichael et. al. (1) state that smaller increments produce more accurate results, and so it is assumed that the values presented in the next section are the most reliable.

EFFECTS OF SURFACE HEATING

Figure 1 plots the rise in surface temperature as a function of time for each of the three initial surface temperatures. It should be noted that the pattern of increase in temperature with time is virtually independent of the initial pavement temperature. Also the shape of the curve indicates that the surface temperature is continuing to rise, as would be expected. The maximum surface temperature reached after 10 minutes exposure is just below 220 degrees Fahrenheit. This temperature is very close to the upper limit for compaction temperature used in construction specifications. The principal reason for this limit to compaction temperatures is to ensure that there is no excessive hardening of the binder in the asphalt which could lead to loss of durability of the mix or cracking under low temperature conditions. Thus under the most extreme condition investigated there is some possibility of ageing of the asphalt cement in the pavement. However it must be emphasized that this is an extreme condition which is unlikely to occur during the operation of vectored thrust aircraft. It should also be noted that the computation does not consider the cooling effects of wind which may be significant in many cases.

In summary it can be stated that the operation of vectored thrust aircraft is unlikely to cause excessive hardening of the asphalt cement in a pavement surface, but excessive exposure (10 minutes or more) could be damaging.

STRUCTURAL SIGNIFICANCE OF HEATING

Calculation procedure

The use of vectored thrust for aircraft operation will have the effect of raising the temperature of the pavement. This, in turn will reduce the Stiffness of the pavement layer and could therefore influence the build up of distress in the pavement.

Figures 2 - 5 show the calculated temperature profiles for exposure times of 1,2,5, and 10 minutes respectively. As would be expected the greatest depth of penetration of the heating effect occurs at the 10 minute exposure time, reaching a depth of approximately 2.7 inches. In order to present a complete picture of the temperature - depth profiles the data from Figures 2 - 5 have been grouped together according to the initial pavement temperature and are presented in this form in Figures 6,7,8. It can be seen from these figures that there is no difference in the temperature profile after 1 and 2 minutes exposure.

In order to asses the potential structural significance the pavements were evaluated using conventional mechanistic procedures. The evaluation is based on asphalt strain only and therefore relates to potential fatigue damage only. The following procedure was adopted:-

1) An appropriate pavement design was selected.

2) The worst case temperature profile was selected.

3) The pavement was evaluated assuming a constant temperature profile.

4) The pavement was evaluated assuming the calculated worst case temperature profile.

The following is a detailed description of this procedure.

Step 1. Pavement design.

Flexible Pavement Design Program (FAD506) provided by the U.S. Army Corps of Engineers Waterways Experiment Station was used to develop the pavement design. The principal input data for the program was as follows;

Airfield class = Airforce light field

Subgrade CBR= 5%

Base CBR= 80%

Frost code = 0

The airfield class "light field" was chosen since the controlling aircraft is the F-15, and this was considered to be representative of the type of aircraft which could be operating with vectored thrust. A copy of the printout from the design program is presented in appendix A.

Step 2. Worst case temperature profile.

The temperature profile selected as the worst case was a 10 minute exposure with an initial temperature of 32 degrees F.

Step 3. Evaluation of the pavement at constant temperature

The computer program AIRPAVE version DRA-9.86.03 supplied by the U.S. Army Corps of Engineers Waterways Experiment Station was used to evaluate the pavement. Asphalt stiffness was determined from the work published by Kingham and Kallas (5) for a loading frequency of 1 Hz. Input data for the analysis were as follows:-

LAYER NO.	STIFFNESS PSI	POISSON RATIO	THICKNESS IN.
1	1800000	0.4	5.0
2	20000	0.3	22.5
3	7500	0.4	

All interfaces were rough, and the loading data was obtained from the data file which accompanies AIRPAVE.

A copy of the output for this evaluation is presented in appendix B. The asphalt strain calculated was 227 microstrain.

Step 4. Evaluation of the pavement after heating.

As for step 3 AIRPAVE was used for this evaluation. For this condition the asphalt layer was subdivided into three sub layers in order to model the effects of the temperature gradient. The top layer was 1 inch thick and has a mean temperature of 100 degrees F. The second layer was 1.7 inches thick and had a mean temperature of 40 degrees F. Input data for the analysis was as follows:-

LAYER	STIFFNESS	POISSON	THICKNESS
PSI	RATIO	IN.	
1	50000	0.4	1.0
2	900000	0.4	1.7
3	1800000	0.4	2.3
4	120000	0.3	22.5
5	7500	0.4	

A copy of the output for this evaluation is included in appendix C. The asphalt strain calculated was 257 microstrain.

Interpretation of the results.

It was found that the computation of allowable passes in AIRPAVE was performed with the strain calculated at the bottom of the top layer. This was not suitable for the comparative study since the pavement with a temperature gradient required use of the strain at the bottom of the third layer for the evaluation. Therefore the equation for the fatigue strain was used directly. It should be noted that this equation computes the member of coverages NOT the number of passes as quoted by AIRPAVE. However since these two parameters are connected by a constant which depends only on the traffic area the relative effect of the heating due to vectored thrust is shown accurately.

The asphalt fatigue equation is:-

Allowable strain = 10^{-A}

where :-

$$A = \frac{1}{5}\left[\mathrm{Log(cov.)} + 2.665\mathrm{x}\log\left(\frac{E}{14.22}\right) + 0.392\right]$$

This equation yields 16,990 coverages for the pavement which is not subject to a vectored thrust induced temperature gradient and 9,131 coverages for the pavement which is. It may therefore be concluded that in the event of exposure to vectored thrust for 10 minutes, the number of coverages of an F-15 aircraft that a pavement designed for this aircraft can support will be significantly reduced. It must be noted that this conclusion is based on an assumed worst case and must be evaluated with respect to the actual operating parameters of aircraft using vectored thrust.

EFFECT OF JET BLAST

The purpose of this section is to consider the possibility of erosion of a pavement surface subjected to the blast from aircraft employing vectored thrust. It is beyond the scope of this investigation to undertake any tests in relation to this problem, however an investigation of the literature has revealed that surface erosion under jet blast has been investigated at the Waterways Experiment Station in the past (3).
One conclusion of the report states that:- "Asphaltic concrete will give satisfactory performance under traffic and blast of jet planes, except in areas where afterburner checks are made. .." It was also noted that certain aircraft produce minor erosion.
This earlier work indicates that there is a definite possibility that vectored thrust aircraft will cause erosion of the surface of asphalt pavements.

CONCLUSIONS AND RECOMMENDATIONS

It may be concluded that aircraft fitted with vectored thrust can cause additional structural damage to pavements as a result of heating effects. It is also concluded that erosion is possible as a result of the blast from the vectored thrust.

It is recommended that the operating parameters of aircraft using vectored thrust be investigated as this has considerable significance in relation to the damage potential. The analysis above provides sufficient data for a preliminary assessment of the probability of damage, therefore permitting a decision in relation to further investigation.

REFERENCES

(1) MODELLING HEATER TECHNIQUES FOR IN-PLACE RECYCLING OF ASPHALT PAVEMENTS Carmichael, T, Boyer, R E, Hokanson, L D Proceedings of the Association of Asphalt Paving Technologists, Volume 46, February 1977, pp 526 - 537

(2) GRAPHICAL SOLUTIONS OF CARTESIAN COORDINATES Clazie, R, Hwang, K C, Porter, J S, Longwell, P A American Society of Mechanical Engineers Paper No 63-HT-8 Boston Heat Transfer Conference, Boston, Mass (October 1962)

(3) SUMMARY OF INVESTIGATIONS OF JET BLAST, FUEL SPILLAGE AND TRAFFIC ON EXPERIMENTAL TAR-RUBBER-CONCRETE PAVEMENTS Technical Memorandum No 3-420

(4) LABORATORY FATIGUE AND ITS RELATIONSHIP TO PAVEMENT PERFORMANCE Kingham, R I and Kallas, B F Proceedings, Third International Conference on the Structural Design of Asphalt Pavements, Vol 1, University of Michigan, Ann Arbor, Mich, 1972

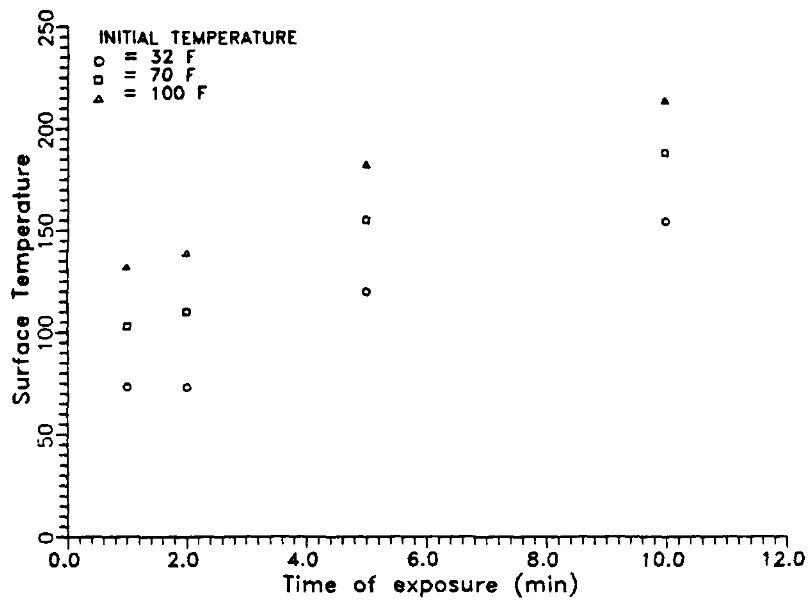

FIGURE 1. Temperature profiles as a function of the time of exposure to the vectored thrust.

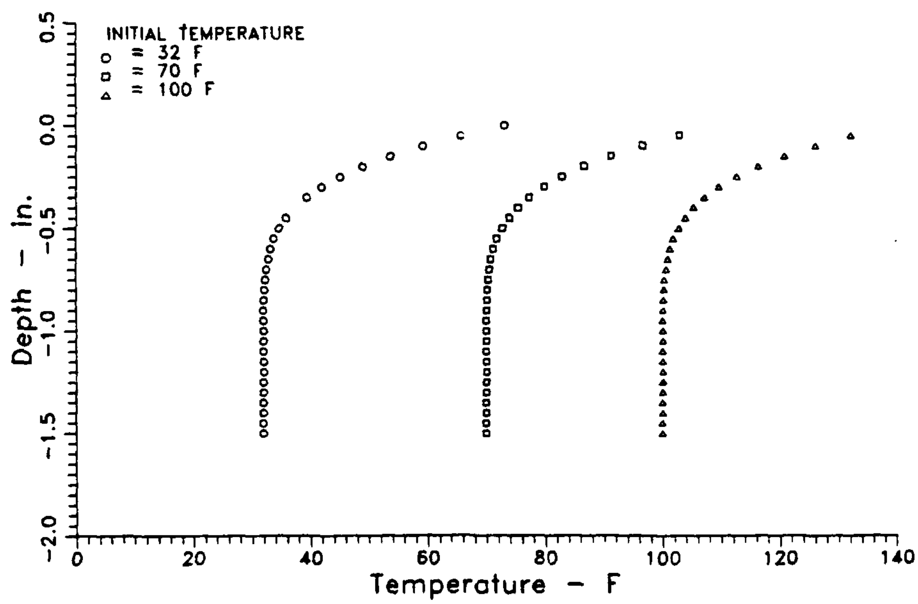

FIGURE 2. Temperature profiles as a function of depth after one minute of exposure to vectored thrust

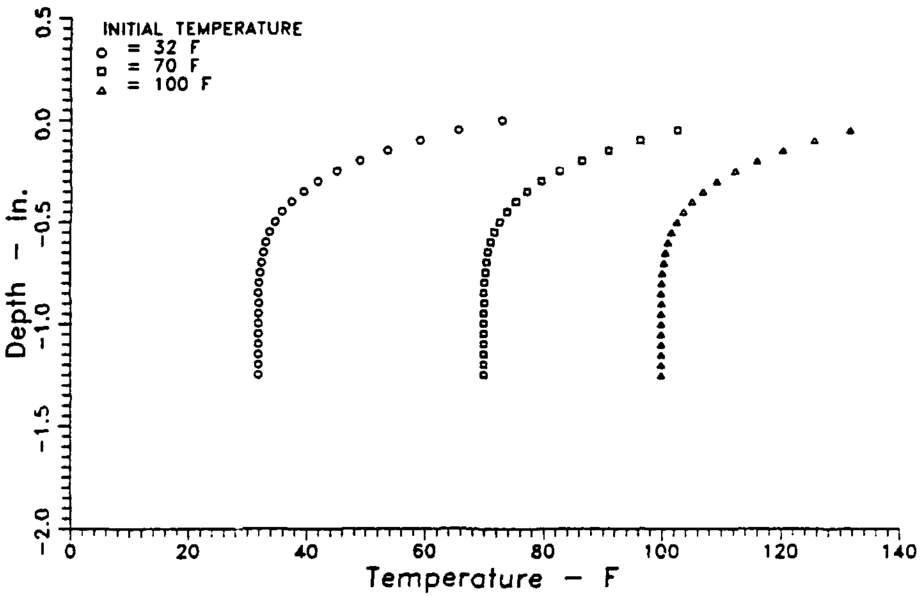

FIGURE 3. Temperature profiles as a function of depth after two minutes of exposure to vectored thrust.

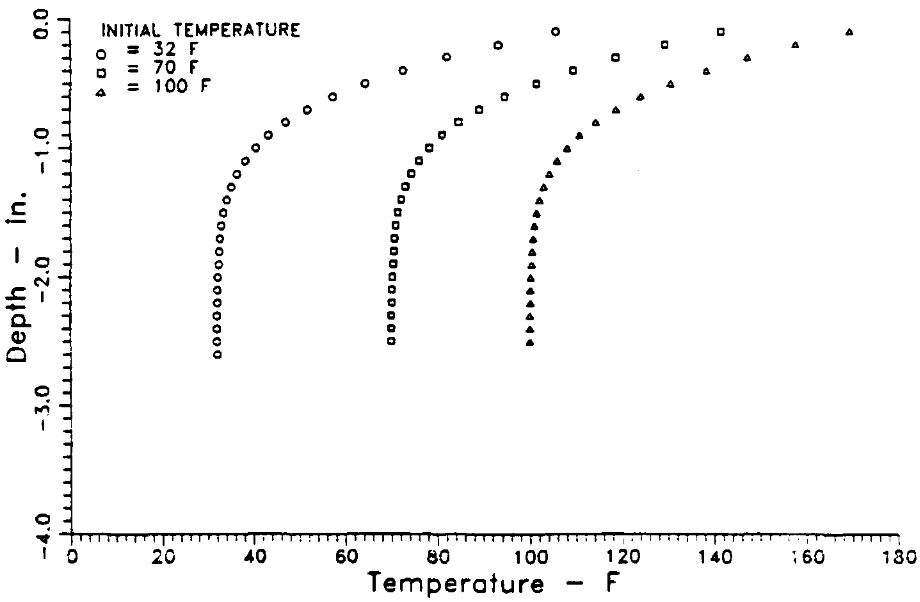

FIGURE 4. Temperature profiles as a function of depth after five minutes of exposure to vectored thrust.

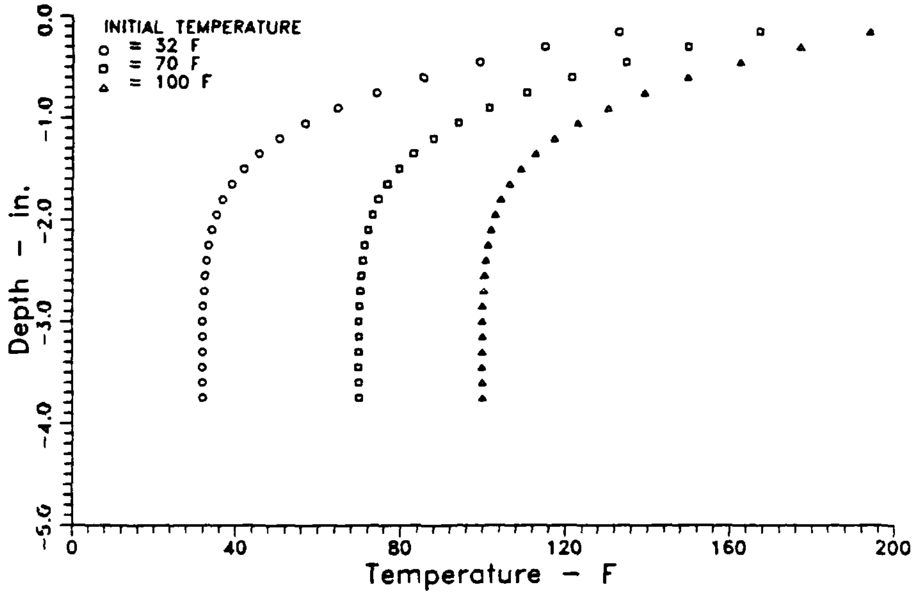

FIGURE 5. Temperature profiles as a function of depth after ten minute of exposure to vectored thrust.

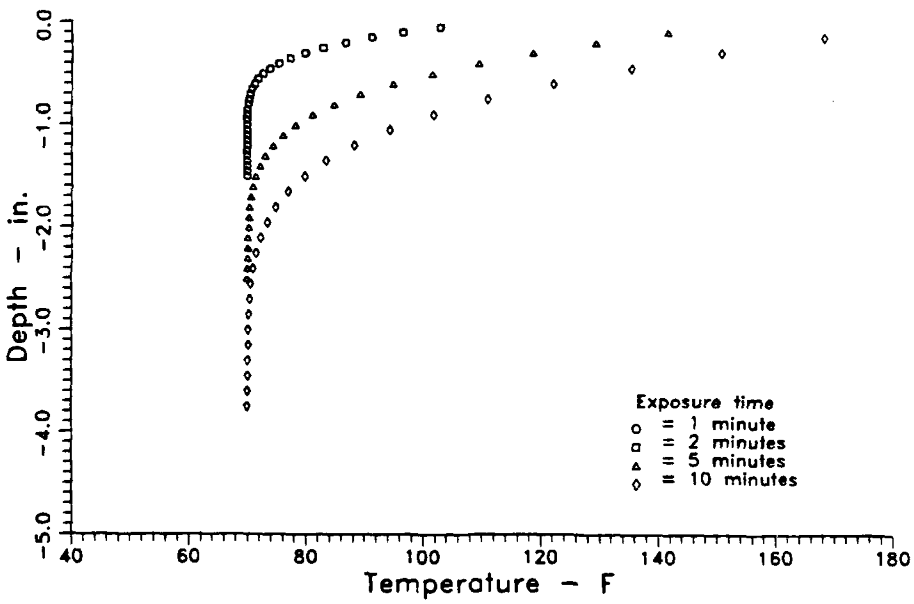

FIGURE 6. Temperature profiles as a function of depth for an initial temperature of 32 degrees F.

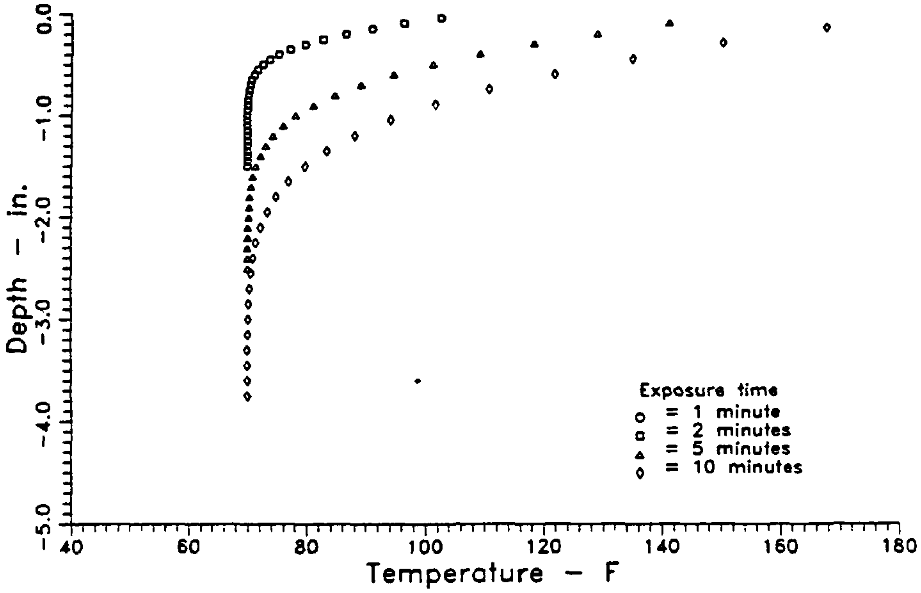

FIGURE 7. Temperature profiles as a function of depth for an initial temperature of 70 degrees F.

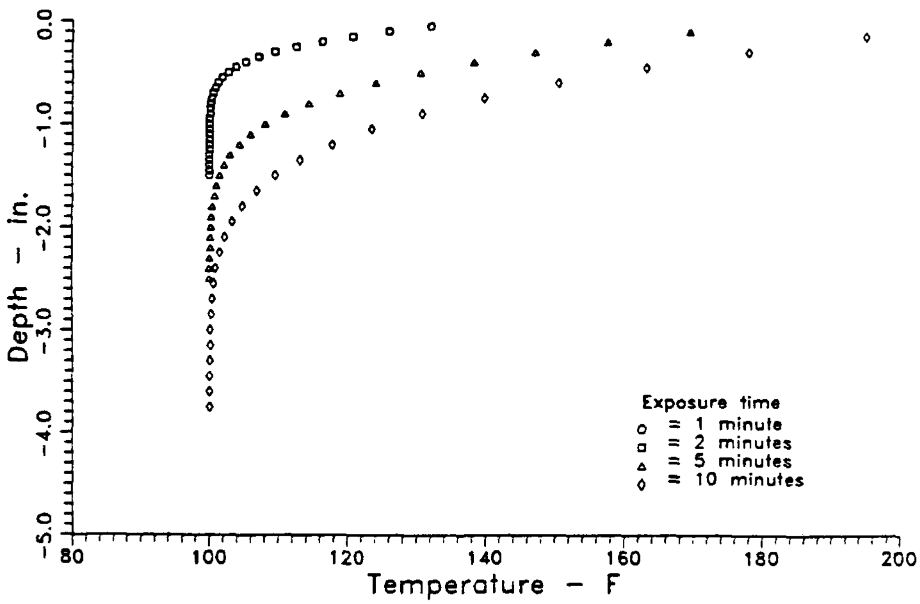

FIGURE 8. Temperature profiles as a function of depth for an initial temperature of 104 degrees F.

APPENDIX A

PRINTOUT FROM THE DESIGN PROGRAM

FLEXIBLE PAVEMENT DESIGN PROGRAM
(F A D 5 0 6)
U. S. ARMY CORPS OF ENGINEERS
WATERWAYS EXPERIMENT STATION
VICKSBURG, MISS. 39180

REF. MANUALS TM 5-825.2/AFM 88-6 CHAPTER 2

TIME 08:36:17 DATE 10-01-1987

AIRFIELD CLASS = AIR FORCE LIGHT FIELD
SUBGRADE CBR = 5
BASE CBR = 80

FOR	DESIGN LOAD	DESIGN PASSES	EQUIV PASSES
F-15	68000	100000	100000
C-141	345000	100	40480

CONTROLLING AIRCRAFT

FOR F-15 DESIGN LOAD 68000 DESIGN PASSES 140480

TRAF AREA	SURFACE THICKNESS	BASE THICKNESS
A	5.0	22.5
B	4.0	22.5

FOR	DESIGN LOAD	DESIGN PASSES	EQUIV PASSES
F-15	51000	100000	100000
C-141	258750	100	27445

CONTROLLING AIRCRAFT

FOR F-15 DESIGN LOAD 51000 DESIGN PASSES 127445

TRAF AREA	SURFACE THICKNESS	BASE THICKNESS
C	4.0	18.5

FOR	DESIGN LOAD	DESIGN PASSES	EQUIV PASSES
F-15	51000	1000	1000
C-141	258750	1	34

CONTROLLING AIRCRAFT

FOR F-15 DESIGN LOAD 51000 DESIGN PASSES 1034

TRAF AREA	SURFACE THICKNESS	BASE THICKNESS
OVERRUN	DBST	13.5
SHOULDER	2.0	12.0

NOTES 1) For 150 feet of OVERRUN use 2 inches of dense graded asphaltic concrete for blast protection.
2) Base of OVERRUN to be minimum 50 CBR material.

ADDITIONAL NOTE: Values in () are computed thicknesses and do not take into consideration the minimums in manual.

APPENDIX B

PRINTOUT FROM AIRPAVE FOR CONSTANT TEMPERATURE

***********************"AIRPAVE" VERSION DRA-9.86.03***********************

PROBLEM NUMBER 1

CONSTANT TEMP.

PAVEMENT INPUT PARAMETERS

LAYER NO.	THICKNESS IN.	MODULUS PSI	POISSON'S RATIO	INTERFACE COMPLIANCE
1	5.00	1800000.	0.40	0.
2	22.50	120000.	0.30	0.
3	SEMI-INF	7500.	0.40	0.

PAVEMENT EVALUATION SUMMARY

DESIGN AIRCRAFT	DESIGN LOAD, KIPS	DESIGN PASS LEVEL	ALLOW-ABLE LOAD, KIPS	ALLOWABLE PASSES OF DESIGN AIRCRAFT	PCN
GROUP 17 : F-15 C-D	68.0	100000.	68.0	159736.	34

BLIST FOR PROBLEM NUMBER 1

GROUP 17 : F-15 C-D

STRAINS FROM BISAR

EVALUATION POSITION	X,IN.	Y,IN.	VERTICAL STRAIN AT TOP OF SUBGRADE, IN/IN	DEPTH, IN.	RADIAL STRAIN AT BOTTOM OF AC LAYER, IN/IN	DEPTH, IN.
1	0.0	0.0	0.4252646E-03	27.5	0.2267826E-03	5.0

FLEXIBLE PAVEMENT EVALUATION

LAYER 1 THICKNESS= 5.00 OVERLAY THICKNESS= 0.00
ALLOWABLE ASPHALT STRAIN= 0.249E-03 COMPUTED STRAIN= 0.227E-03
ASPHALT STRAIN RATIO= 1.10
ALLOWABLE SUBGRADE STRAIN= 0.942E-03 COMPUTED STRAIN= 0.425E-03
SUBGRADE STRAIN RATIO= 2.22
NO. OF PASSES= 100000 PRIMARY TRAFFIC AREA
DESIGN AIRCRAFT LOAD= 68000. ALLOWABLE LOAD= 74677.
CALCULATED SUBGRADE CBR= 5.0 IMPACT FACTOR= 1.00

MINIMUM RATIO= 1.10
THICKNESS OF LAYER 1 = 5.00

APPENDIX C

PRINTOUT FROM AIRPAVE FOR SELECTED TEMPERATURE GRADIENT

```
***************************************************************************
***********************"AIRPAVE" VERSION DRA-9.86.03***********************
***************************************************************************

                              PROBLEM NUMBER    1

    TEMPVAR



              PAVEMENT INPUT PARAMETERS
              *************************

LAYER   THICKNESS    MODULUS     POISSON'S   INTERFACE
 NO.       IN.         PSI        RATIO      COMPLIANCE
*****   *********   *********   *********   **********


  1        1.00       50000.      0.40           0.
  2        1.70      900000.      0.40           0.
  3        2.30     1800000.      0.40           0.
  4       22.50      120000.      0.30           0.
  5      SEMI-INF      7500.      0.40           0.

                        PAVEMENT EVALUATION SUMMARY
                           DESIGN           ALLOW-   ALLOWABLE
                       **************       ABLE     PASSES OF
        DESIGN         LOAD.     PASS       LOAD.    DESIGN
       AIRCRAFT        KIPS      LEVEL      KIPS     AIRCRAFT     PCN
******************* ******   ********   ******   *********    ***

GROUP 17 : F-15 C-D     68.0   100000.     68.0   45728496.     60

***************************************************************************
***************************************************************************
***************************************************************************
                        BLIST FOR PROBLEM NUMBER    1

***************************************************************************

                           GROUP 17 : F-15 C-D

*************************STRAINS FROM BISAR*************************

                                VERTICAL STRAIN          RADIAL STRAIN
                                  AT TOP OF               AT BOTTOM OF
EVALUATION                        SUBGRADE.     DEPTH,     AC LAYER,     DEPTH.
 POSITION     X,IN.   Y,IN.        IN/IN         IN.        IN/IN         IN.
**********    *****   *****   **************   ******   *************   ******

    1          0.0     0.0     0.4994071E-03    27.5     0.2570633E-03    5.0


                        FLEXIBLE PAVEMENT EVALUATION

    LAYER 1 THICKNESS=  1.00          OVERLAY THICKNESS=  0.00
    ALLOWABLE ASPHALT STRAIN= 0.168E-02     COMPUTED STRAIN= 0.257E-03
    ASPHALT STRAIN RATIO=  6.54
    ALLOWABLE SUBGRADE STRAIN= 0.942E-03     COMPUTED STRAIN= 0.499E-03
    SUBGRADE STRAIN RATIO=  1.89
    NO. OF PASSES=     100000      PRIMARY   TRAFFIC AREA
    DESIGN AIRCRAFT LOAD=      68000.       ALLOWABLE LOAD=    128312.
    CALCULATED SUBGRADE CBR=    5.0      IMPACT FACTOR=    1.00

    MINIMUM RATIO=  1.89
```

END

DATE

FILMED

10-88

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