Influence of Shape, Size, and Surface Texture on the Stiffness and Fatigue Response of Asphalt Mixtures

C. L. MONISMITH, Institute of Transportation and Traffic Engineering,
University of California, Berkeley

•THE PURPOSE of this paper is to briefly summarize the results of research related to the influence of shape, size (including size distribution), and surface texture of aggregates on the stiffness and fatigue response of asphalt paving mixtures. Because mixture stiffness influences the fatigue behavior of asphaltic concrete, a brief discussion of stiffness is presented first. Data are then given to illustrate the effects of aggregate characteristics on the fatigue response of asphalt paving mixtures.

MIXTURE STIFFNESS

Stiffness as used herein denotes the relationship between stress and strain, both as a function of the time of loading and temperature.

$$S(t,\ T) = \frac{\sigma}{\epsilon} \tag{1}$$

where

$S(t,\ T)$ = mixture stiffness at a particular time and temperature, psi or kg per sq cm; and

σ, ϵ = axial stress and strain respectively.

This definition corresponds to that suggested originally by Van der Poel (1).

The dependence of stiffness on time of loading is shown in Figure 1. At short loading times, the stiffness approaches a constant value and, in effect, is analogous to a modulus of elasticity. As the time of loading increases, the stiffness decreases. Over the range in times and temperatures encountered in pavements, the stiffness of asphalt mixtures may vary from about 4×10^6 psi (at cold temperatures and short loading times) to about 1×10^3 psi (at high temperatures and long loading times). From a fatigue standpoint, stiffness is important because it will influence the stresses and strains developed in the asphaltic concrete under loading and, as will be seen subsequently, these stresses or strains appear to be the damage determinant for fatigue.

Both the asphalt and aggregate have an influence on mixture stiffness. The harder the asphalt is, the stiffer the mixture will be, particularly at higher temperatures and slower rates of loading (2). In addition, there appears to be an optimum asphalt content for maximum mixture stiffness. This is illustrated by the data shown in Figure 2. At first, stiffness increases as asphalt content increases and then decreases with further increases in the amount of asphalt.

In the case of aggregate, available data indicate that the surface texture of aggregates may have little influence on stiffness, provided that mixtures are compared at their design asphalt contents. This is illustrated by the data given in Table 1 (3). Stiffness measurements (in flexure) are compared for two aggregates, one a rough-textured material and the other a smooth-textured material, with the same gradation. When the stiffnesses of the mixes are compared at the same void content, they are essentially the same.

The data given in Table 1 were obtained for mixtures that had been prepared at their design asphalt contents, which were based on the State of California method of mix design (3). For the rough-textured material, the design asphalt content is considerably higher than it is for the smooth-textured material. Thus texture does not appear to have an effect on stiffness when comparisons are made at the respective design asphalt contents. However, the mix made with the smooth-textured material at the same asphalt content as that for the rough-textured material (in this case 5.9 percent) would be considerably less stiff than the mix made with the rough-textured material. Accordingly, under these circumstances, surface texture would appear to have a significant influence.

The size distribution of the aggregate also appears to have an influence on mixture stiffness; a dense-graded aggregate produces a mixture stiffer

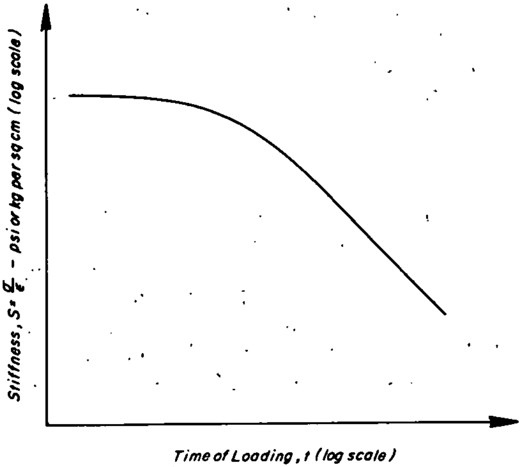


Figure 1. Influence of time of loading on stiffness of an asphalt paving mixture.

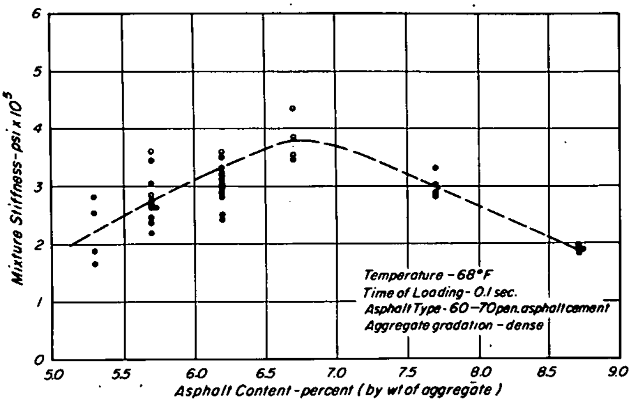


Figure 2. Influence of asphalt content on flexural stiffness of asphalt concrete.

TABLE 1

DYNAMIC STIFFNESS MEASUREMENTS

Aggregate	Asphalt Grade	Percentage Asphalt Content by Aggregate Weight	40 F		75 F	
			Percentage Air Voids	Dynamic Stiffness[a] (psi)	Percentage Air Voids	Dynamic Stiffness[a] (psi)
Watsonville (rough-textured, angular)	85-100	5.9	3.0	65.5×10^4	3.7	10.6×10^4
			3.6	52.6×10^4	4.6	7.7×10^4
			4.5	46.7×10^4	5.1	7.3×10^4
Watsonville (rough-textured, angular)	40-50	5.9	1.8	114×10^4	3.5	24.9×10^4
			3.4	65.9×10^4	3.9	25.9×10^4
			3.5	52.2×10^4	3.9	30.0×10^4
Cache Creek (smooth-textured, rounded)	85-100	4.5	3.6	52.2×10^4	3.2	14.7×10^4
			4.0	47.5×10^4	4.0	14.3×10^4

[a] Dynamic flexural stiffness: time of loading, 0.1 sec; stress, 100 psi.

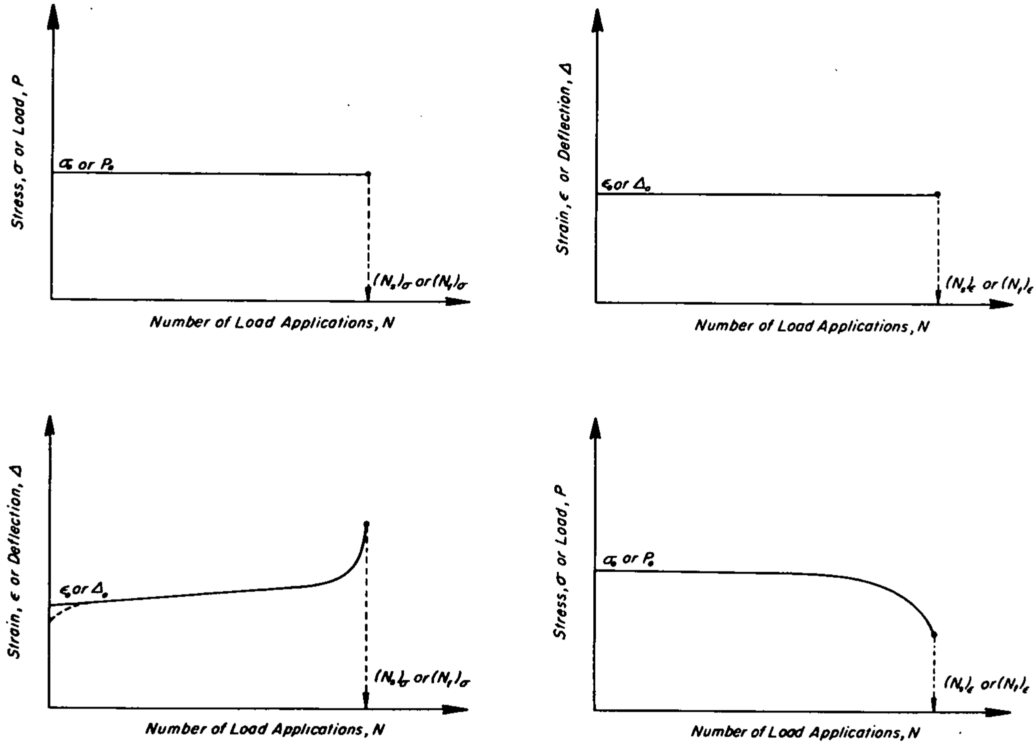
than that produced by an open-graded material. In general, one can conclude that both texture and size distribution influence mixture stiffness. For a particular hardness of asphalt and asphalt content, mixture stiffness is increased as an aggregate rougher in texture is used and as the aggregate grading is changed from open to dense.

FATIGUE RESPONSE

To indicate the influence of aggregate characteristics on the fatigue behavior of asphalt mixtures requires a consideration of the methods used for determining fatigue response. In addition, because certain conflicting conclusions might be drawn with respect to desirable mixture characteristics, the method for determining fatigue response in the laboratory must be related to the performance of the mix under load on the pavement structure. Accordingly, in this section, a brief discussion of mode of laboratory loading for fatigue testing and the applicability of the various modes of loading to field response will be presented so that the available data on mixture response may be viewed within a reasonable framework.

Mode of Loading

Mode of loading is used to describe how stress and strain levels are permitted to vary during fatigue loading. If the nominal stress or load is maintained at a constant level throughout the life of the specimen, testing is of the controlled-stress or controlled-load mode. If the nominal strain or deflection is maintained at a constant level, testing is of the controlled-strain or controlled-deflection mode. Both modes of loading are shown schematically in Figure 3. By performing tests in either mode



a. Controlled - Stress

b. Controlled - Strain

Figure 3. Behavior of materials in controlled-stress and controlled-strain fatigue tests.

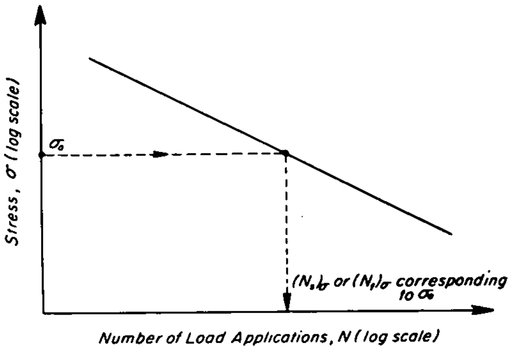


Figure 4. Stress versus load applications in controlled-stress tests.

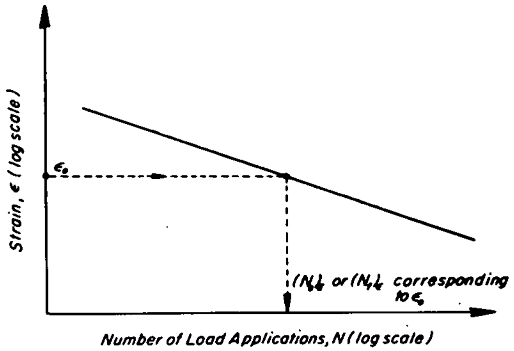


Figure 5. Strain versus load applications in controlled-strain tests.

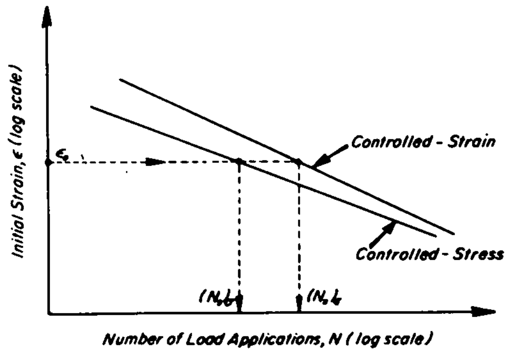


Figure 6. Initial strain versus load applications in controlled-stress and controlled-strain tests.

of loading at different stress or strain levels, one may obtain fatigue diagrams such as those shown in Figures 4, 5, and 6.

Interpretation of the results of these tests may lead to some conflicting conclusions. For example, in controlled-strain tests, mixture stiffness, for a particular combination of asphalt and aggregate, appears to influence the strain versus cycles-to-failure relationship in that the stiffer the mix, the shorter the fatigue life at a particular strain level. On the other hand, in controlled-stress tests, the higher the stiffness, the longer is the fatigue life at a particular stress level (3).

These tests merely represent limits of a range in possible modes of loading. In actuality, neither of the tests may be strictly applicable to define the performance of an asphalt mixture as it exists in the field. One may, however, choose one of the methods for a particular situation as a practical expedient until such time as a better definition of the problem can be obtained. Some guides for selection are presented in the following section.

Applicability of Various Types of Fatigue Tests

An indication of the applicability of the various fatigue tests was obtained by performing an analysis of a series of three-layer elastic systems in which the thickness and stiffness of the asphaltic concrete layer were varied to assess the influence of these variables on the computed stresses and strains on the asphaltic concrete layer (3). Because results of fatigue tests are usually presented in terms of stress or strain, the analysis should thus assist in determining the applicability of a specific mode of loading.

In these analyses, the structural section consisted of a layer of asphaltic concrete varying in thickness from 1 to 9 in. and an untreated base varying from 25 to 17 in. In all analyses, the total thickness was maintained at 26 in. Results of the analyses are shown in Figures 7 and 8, which also show the modular values for the various components of the structural sections.

Figure 7 shows that, regardless of the stiffness of the asphaltic concrete (for the range in moduli investigated), the tensile strains on the underside of the asphaltic

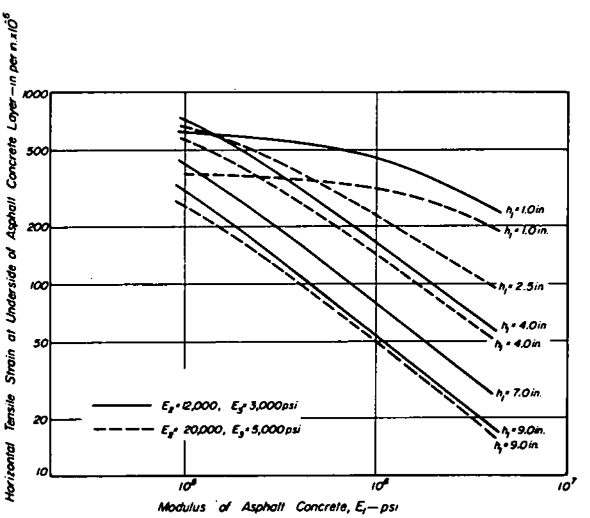


Figure 7. Influence of stiffness of asphaltic concrete, layer thickness, and modulus of base and subgrade on tensile strain on the underside of the asphaltic concrete layer (thick pavement section).

concrete of the 1-in. thick surfacing are essentially constant. On the other hand, for the thicker asphaltic concrete layers, the tensile strain is reduced markedly as the stiffness of the asphaltic concrete is increased. This would imply that for thin surface layers, regardless of the stiffness of the asphaltic concrete, its performance is governed primarily by the underlying materials. In thicker layers, however, the asphaltic concrete will begin to contribute more to the behavior of the section and exert more influence on the strains to which it is subjected. Thus it would appear that controlled-strain tests would be useful to define the performance of mixtures used in comparatively thin layers of asphaltic concrete, layers approximately 2 in. or less in thickness.

Figure 8 shows that, for thin layers of asphaltic concrete, the tensile stress at the underside of the layer changes quite markedly with change in layer stiffness. As the thickness of the layer increases, however, the change in stress with layer stiffness is less marked, e.g., approximately a factor of 2 for the 9-in. thick layer with a change in stiffness by a factor of 40. Because the change in strain is much larger than this, by at least a factor of 10, it appears that a test reflecting mixture stiffness advantageously would be more appropriate to represent the fatigue behavior of asphaltic concrete. For these conditions, it can be inferred that the controlled stress would thus be more representative.

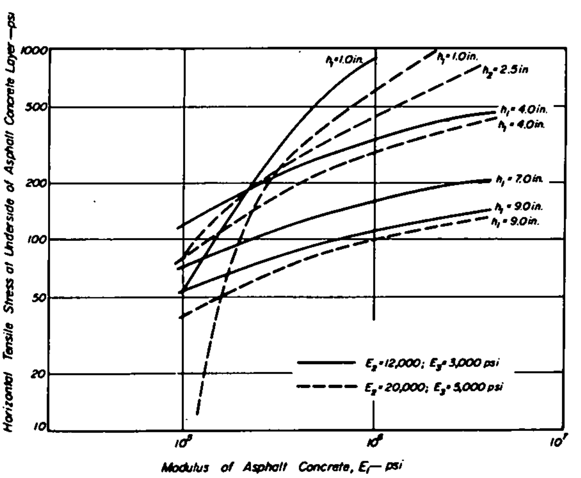


Figure 8. Influence of stiffness of asphaltic concrete, layer thickness, and modulus of base and subgrade on tensile stress on the underside of the asphaltic concrete layer (thick pavement section).

Because a true controlled-stress condition may never be reached in practice (4), it is difficult to precisely define a minimum pavement thickness for which the results of controlled-stress tests would seem appropriate. It is suggested, however, that a 6-in. thick layer of asphaltic concrete be considered, at least at this time (1968), as the lower limit. Although the two types of fatigue tests, noted in the preceding, give an indication of desirable mixture characteristics, recent information (5) suggests that controlled-stress tests will provide a conservative estimate of fatigue response for any mixture regardless of the thickness of the asphaltic concrete.

Controlled-Stress Tests

The infleunce of aggregate surface texture on fatigue resistance is shown in Figure 9 (6). As long as there is sufficient asphalt in the mixture for the particular aggregate, rough-textured materials tend to perform better than smooth-textured materials for identical asphalt contents. This effect is probably caused in part by increased stiffness associated with the rough-textured materials.

Comparisons made of fatigue response at constant stiffness, as noted before, would show in all probability that the mixture containing rough-textured material has an asphalt content higher than that of the mixture containing the smooth-textured material. Under these circumstances, the mixture containing the rough-textured aggregate would show a longer fatigue life because the strain in the asphalt (7), defined as

$$\epsilon_B = \frac{\epsilon}{B_V} \qquad (2)$$

where ϵ_B = asphalt strain, ϵ = mixture strain, and B_V = volume concentration of asphalt, would be less than that in the mix containing the smooth aggregate.

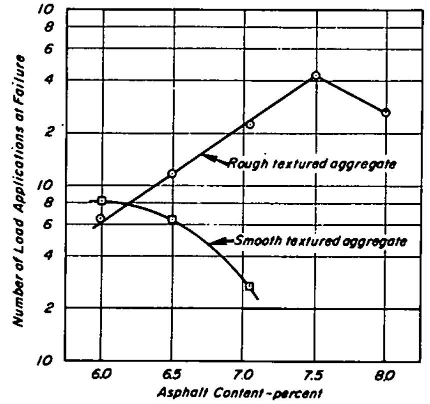


Figure 9. Asphalt content versus number of load applications at failure for two aggregate types.

Limited data are also available concerning the influence of aggregate gradation on fatigue response. Figures 10 and 11 show data obtained from tests on two mixtures: one containing a dense-graded aggregate and the other an open-graded material (3). For comparable asphalt contents, longer service lives are exhibited by the dense-graded mixtures than by the open-graded mixtures. This is caused in part by the increased stiffness associated with the dense-graded mixture and in part by its lower void content.

The influence of fines content (percentage passing the No. 200 sieve) is illustrated by data presented by Pell (7). His data, shown in Figure 12 for a mix in which the asphalt content was maintained constant at 6 percent but the mineral filler was varied from 0 to 17 percent passing the No. 200 sieve, illustrate that as the fines content is increased the fatigue life at a particular stress level is improved. However, with further increase in filler content beyond a certain level (in this mix, 9 percent), the fatigue life was again reduced, probably because of insufficient asphalt for the amount of fines present.

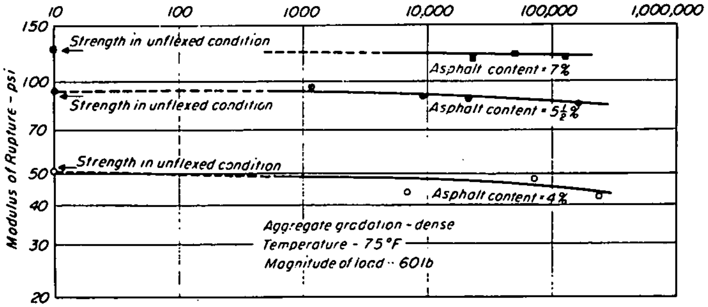


Figure 10. Effect of asphalt content on the behavior of dense-graded mixtures subjected to repeated load applications.

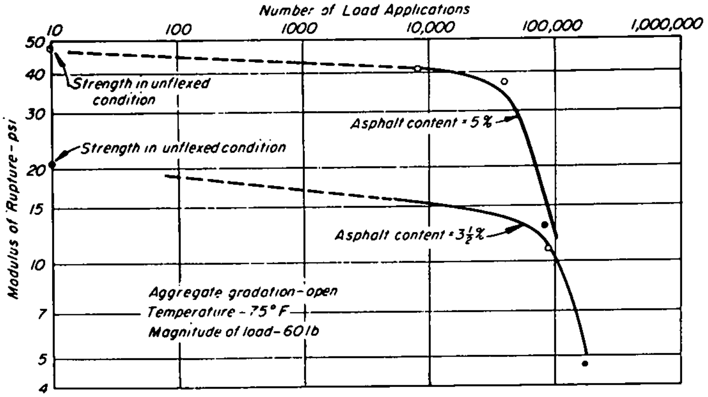


Figure 11. Effect of asphalt content on the behavior of open-graded mixtures subjected to repeated load applications.

Controlled-Strain Tests

Limited data concerning the influence of aggregate type in fatigue behavior in controlled-strain tests are shown in Figure 13 (3). The Watsonville material is a rough-textured granite, whereas the Cache Creek material is a smooth, rounded gravel (Table 1). Both types of aggregate, however, have the same gradation, and both mixtures were designed according to the State of California mix design procedure. The asphalt content was 5.9 percent for the mixture containing the granite and 4.5 percent for the mixture with the gravel. Because both mixtures had essentially the same stiffness characteristics (Table 1), stiffness cannot be used to explain the difference in response as shown in Figure 13.

In this instance, the difference is no doubt caused by the increased asphalt content associated with the Watsonville material, which in turn resulted in a reduced strain in the asphalt (Eq. 2). It is interesting to conjecture, however, that, had both mixtures been tested at the 5.9 percent asphalt content, in all probability the mixture containing the rounded material would have produced superior performance because of its reduced stiffness as compared with the granite. Although no published data are available, it appears that more open-graded aggregates (less than 3 percent passing the No. 200 sieve) tend to perform better in controlled-strain tests than more densely graded materials, provided that comparisons are made at comparable asphalt contents. Such differences can be explained by differences in mixture stiffness, with less stiff mixtures produced by the more open-graded materials than by those that were dense-graded.

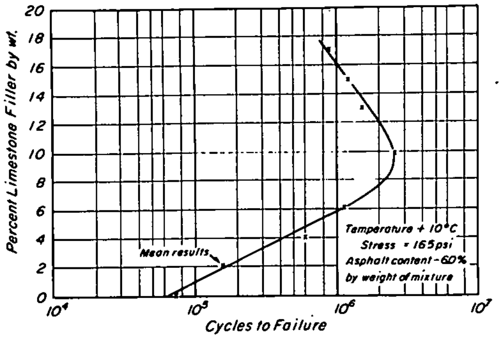


Figure 12. Influence of filler content on fatigue response of asphaltic concrete.

SUMMARY

The data presented in this paper indicate that aggregate characteristics affect both stiffness and the fatigue response of asphalt paving mixtures. In addition, it has been demonstrated that stiffness and fatigue response are interrelated.

For thick pavement sections, it appears desirable to utilize rough-textured materials with dense gradations and to produce well-compacted mixtures because all of these factors tend to increase mixture stiffness. On the other hand, in thin pavement sections, it appears that more open-

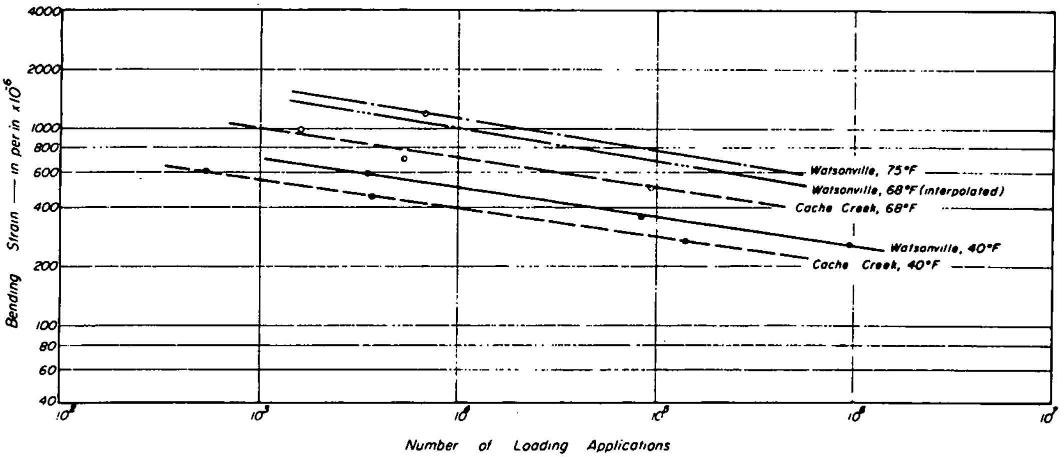


Figure 13. Comparison of controlled-strain amplitude fatigue test results for specimens containing Watsonville granite and Cache Creek gravel.

graded aggregates should be utilized because flexibility is increased somewhat with reduction in fines content (minus No. 200 material). In thin sections, the effect of surface texture is not so apparent because of conflicting demands for load-carrying ability (stability). At comparable asphalt contents, mixtures produced with smooth-textured materials may be more desirable because they produce less stiff mixtures. However, if stability is not adequate for the loading conditions, then the rough-textured material appears more desirable.

The results discussed here provide some indication for the design of thicker sections of asphaltic concrete, that is, sections containing asphaltic concrete bases. The resistance of such sections to repetitive loading (fatigue) will be improved, it appears, by using as much asphalt as possible rather than by producing mixtures that tend to be lean as is current practice in some areas. Figure 2 shows, for example, that the increased asphalt content results in increased mixture stiffness (up to a point beyond that required for optimum stability), which in turn results in improved performance.

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