BEHAVIOR OF COLD MIXES UNDER REPEATED COMPRESSIVE LOADS

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• RECENT studies dealing with repeated loads have been concerned with the behavior of hot bituminous mixes. Cold mixes, however, have received limited interest. A cold bituminous mix is prepared by mixing the aggregates with a cutback asphalt. This mix may be spread and compacted at atmospheric temperature. Cold mixes remain workable for long time periods; hence, in addition to being suitable for immediate use, they may be transported for long distances and placed in stockpiles for future use. The advantages gained from such a bituminous mix that is not dependent on temperature for mixing, placing, and drying of the aggregates are mainly economic. The increasing use of cold mixes, because of their economic aspects, warrants research that will produce a better understanding of the behavior of cold mixes.

The objectives of this research are to study the behavior of bituminous-aggregate mixes (BAMs) under repeated compressive load (fatigue life) in unconfined conditions and to determine the modulus of resilience of these mixes under specific conditions. The study includes the influence of such variables as cutback content, aggregate gradation, type of cutback, curing time, and temperature on the fatigue life of BAMs.

The modulus of resilience is defined as the applied compressive stress divided by the resilient (recoverable) strain. It was introduced to the asphaltic material research by Hveem (2). Later, Seed et al. (5, 6) evaluated the modulus of resilience for compacted subgrade clayey soil and granular bases. Recently, Terrel and Monismith (7) determined the modulus of resilience of a BAM. Although Terrel and Monismith were primarily interested in the influence of curing time, they did indicate the influence of confining pressure and temperature on the modulus of resilience. The importance of the modulus of resilience as determined by experimental work is that it can be incorporated in elastic theories to determine the deflection or the stresses of a pavement when subjected to a specific loading.

MATERIAL

Two different types of cutback asphalt were used in this study. The first was rapid-curing asphalt (RC-800) obtained from Sinclair Refinery, Wood River, Illinois. The RC-800 contained 21.3 percent volatiles by total weight. The specific gravities of the solvent and residue were 0.77 and 1.02 respectively. The rapid-curing cutback was used to prepare 95 percent of the tested specimens. The second type of cutback was medium-curing asphalt (MC-250) obtained from the same source as RC-800. The MC-250 contained 21.3 percent volatiles by total weight. The specific gravities of the solvent and residue were 0.79 and 1.01 respectively.

Aggregates were obtained from Pontiac Gravel Co., Mohamet, Illinois. The origin of these aggregates is glacial outwash of Wisconsian age. The coarse aggregate, passing a ³⁄₄-in. sieve and retained on a No. 8 sieve, has a bulk specific gravity of 2.58. The fine aggregate, passing a No. 8 sieve and retained on a No. 200 sieve, has a specific gravity of 2.65. Two aggregate gradations were used: dense and open. The gradations of the aggregates are as follows:

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Aggregate Gradation	Sieve Size, Percent Passing							
	¾ in.	½ in.	⅜ in.	No. 4	No. 10	No. 40	No. 80	No. 200
Dense	100	85	76	61	46	24	13	6
Open	100	84	72	49	30	8	0	0

A pit-run gravel was simulated by passing a loess material through a No. 200 sieve. The clay fraction of the loess was approximately 10 percent, the liquid limit was 28 percent, the plastic limit was 25 percent, and the plasticity index was 3 percent.

MIX DESIGN

Methods for designing cold mixes are not thoroughly standardized, perhaps because cold mixes are not used as extensively as hot mixes. The existence of a large number of types and grades of cutback asphalts, which make them practically applicable to every condition of temperature, aggregate, and paving equipment, may be responsible for the lack of a rational design method.

Accordingly, a laboratory program was carried out to answer the following questions.

1. For a certain cutback content, what are the drying (between mixing and molding) and curing times (between molding and testing) that give the maximum stability?
2. For determined drying and curing times, what is the cutback content that gives the maximum density?

It is realized that maximum stability and maximum density are probably not the only criteria that should be considered in designing BAMs. However, because this investigation was not directed toward developing a design procedure, it was felt that these two criteria would produce a satisfactory mix. Laboratory results indicated that maximum stability (as measured in the Hveem stabilometer) of the dense mix can be achieved at a drying time of 4 hours in an oven adjusted to a temperature of 180 F and a curing time of 10 days at room temperature (approximately 75 F). The maximum density was obtained at a cutback content of 7 percent. These values were used as a guide for selecting the magnitude of the variables considered in the investigation.

VARIABLES

The variables in this study include (a) testing temperature (19, 22, and 25 C), (b) cutback content (6, 7, and 8 percent), (c) aggregate gradation (dense and open), (d) curing time (10 days and 300 days), and (e) type of cutback asphalt (RC-800 and MC-250).

TESTING PROCEDURES

Cylindrical specimens 3⅞ in. in diameter and 6 in. in height were fabricated in a steel double-plunger mold. Each group of specimens having the same properties and tested under similar conditions is defined as a series. The designation of the eight test series and their properties are given in Tables 1 and 2.

A testing machine of the constant-displacement type was used to apply repeated compressive stresses to the unconfined specimens. The displacement was produced by an adjustable motor-driven eccentric operating a series of levers. Figure 1 shows the testing machine. The loads applied to the specimen were equivalent to the force required to cause a deflection in a steel bar dynamometer equal to the vertical movement of the oscillating shaft of the machine. Necessary readjustments of the load during the course of the tests were accomplished by varying the length of the adjustable connecting rod, H.

The loads were applied at a rate of 730 cpm. The hand crank, O, was used only when the machine was stopped to allow the measurements of the total deformation experienced by the test specimen when subjected to a specific load through two dial indicators.

The testing machine was placed in a controlled-temperature environment. A minimum stress of ¼ psi was maintained on the specimen to avoid the dynamic effects

Table 1. Series designation of BAMs used in repeated load tests.

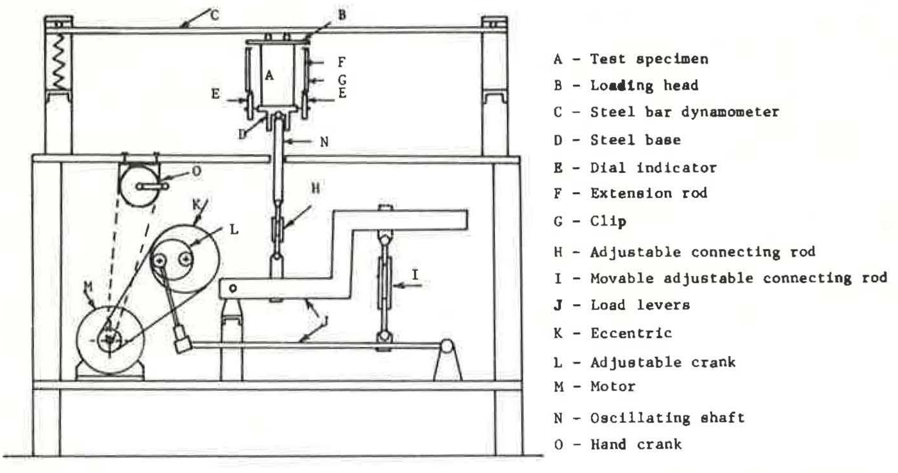
Series	Gradation	Top Size (in.)	Cutback Type	Cutback Percent	Curing Time (days)	Testing Temperature (deg C)
I	Dense	¾	RC-800	7	10	25
II	Dense	¾	RC-800	7	10	22
III	Dense	¾	RC-800	7	10	19
IV	Dense	¾	RC-800	8	10	22
V	Dense	¾	RC-800	6	10	22
VI	Open	¾	RC-800	7	10	22
VII	Dense	¾	RC-800	7	300	22
VIII	Dense	¾	MC-250	7	120	22

Table 2. BAM test results.

Series	Unit Weight Average pcf	Unit Weight c_v Percent	Unconfined Compressive Strength Average pcf	Unconfined Compressive Strength c_v Percent	Amount of Voids (percent)	Amount of Water (percent) Original	Amount of Water (percent) After 10 Days	Amount of Volatiles (percent) Original	Amount of Volatiles (percent) After 10 Days
I, II, III	139.4	0.59	61.5	6.07	6.1	4.8	0.07	1.49	0.04
IV	140.8	1.00	52.6	14.10	3.8	4.8	0.10	1.70	0.22
V	137.9	0.32	55.6	0.75	8.1	4.8	0.06	1.28	0.04
VI	136.9	1.13	35.1	11.05	7.8	–	–	–	–
VII	136.5	0.12	156.5	0.0	8.1	–	–	–	–
VIII	140.1	0.50	22.6	0.41	4.4	–	–	–	–

Notes: c_v defines the coefficient of variation. See Herrin (1) for procedures used to determine water and volatile contents.

Figure 1. Fatigue testing machine.



caused by complete stress removal and subsequent reloading. The machine was turned off to measure the deformation at a specified number of load applications. The hand crank was turned one cycle, causing the oscillating shaft to be displaced once. The maximum reading of one dial indicator (occurring when the shaft is at its highest position) represented the total deformation; the minimum reading (occurring when the shaft was at its lowest position) represented the residual deformations. At the same time, the second dial indicator was read. The average value of residual and total deformations at a specified number of load applications was determined, and the modulus of resilience was computed. The total number of test specimens was 117. The maximum number of test specimens per series was 28 (series II), the minimum was 6 (series VIII), and the average was 14.

FAILURE CRITERION

The variation in residual strain with number of stress applications at different stress levels for several specimens from series II is shown in Figure 2. The plotted data indicate that the relations between the residual strain and the logarithm of number of load applications could be divided into three portions: A, B, and C. Part A appeared to be a straight line, part B to be slightly curved, and part C to have a sharp curvature and probably could be defined as an excessive permanent deformation zone. This behavior was found to be true at different stress levels and for approximately 95 percent of the BAM specimens. A common factor among all the plots was that part B always encompassed 1 percent residual strain. A designer should certainly not use a mix when it is in the condition of part C. Part A was generally encountered at a low residual strain percentage. Thus, the number of load repetitions required to reach 1 percent residual strain was used as a failure criterion.

TEST RESULTS

The axial compressive strains (total and residual) were plotted against the logarithm of number of stress applications for each specimen. The number of stress applications at 1 percent residual strain was determined and is reported as N_f. The resilient strain was determined at 1 percent residual strain, and the corresponding modulus of resilience was calculated (applied stress divided by resilient strain at failure). In general, the value of the modulus of resilience appeared to be constant in the vicinity of 1 percent residual strain (Fig. 3).

The N_f and resilient strain at 1 percent residual strain were used to prepare two diagrams for each series: One was a plot of the axial compressive stress, σ, versus logarithm of number of stress applications to failure, $\sigma - N_f$ diagram, and the other was a plot of the calculated modulus of resilience versus the axial compressive strength. The influence of the variables studied, temperature, cutback content, aggregate gradation, curing time, and type of cutback on the fatigue life and the resilience characteristics of BAM specimens is shown in Figures 4 through 9. The equations shown in Figures 4, 6, and 8 represent the best fitting line through the experimental data for a specific series.

DISCUSSION OF EXPERIMENTAL RESULTS

Influence of Testing Temperature

The effect of temperature on the fatigue life and resilience characteristics of BAM specimens was investigated by testing the specimens at 25, 22, and 19 C. The experimental results indicated that the resistance of the BAM specimens to fatigue failure increased with a decrease in the testing temperature (Fig. 4). Specimens tested at lower temperatures sustained a larger number of load applications to failure than those tested at higher temperatures.

The viscosity of the binder may be defined as the property that retards flow; therefore, when a force is applied to the binder, the higher is the viscosity, the slower is the deformation of the binder (8). The decrease in the temperature caused an increase in the binder's viscosity, which consequently produced greater resistance to deformation.

Figure 2. Residual strain versus number of stress applications at different stress levels for selected specimens, series II.

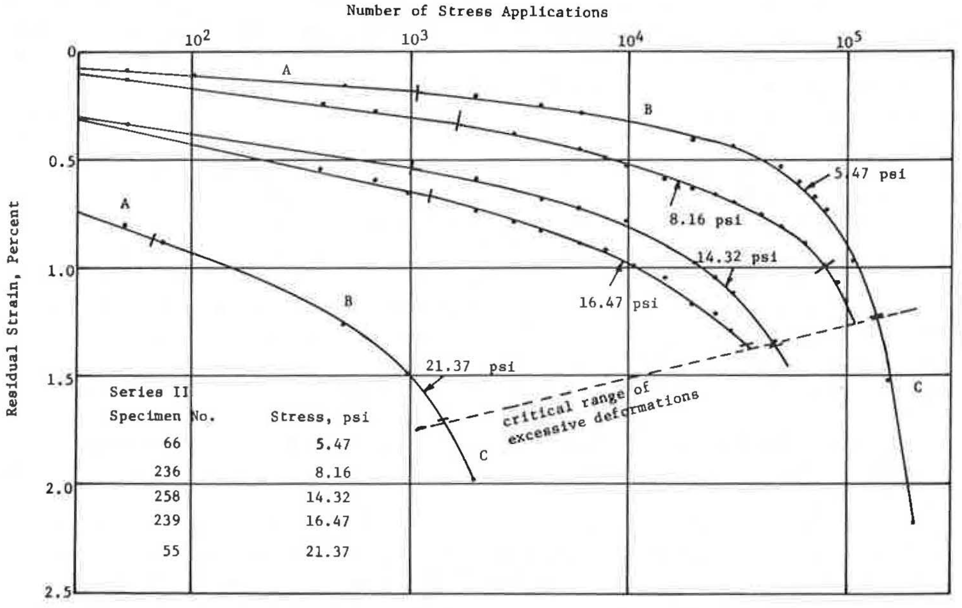
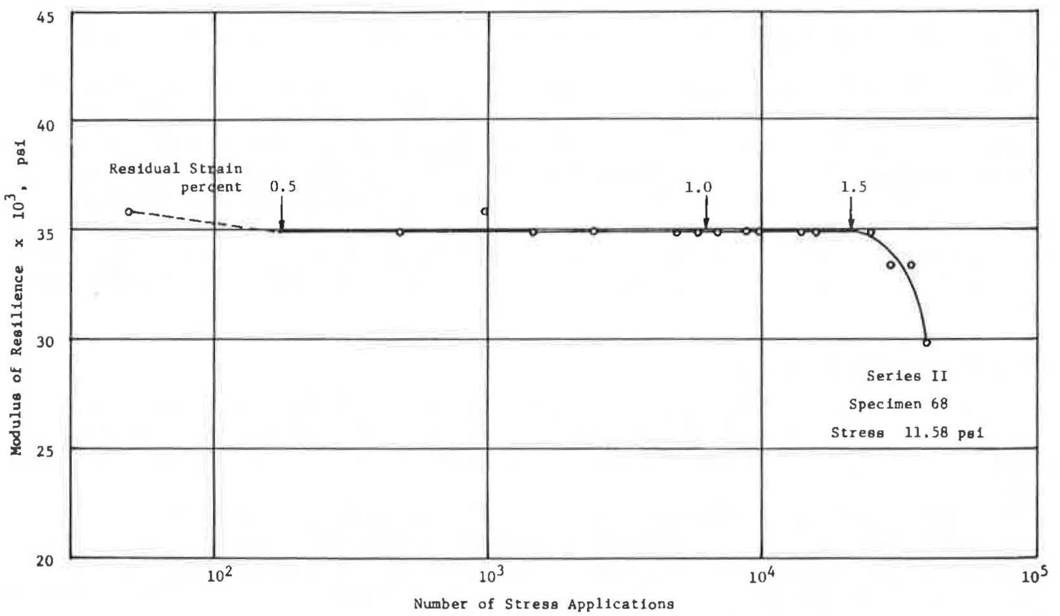


Figure 3. Variation of modulus of resilience with number of stress applications.



Thus, BAM specimens tested at relatively low temperatures need a larger number of repetitions to reach 1 percent residual strain than those tested at higher temperatures (until the glass transition point of the asphalt is about reached). At temperatures lower than the glass transition point, the asphaltic mix probably behaves brittlely because the binder changes from the liquid to the brittle condition. If the brittle condition is reached, the number of load applications to failure may decrease considerably.

Another explanation for the increase of fatigue life of BAMs with a decrease in temperature can be made in terms of the so-called molecular chain concept used by Marek (3). According to the molecular chain concept, asphalts are composed of a long, polymer-like molecular chain structure. The behavior of the asphalt is related to the response of the molecular chain acting by itself and in combination with applied stresses.

When the repeated compressive load is applied, a certain amount of stretching and untwisting of the polymer chains may result. This process is reflected by the gradual increase in permanent deformations of the specimens with an increase in the number of load applications as shown in Figure 2. Thus, at a relatively low temperature, the asphalt film needed a larger number of load applications to undergo a certain amount of stretching and untwisting. At higher temperatures, however, the molecular structure was relatively loose; consequently, the resistance to uncoiling and stretching of the chain decreased. Therefore, the same amount of stretching could be reached at higher temperatures by a relatively smaller number of load applications, as was reached at lower temperatures.

The variation of the modulus of resilience with the applied stress (Fig. 5) indicated that the modulus generally decreased rapidly with an increase in the applied stress. However, at stresses of about 15 psi, there was little change. At higher stresses, there was an increase in the modulus with further increase in applied stress (Fig. 5). The general shape of the modulus of resilience-normal stress relations of BAMs is similar to the shape of the same relation of compacted subgrade material tested in repeated load triaxial compression (5). However, the magnitude of the modulus of resilience of series II at stresses between about 10 to 20 psi was approximately 10 times that of the subgrade soil from the AASHO test road (tested at a confining pressure of 3.5 psi) (5).

The molecular chain concept can be used to explain the change in the modulus with temperature. Because the mobilization of the chain and/or segments of chains decreases at relatively low temperatures, the ability of the chains to deform is reduced. Not only will the total deformations be small, but also the ability of the film of the binder to recover after the load is removed will be greatly reduced because of the decrease in the mobilization of the chains. The result is relatively low resilient deformations and a high modulus of resilience. At high temperatures, however, the molecular structure will be relatively loose, and the reverse of the previous situation may occur.

Influence of Cutback Content

Figure 6 shows that the fatigue life of BAM specimens slightly increased with an increase in the RC-800 cutback content from 6 to 7 percent. An increase in the cutback content to 8 percent, increased the fatigue life of the BAM specimens at stresses above 9 psi.

It can be concluded that the increase in the cutback content above optimum (maximum density occurred at approximately 7 percent) caused an increase in the fatigue life of BAM specimens. This conclusion agrees with Pell's conclusion (4) that the fatigue life of the sandsheet specimen, tested under flexural repeated load, increases with an increase in the asphalt content up to optimum.

The increase in the fatigue life with an increase in the cutback content tends to support the idea that film thickness has considerable influence on fatigue behavior of BAMs. Such behavior tends to be in line with a hypothesis that states that the reduction in the film thickness during the application of the repeated load may govern the fatigue behavior of the BAM until zone C is reached (Fig. 2). Thicker films would tend to require a larger number of load repetitions in order to be reduced to a critical value at

Figure 4. Influence of testing temperature on fatigue life of BAMs.

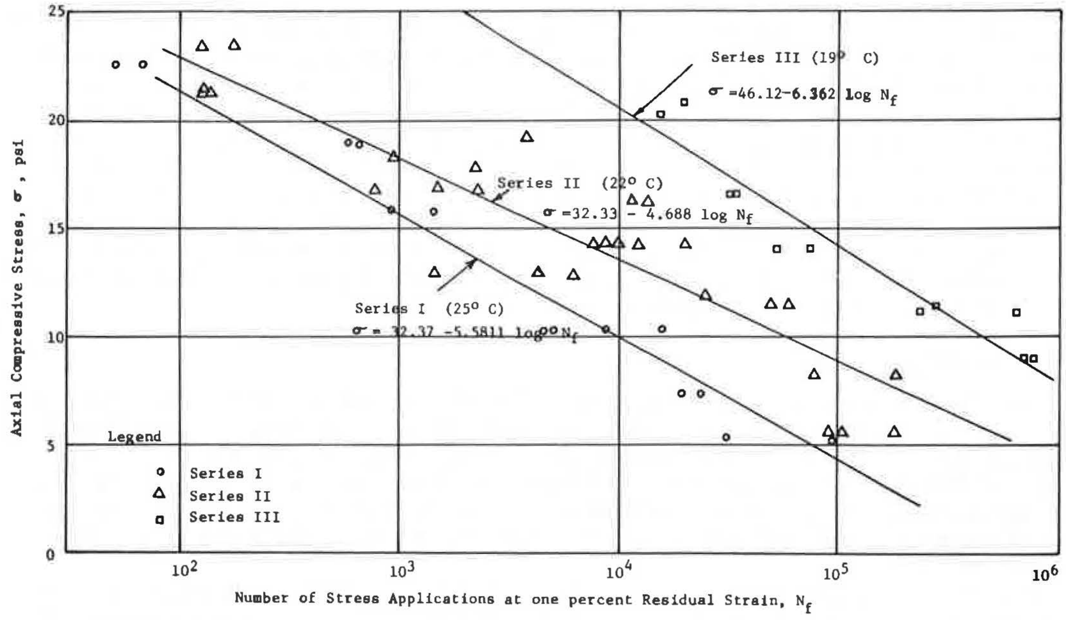
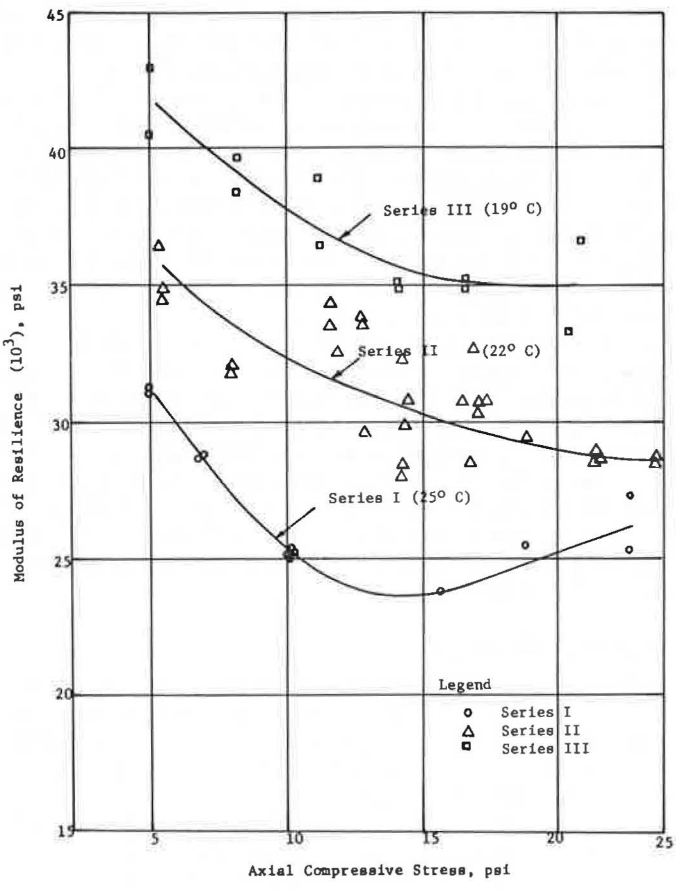


Figure 5. Influence of testing temperature on the modulus of resilience.



zone C when compared with thinner ones. When the film reaches a critical value, the specimen may give way in tension.

The variation in the modulus of resilience with the amount of cutback is shown in Figure 7. In general, there appears to be an optimum cutback content, as mixes with 7 percent cutback had greater modulus than mixes with 6 percent. Mixes with 8 percent cutback have a lower modulus than mixes with 6 percent cutback. This additional decrease in the modulus may be due to the curing process. According to the results given in Table 2, the amount of volatiles left in series IV (8 percent RC-800) after 10 days' curing was 12.9 percent (of the original value) compared to 2.7 percent and 3.1 percent for series II (7 percent RC-800) and series V (6 percent RC-800) respectively. It appears, therefore, that the binder in the specimens prepared with 8 percent RC-800 has a lower viscosity as compared to those prepared with 7 percent and 6 percent RC-800, which would produce a slightly lower modulus.

Influence of Gradation

Test results of the open- and dense-graded mixes are shown in Figure 8. The figure indicates that dense-graded mixes have more resistance to fatigue failure than do open-graded mixes. Because 7 percent cutback asphalt was used in both cases, it is expected that the open-graded mix would have a relatively larger number of voids than the dense-graded mix. Evidence of this is given in Table 2. The increase in the number of voids may have contributed toward the decrease of the fatigue life of the open-graded mixes.

The influence of gradation on resilience characteristics is shown in Figure 9. The open-graded mixes experienced a unique behavior with respect to the other mixes. The shape of the curve does not follow the general shape that was observed in the other seven series. For an open-graded mix, Figure 9 shows an increase in the values of the modulus of resilience up to about 12.5 psi, then a sharp decrease in the modulus with further increase in the axial compressive stress.

The curves representing series I (dense graded, 25 C) were plotted with those for series VI (Figs. 8 and 9) for purposes of comparison. Figure 9 indicates that the values of the modulus of resilience of series VI (open graded, 22 C) are higher than those of series I (dense graded, 25 C) within a range of axial compressive stress of about 9 to 19 psi. Statistical comparison between the fatigue response (slope of the regression lines) of the two series, however, indicated a significant difference between the two series (at 95 percent confidence level). However, series I (dense graded, 25 C) (Fig. 8) had better fatigue resistance than series VI (open graded, 22 C) even though it had less modulus of resilience.

This example should warn the engineer that one must not use the modulus of resilience alone when using a theoretical analysis (instead of the conventional modulus of elasticity) to evaluate a bituminous mix in the design of transportation structures. High modulus of resilience may appear to be the only factor to consider, but this is a misleading concept. The evaluation should also consider the fatigue resistance of the material. Therefore, it does not seem appropriate to use a material with a high modulus of resilience without taking a careful look at its fatigue characteristics. It appears, then, that two figures similar to the σ - N_f diagram and modulus of resilience-stress relation should go hand in hand when selection of a material for use in transportation structures is being made.

Influence of the Curing Time

The influence of curing time was studied by curing series II and VII for about 10 and 300 days respectively. It was not possible to obtain data concerning the fatigue life of series VII because of the very slow rate of residual deformations that was experienced by the test specimens. Consequently, comparison between the two series will be limited to the resilience characteristics.

Because a considerable time elapsed between the testing of the two series, it would be appropriate to explain first what could happen to the binder as time passed. Tests performed on representative specimens of series II indicated that the amounts of water

Figure 6. Influence of cutback content on fatigue life of BAMS.

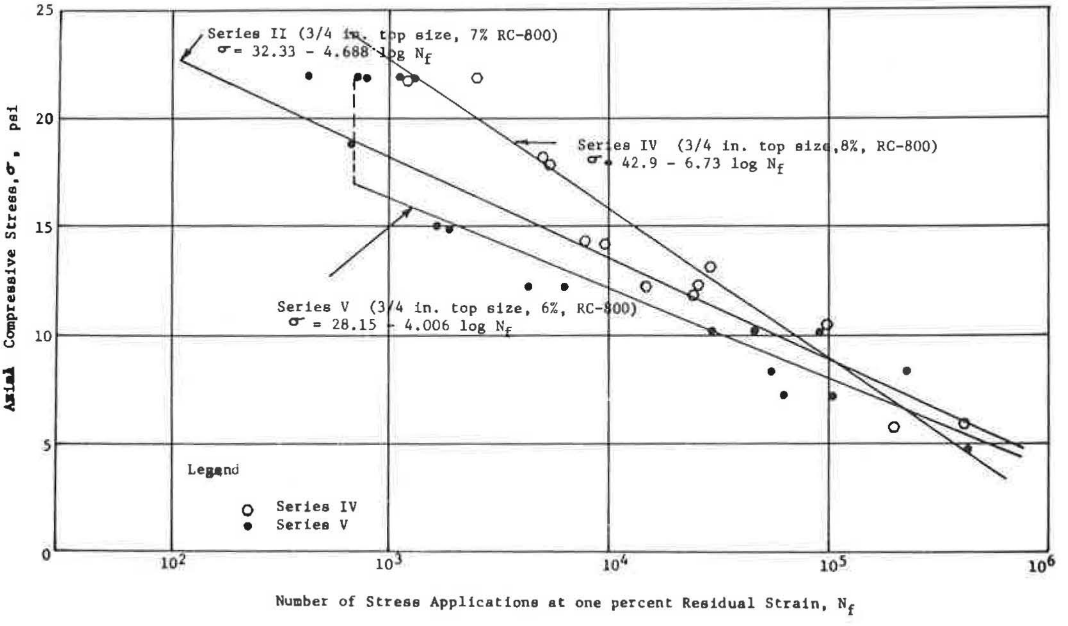


Figure 7. Influence of cutback content on the modulus of resilience.

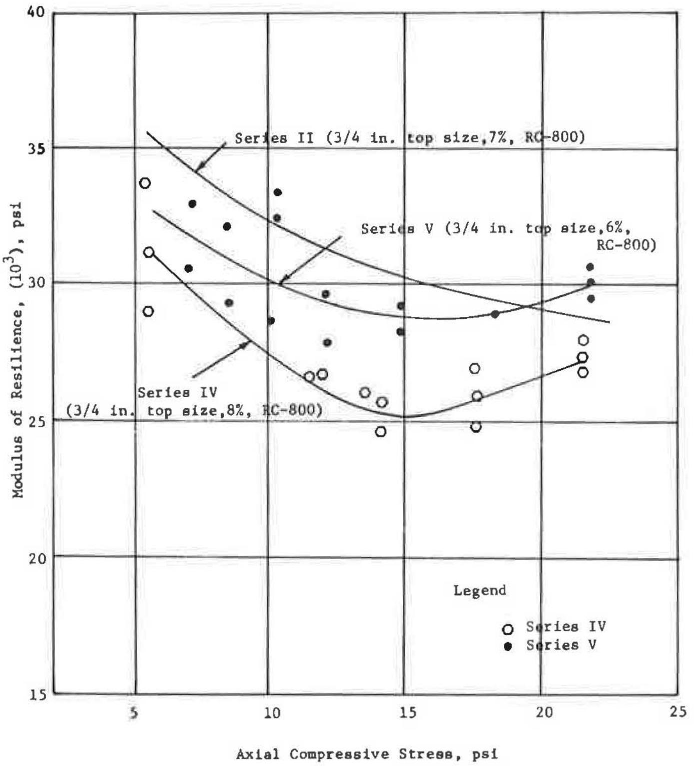


Figure 8. Influence of gradation on fatigue life of BAMs.

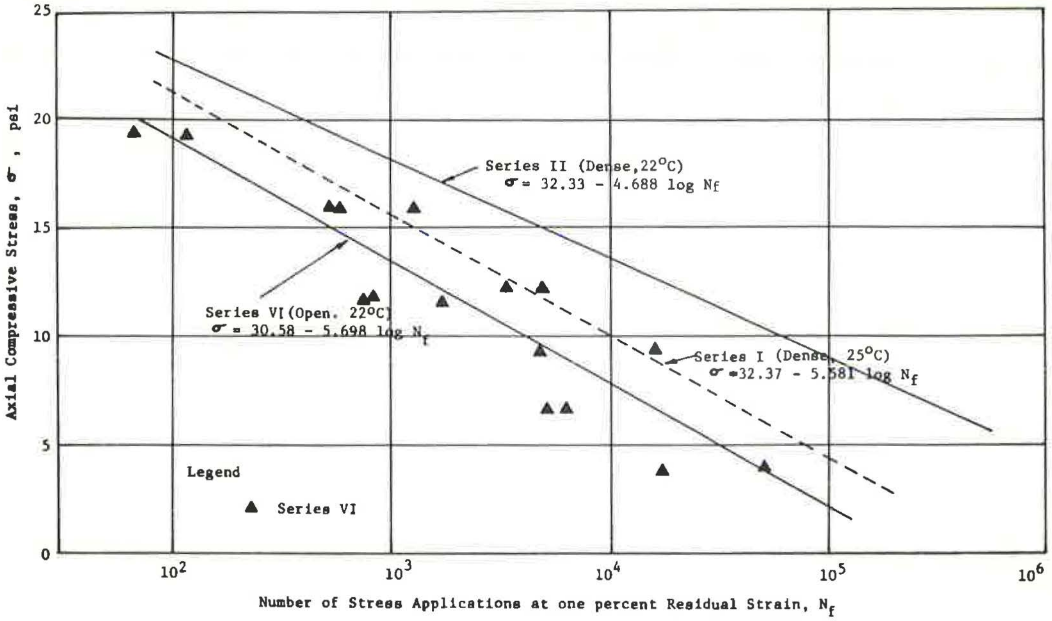
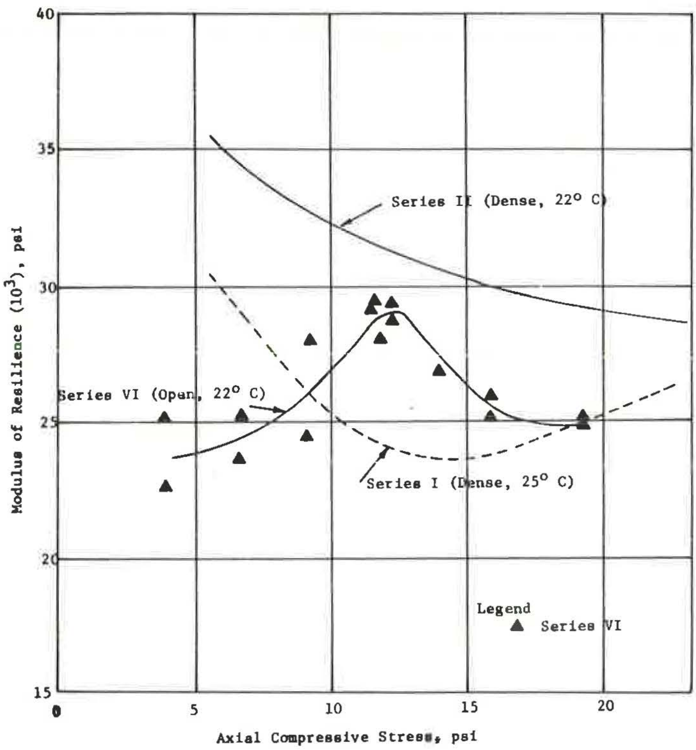


Figure 9. Influence of aggregate gradation on the modulus of resilience.



and the number of hydrocarbon volatiles left in the specimens after a curing period of 10 days were 1.5 percent and 2.7 percent (with respect to the original amount) respectively. Therefore, it is expected that the amount of water and the number of hydrocarbon volatiles left in specimens representing series VII (cured for about 300 days) would be close to zero before the curing period elapsed. In addition, an increase in the viscosity of the asphalt residue probably occurred because of the complete evaporation of the volatiles over the 300-day period. The increase in the viscosity of the residue means an increase in the molecular chain strength. In other words, the resistance to bond rotation and chain deformation might also have increased. Consequently, the application and removal of the repeated loads would result in relatively small and total resilient deformations. Thus, BAM specimens with higher binder viscosities are expected to have higher moduli of resilience than those with lower ones.

Figure 10 shows the influence of curing time on modulus of resilience. The figure indicates an average increase of about 80 percent in the modulus values, over a stress range from about 5 to 20 psi, because of an increase in the curing period from about 10 to 300 days. If the comparison is made with respect to the values of the modulus of resilience for compacted clay (tested in repeated-load triaxial compression at a confining pressure of 3.5 psi) reported by Seed et al. (5), then the modulus of BAM specimens (cured for about 300 days) would be about 19 times the modulus of the subgrade (over a stress range from about 10 to 20 psi). The increase of the modulus of resilience with curing time of BAM specimens prepared with MC-800 and tested in repeated-triaxial compression at confining pressures of 5 to 40 psi and a deviator stress of 10 psi was also reported by Terrel and Monismith (7).

Influence of Type of Cutback

The influence of type of cutback was studied by using an RC-800 cutback to prepare specimens of series II and an MC-250 to prepare those of series VIII. Test results

Figure 10. Influence of curing time on the modulus of resilience.

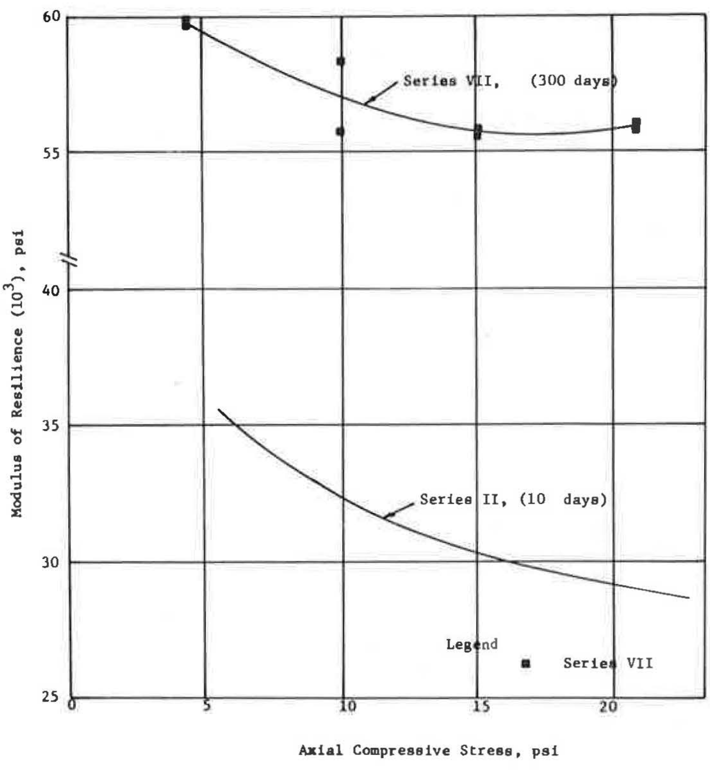


Figure 11. Influence of type of cutback asphalt on fatigue life of BAMS.

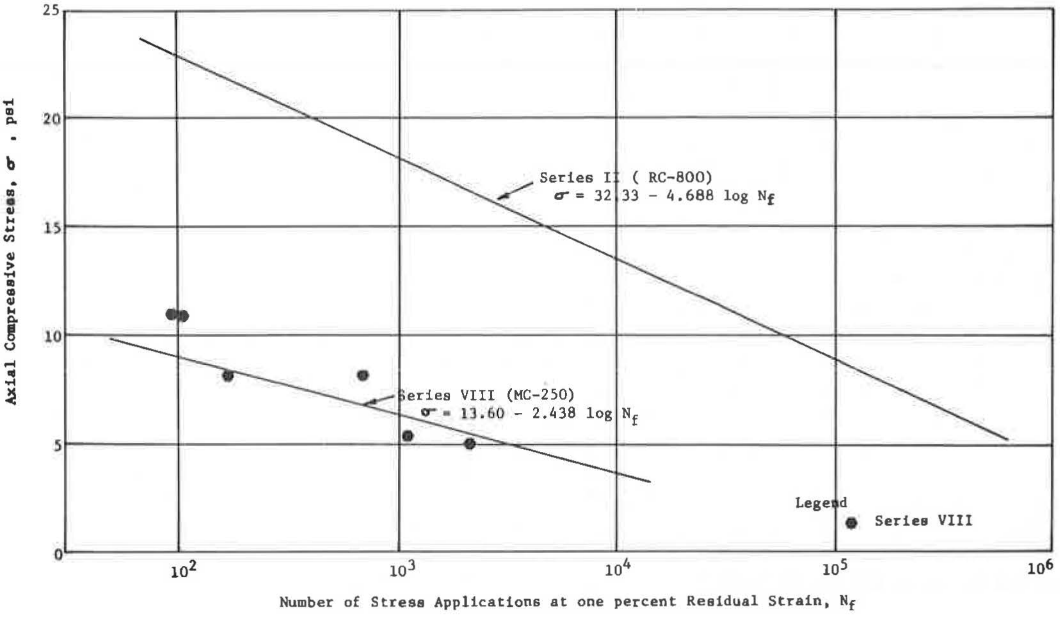
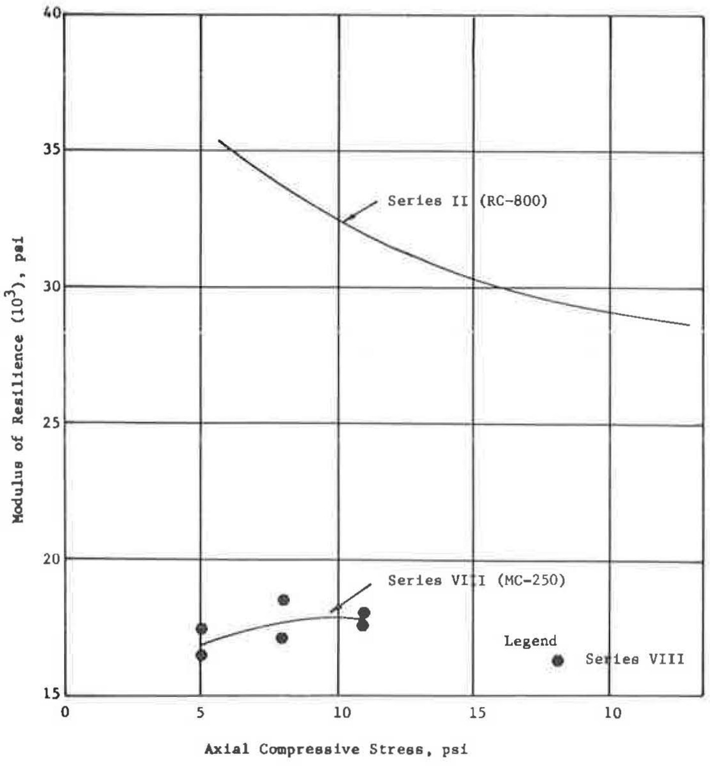


Figure 12. Influence of type of cutback asphalt on the modulus of resilience.



indicated that specimens prepared with the RC-800 cutback and cured for 10 days had better resistance to fatigue failure than those prepared with the MC-250 cutback and cured for 120 days (Fig. 11). Furthermore, specimens prepared with the MC-250 cutback had the shortest fatigue life among all of the other series investigated.

If the water and volatiles evaporated from the specimens of series II (RC-800) and series VIII (MC-250), the residue of the asphalt cement would govern the fatigue behavior of both series (other variables being similar). The major difference between the asphalt cement of the two types of cutback is the degree of viscosity. The RC-800 cutback is produced from an asphalt cement of a higher viscosity than that of the MC-250 cutback. The high-viscosity asphalt cement may resist shear stresses more than a softer one. As a result, specimens prepared with an RC-800 cutback have a higher resistance to the fatigue failure than those prepared with an MC-250 cutback (Fig. 11).

Figure 12 shows the influence of the type of cutback asphalt on the modulus of resilience. Because of the relatively low fatigue resistance of the specimens prepared with the MC-250 cutback, the maximum applied axial stress was about 11 psi. It does not seem that the modulus of resilience-stress relation of series VIII (MC-250) follows the general shape of the other series. The limited amount of experimental data of series VIII indicates that the modulus may increase with an increase in the axial stress from about 5 to about 9 psi and that it was constant from 9 to about 11 psi.

Figure 12 indicates also that the moduli of resilience of specimens prepared with the RC-800 cutback are much higher than those prepared with the MC-250 cutback. This increase is probably due to the high viscosity of the binder of the specimens prepared with the RC-800 cutback as compared to those prepared with the MC-250 cutback.

It can be concluded that specimens prepared with a high-viscosity asphalt cement tend to resist the fatigue failure much more than those prepared with a low-viscosity asphalt cement.

Endurance Limit

Repeated compressive tests performed in this investigation indicated no sign of the possibility of the existence of an endurance limit (Figs. 4, 6, 8, and 11) in the BAM specimens.

CONCLUSIONS

The following conclusions can be drawn from this study and are limited to the test materials and conditions.

1. Bituminous aggregate mixes exhibited progressive failure over a range of axial unconfined compressive stresses of about 4 to 24 psi.
2. Three distinct zones were observed on a plot of the residual strain versus the logarithm of number of repetitions. The zones had the following shapes: (a) straight line, (b) slight curvature, and (c) excessive curvature where the residual strain increased rapidly with little increase in the number of load applications. One percent residual strain always occurred at the slight curvature zone.
3. The fatigue life of BAMs tested under repeated compressive stresses are highly temperature dependent: Within the temperature range studied, the lower is the temperature, the longer is the life.
4. An increase in the cutback content from 6 to 8 percent increased the fatigue life of the BAM specimens. It should be noted that maximum density in a specimen does not necessarily result in maximum fatigue resistance because the maximum density occurred at a cutback content of 7 percent.
5. The viscosity of the binder has a significant influence on the fatigue life of BAMs. The higher is the viscosity, the longer is the life. BAM specimens prepared with MC-250 had the shortest fatigue life when compared with all series investigated.
6. In this investigation, there was no indication of the existence of an endurance limit for the BAMs.
7. In most cases, the modulus of resilience decreased with an increase of axial stresses to about 15 psi; it then leveled off and increased with further increase in the

stress up to about 24 psi. This behavior agrees with the relation of the modulus of resilience versus deviator stress for compacted subgrade soils (AASHO Road Test).

8. The moduli of resilience of BAMs are also temperature and viscosity dependent. The modulus increased with a decrease in the temperature, within the temperature range studied, and with an increase in the viscosity of the binder.

9. The magnitude of the modulus of resilience of dense-graded bituminous aggregate mix prepared with $^3/_4$-in. top size, 7 percent RC-800, cured for about 10 days, and tested at 22 C was found to be about 10 times as much as the modulus of resilience of subgrade AASHO Road Test (tested at a confining pressure of 3.5 psi) over a range of stress from 10 to 20 psi. When the curing time of BAM specimens increased to about 300 days, the previous ratio increased to about 19 over the same range of stresses.

10. The values of the modulus of resilience increased about 80 percent over a stress range from 5 to 20 psi when the curing time increased from 10 to about 300 days. Thus, curing has a very significant effect on the resilience characteristics of BAMs.

11. Both fatigue and resilience characteristics should be studied together when a selection of material for transportation structures is being made. Higher values of the modulus of resilience do not necessarily mean better fatigue resistance.

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