FATIGUE BEHAVIOR OF CONVENTIONAL AND RATIONALLY DESIGNED BITUMINOUS MIXES ON SIMULATED SUBGRADE

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Three dense bituminous mixes were designed by a method that takes into consideration the shape, size, size distribution, and surface texture of mineral aggregates and boundary condition of the mold. Laboratory investigation into the fatigue properties of these mixes was carried out on slab specimens having a thickness of the same order of the wearing course. A simulated subgrade, based on the Westergaard assumption, was designed to support the slab specimens subjected to a constant nonreversed stress type of loading. The effect of variables such as the binder content, shape of coarse aggregate, rate of deformation, and initial vertical deflection on the fatigue life of slab specimens was investigated. Life of the mixes can be predicted from either the initial deflection of the specimen, the rate of increase in this deflection, or both. Fatigue life correlated very well with these two variables combined. The experimental results showed that the fatigue strength of the three rationally designed mixes was superior to that of the B. S. 594 wearing course mix made of the same type of stone.

•DESIGN of a bituminous mix should take into consideration not only rutting, plastic flow, Marshall stability, durability, and skid resistance but also fatigue cracking (1, 2, 3, 4).

There is a great need for detailed information on the bending characteristics of bituminous mixes, their fatigue behavior, and the effect of many variables on this behavior (5, 6, 7, 8).

To gain knowledge on the fatigue behavior of bituminous mixes, a laboratory investigation was carried out on four mixes to determine the effect of variables such as binder content, shape of coarse aggregate, and rate of vertical deflection on their fatigue behavior and to establish the relative merits of these mixes against the conventional British Standard 594 rolled asphalt wearing course mix.

TEST AND MODE OF LOADING

Previous researchers mainly used either controlled stress (9) or controlled strain (7) loading conditions. Some few, however, employed constant deflection loading conditions (10).

Some researchers applied the stress or strain as reversed or partially reversed to limit the magnitude of accumulated deformation in the viscoelastic materials; others did not reverse the loading conditions.

Some researchers supported tested beams (10) or slab specimens (11, 12, 13) on springs to simulate, to some extent, actual road conditions or worked directly on tracks (9). Others dealt with the more fundamental approach to the problem and worked on cylindrical and beam specimens without any simulation.

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In summary, there have been many variations in the type of tests, mode of loading, and shape of specimens used. All of these variations have a great influence on the fatigue behavior of the bituminous mix, and they present a great deal of difficulty in interpreting the results.

It is believed, however, that this difficulty can, to some extent, be decreased and controlled if a test that simulates actual road conditions is used. With this in mind, a slab specimen prepared in a realistic way (rolling), having a thickness of the same order of the wearing course, simply supported by a simulative subgrade, and subjected to constant repeated loading was conceived.

This type of test has the following advantages:

1. Provides an improvement over cylindrical specimens whose preparation or testing is far from realistic;
2. Provides an improvement over beams tested with unidirectional bending by allowing plane bending in the slab;
3. Reveals the effect of mix and test variables in the most realistic way;
4. Allows the mixes to be compared and arrayed in roughly the same order both in the laboratory and on the road; and
5. Yields considerable information on the likely performance of that mix on the road.

DESIGN OF SIMULATED SUBGRADE

In analyzing stresses in a rigid pavement, Westergaard (14) considered the subgrade to be a discontinuous medium (similar in action to a mesh of closely spaced springs) in which the vertical deflection at any point is proportional to the pressure at that point and independent of pressure elsewhere. Burmister (15), on the other hand, assumed the subgrade to be an elastic solid that is completely continuous.

Inasmuch as the major portion of elastic deflection on the road was found to occur in the subgrade, many researchers assumed its behavior to be elastic, and they simulated it with steel compression springs (Winkler support) over which they laid the bituminous beam or slab specimens (4, 11). The results with this type of subgrade were easier to interpret than those with Burmister's type of subgrade.

Based on this information, a similar approach was adopted for this research, and a simulated subgrade was designed.

Compression springs, 150 mm long and 25 mm in diameter, that deflect 25 mm under a load of 250 kg were used. To install the springs, half-depth, 25-mm-diameter holes were drilled in a steel plate measuring 800 by 500 by 50 mm and spaced at 65-mm centers in both the longitudinal and transverse directions. The springs were fitted into these holes and were kept upright and prevented from lateral movement by means of a 25-mm-deep steel grid having 26.5-mm-square openings (a clearance of 1.5 mm was allowed for each spring).

Each spring is covered by 50-mm-square by 12.5-mm steel plates bearing on 15-mm-diameter balls to allow for the free movement of these plates. This movement was intended to keep the plates in contact with the bituminous slab resting on them during the deflection of the slab under the action of the load. The keying or stress concentration likely to be produced by fixed top plates was thereby eliminated.

LOADED AREA AND TESTING MACHINE

Specimens were tested by the Instron machine while simply supported on the simulated subgrade. The load was applied by a 75-mm-diameter steel disk faced with a thin piece of solid rubber.

To ensure that the behavior in the horizontal direction of the slab would be as infinite as possible, the slab thickness and the plunger area were chosen to be the practical minimum, the stiffness ratio between the slab and the support was kept low, and the testing temperature was relatively high (around 20 C).

MIXES AND SPECIMENS

Four mixes of gritstone (as coarse aggregate), leighton buzzard sands (as fines), portland cement (as a filler), and 50/60 penetration binder were prepared in 450 by 450 by 50-mm slab specimens at four binder contents each (6, 7, 8, and 9 percent by weight of aggregates). A total of 64 specimens were prepared.

Each specimen while confined in the slab mold was subjected to twelve 1-metric ton roller passes.

The first three mixes were designed to the rational method of mix design (16) that takes into consideration the shape, size, size distribution, and surface texture of mineral aggregates and boundary condition of the mold.

The top three sizes of the coarse aggregates (18, 12, and 9 mm) were not sorted by shape (as produced) in the first mix (mix O), flaky in the second mix (mix F), and nonflaky in the third mix (mix q).

The resulting gradings of these mixes and of the B. S. 594 specification are given in Table 1.

FATIGUE TEST AND RESULTS

In the test, the slab was placed on the top of the simulated subgrade, and a central load of 70 kg was applied repeatedly by the Instron plunger moving at a 3-cm/min rate of deformation. A dial gauge was mounted just beside the edge of the plunger to record the vertical instantaneous elastic deformation and the cumulative permanent deformation.

The test was carried out at room temperature, which varied from 19 to 23 C. The four mixes were tested at each binder content in an order that minimized the effect of temperature variations on fatigue life.

Each specimen was subjected to 10 load cycles so that it could embed itself into the top plate. Then, the effect of rate of deformation on the deflection of the slab was investigated by subjecting each specimen to the following cycle rates: 5, 3, 2, 1, 0.5, 0.3, 0.2, and 0.1 cm/min. Subsequently, a 3-cm/min rate was applied repeatedly until failure.

FAILURE CRITERION

In this type of test, the slab did not fracture completely but continued to act as an intact specimen under the load for a very long time.

Figure 1 shows a typical trace of the permanent deformation per cycle, the cumulative permanent deformation, and the instantaneous elastic deformation of a slab specimen. The two curves of elastic deformation are parallel, but the former exhibits higher values than the latter. This is mainly because the chart records the instantaneous elastic and plastic deformations in the slab together with the deformation in the rubber pad and the instantaneous compaction in the slab area under the piston. The dial gauge, on the other hand, records in a single reading the instantaneous elastic deformations only.

The elastic deformation in both cases shows a continuous gradual increase with the increase in the number of cycles; other researchers (17) found that the elastic deformation was constant.

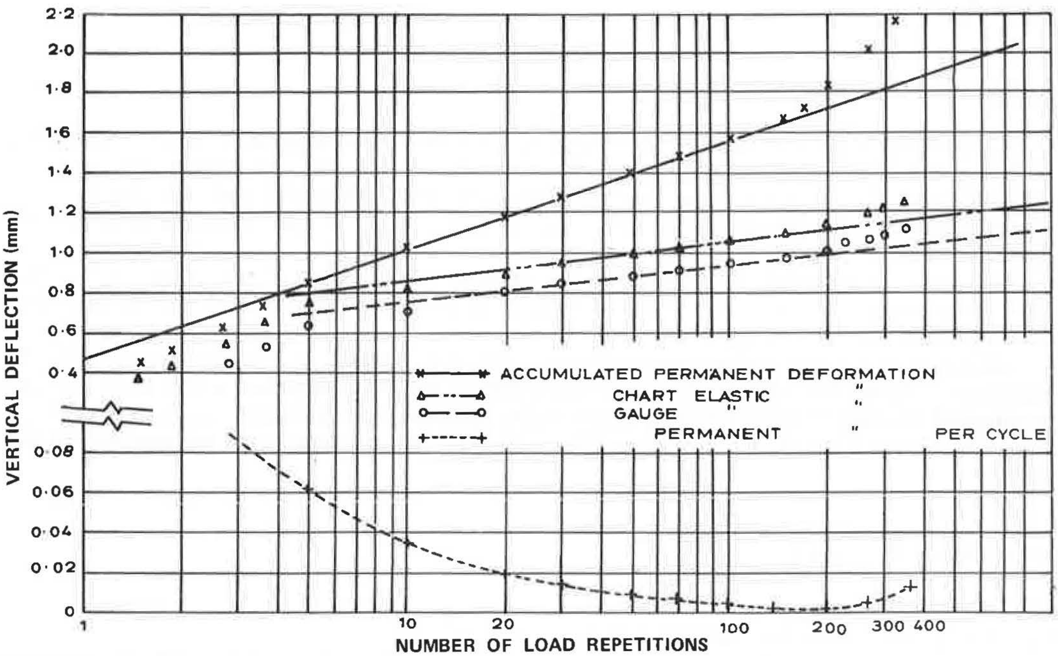
As can be seen in Figure 1 the elastic deformation and the cumulative permanent deformation curves follow one general trend: During the first few cycles, the plots show a rapid initial increase in the deflection mainly because of the embedment of the slab in the top plates. Afterward, the plots start out as straight lines having very small rates of increase in deflection with an increase in the number of cycles. At some state

Table 1. Gradings of mixes (percentage by weight).

Sieve Size	Mix O	F	q	B.S. 594
¾ in.	100	100	100	100
½ in.	95.4	96.4	94.4	98
⅜ in.	88.6	92.3	87.4	84
¼ in.	78.4	84.1	75.8	67
No. 7	68.5	73.5	65.9	67
No. 14	48.8	53.5	44.9	64
No. 25	39	41.2	35.5	58
No. 52	27.9	28.5	25.7	41
No. 100	17.5	16.1	16.4	22
No. 200	8.2	7.1	8.1	8.5

Note: 1 in. = 25.4 mm.

Figure 1. Vertical deflection versus number of load repetitions.



the plots show a deviation upward from the straight lines.

The permanent deformation curve, on the other hand, is different from the other three curves. It shows a very large deformation at the beginning and decreases continuously until it reaches a minimum, where it starts to increase again very slowly.

The permanent deformation curve reaches its minimum at roughly the point at which the other three curves deviate from the straight line. This is considered the failure point of the slab.

A close examination of the underside of the slab after failure showed that dry slabs had cracks similar to the surface alligator cracking observed in actual pavements (6). The rich slabs, on the other hand, did not show these cracks although their curves deviated from the straight line.

CYCLES VERSUS BINDER CONTENT

Results of the average values of the number of cycles to failure of the four mixes are shown plotted against binder content in Figure 2. In that figure, each mix shows a peak value of fatigue life, the maximum exhibited by mix O followed by mix F, B. S. 594, and mix q at 7.2, 7.2, 7.7, and 7.5 percent OBCs respectively. The OBC of mix q appears to be the least critical, which suggests that fatigue life of this mix would not vary much if the binder content was changed well above or below the OBC in order to satisfy other requirements.

Moreover, the fatigue life of B. S. 594 mix is well below that of any of the other mixes at low binder contents. At high binder contents, however, the difference was considerably reduced, suggesting that dry mixes depend more on their interlocking structure in their response to the load. Accordingly, continuously graded mixes (O, F, q) should exhibit higher fatigue life than the gap-graded B. S. 594 mix. At high binder contents, on the other hand, the particles were pushed away (dilated) by the excess binder (above the OBC), and their interlock was reduced. At this stage the four mixes became very similar, consisting mainly of a matrix with stone particles dispersed therein.

That mix F exhibited higher life than both mix q and the B. S. 594 would indicate that flaky particles improved the fatigue life. The propagation of cracks is more frequently through the particles in the flaky mix and around them in the nonflaky mix.

Mix F, however, is still exhibiting lower fatigue life than mix O, indicating that flakiness of the particles benefits life up to a certain limit, beyond which this flakiness might become harmful. Economically, using a limited amount of flaky particles in a bituminous mix would mean fewer restrictions on aggregates incorporating them, and nonflaky particles could be saved for jobs that need them most (e.g., surface dressings).

INCREASE AND RATE OF DEFORMATION OF ELASTIC DEFLECTION

The initial elastic deflection of the specimen is read from the dial gauge elastic curve at the 50th cycle (Figure 1) after the slab has embedded itself into the support. The slope of the straight portion of this curve is the rate of increase in the elastic deflection with the number of cycles. The rate of deformation is the vertical speed of the cross head of the Instron machine.

Average values of the initial vertical deflections in the slab at the 50th cycle (70-kg load at a 3-cm/min rate of deformation) and the increase in deflection per 100 cycles for all the mixes are shown plotted against binder content in Figures 3 and 4.

In Figure 3, each mix shows a minimum value of initial vertical deflection, the lowest of which is exhibited by mix q followed by mixes O, F, and B. S. 594 at 7.3, 7.5, 7.4, and 7.5 percent OBCs respectively.

Figure 4 shows a minimum value of increase in vertical deflection for each mix; the lowest minimum was exhibited by mix F followed by mixes q, O, and B. S. 594 at 7.6, 7.2, 7.3, and 7.7 percent OBCs.

Figure 2. Number of load repetitions to failure versus binder content.

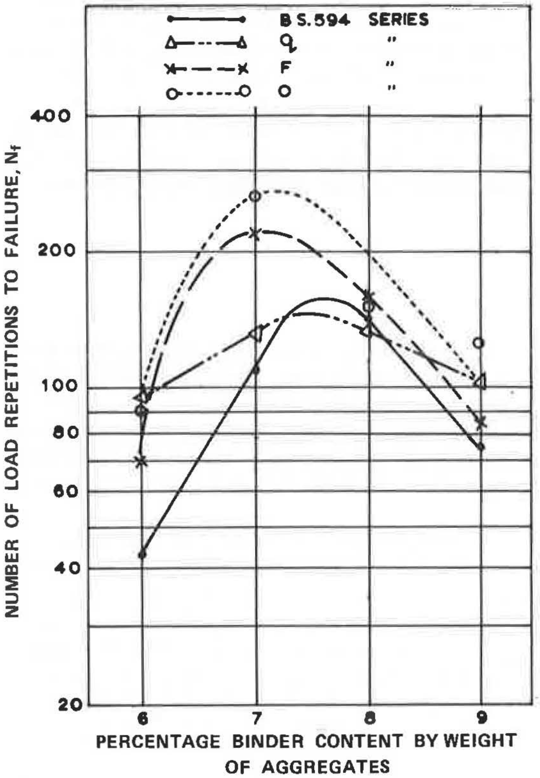


Figure 3. Initial vertical deflection versus binder content.

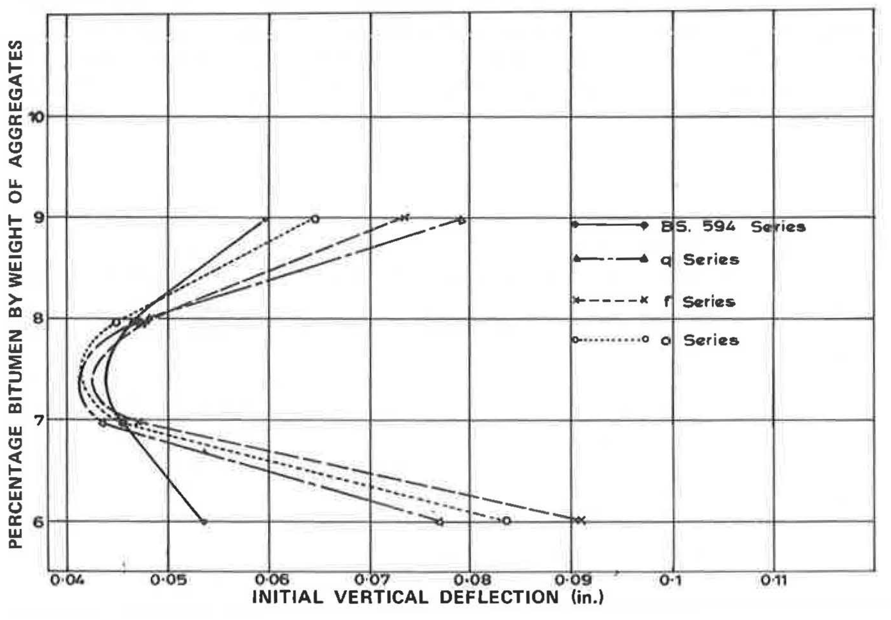


Figure 4. Rate of increase in vertical deflection versus binder content.

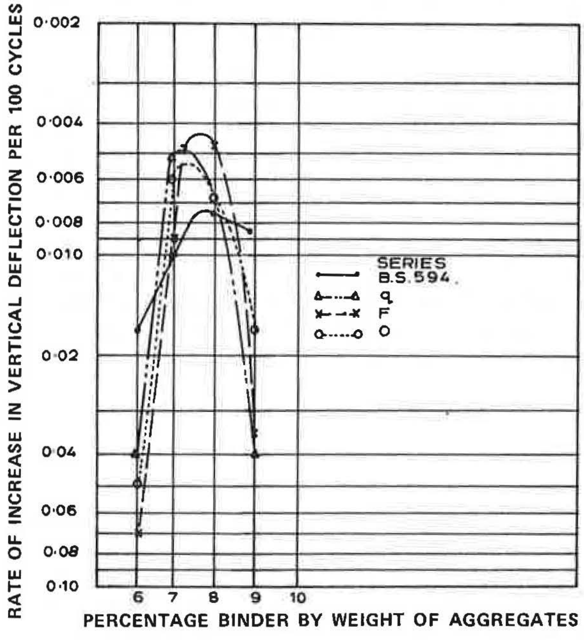
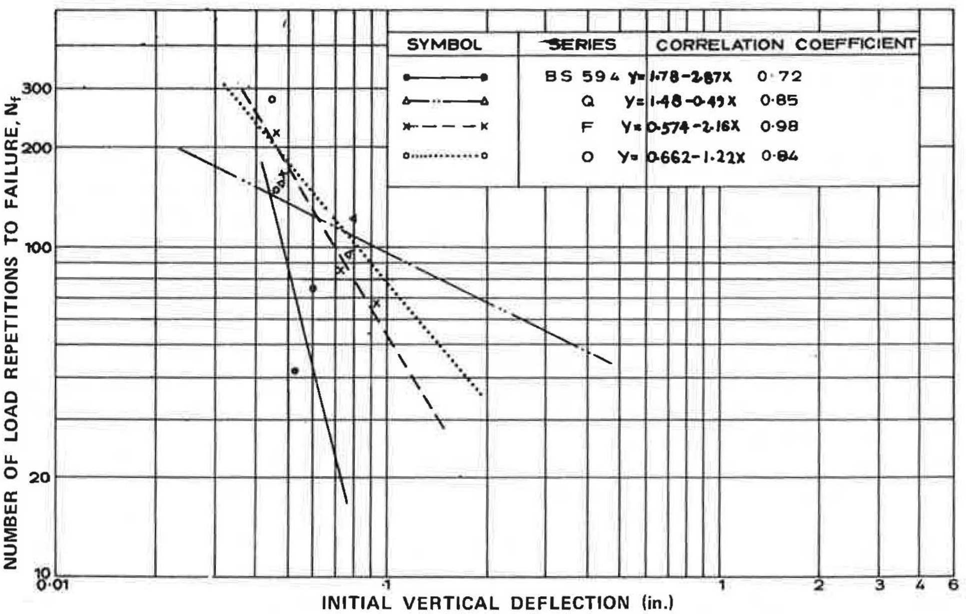


Figure 5. Number of load applications to failure versus initial vertical deflection.



It is apparent from these figures that, whereas the B.S. 594 mix retained its order of merit in both cases, the three dense mixes changed their orders of merit from one figure to another. This was most probably because the initial vertical deflection and increase in vertical deflection are not influenced by the mix properties in exactly the same way.

Mix F, for instance, shows less interlocking than mix q or mix O. Under the action of the load, mix F would suffer more deflection and compaction during the first 50 cycles than the other two mixes. Afterward, the increase in vertical deflection was found to be the lowest (at the OBC) because of the effect of the beam action of the flaky particles and the larger surface area, which would inevitably increase the adhesion.

The orders of merit and OBCs of the four mixes interchanged according to the property analyzed or presented. This means that there is no one unique OBC that gives the maximum fatigue life (Figure 2), minimum initial vertical deflection (Figure 3), and minimum rate of increase in vertical deflection (Figure 4). In the design of a mix, therefore, the binder content should comprise all these properties as well as other requirements such as skid resistance and Marshall stability.

EFFECT OF INITIAL VERTICAL DEFLECTION ON LIFE

Figure 5 shows number of load applications to failure plotted against the corresponding initial vertical deflections (at the 50th cycle of the 3-cm/min rate of deformation) for the four mixes at all binder contents. There is a linear increase in life with the decrease in the initial vertical deflection for each mix; significant correlation coefficients 0.84, 0.94, 0.85, and 0.72 were obtained for mixes O, F, q, and B.S. 594 respectively. No correlation was observed when the results of either the three dense mixes or all four mixes were pooled together.

It is reasonable to infer, however, that the initial vertical deflection could be used to roughly predict the fatigue life of the mix without carrying out the test to failure.

EFFECT OF THE INCREASE IN VERTICAL DEFLECTION ON LIFE

The number of cycles to failure is shown plotted against the corresponding rate of increase in vertical deflection in Figure 6. Linear relationships were obtained with correlation coefficients of 0.87, 0.91, 0.82, and 0.89 for mixes O, F, q, and B.S. 594 respectively. Pooling the results of mixes O, F, and q slightly reduced the correlation to 0.81. When the results of the four mixes were pooled, however, a low (but more significant because of the larger number of results) correlation coefficient of 0.62 was obtained.

This indicates that the increase in vertical deflection bears more relation to the fatigue life than the initial vertical deflection itself. Consequently, this increase in deflection could be used to roughly predict the fatigue life of the mix and to compare mixes without fatigue testing to failure.

In a multiple linear regression analysis, however, life correlated very well with both the initial deflection and the increase in deflection combined. Correlation coefficients of 0.9, 0.996, 0.9, and 0.995 were obtained for mixes O, F, q, and B.S. 594.

Pooling the results of mixes O, F, and q in a similar analysis produced a correlation of 0.84, and it was 0.63 when all four mixes were pooled.

This confirms the view that the three-variable model is superior to the two-variable model as an estimating equation. It also suggests that the combination of initial deflection and the increase in deflection could be used to predict the life better than either of the two variables individually.

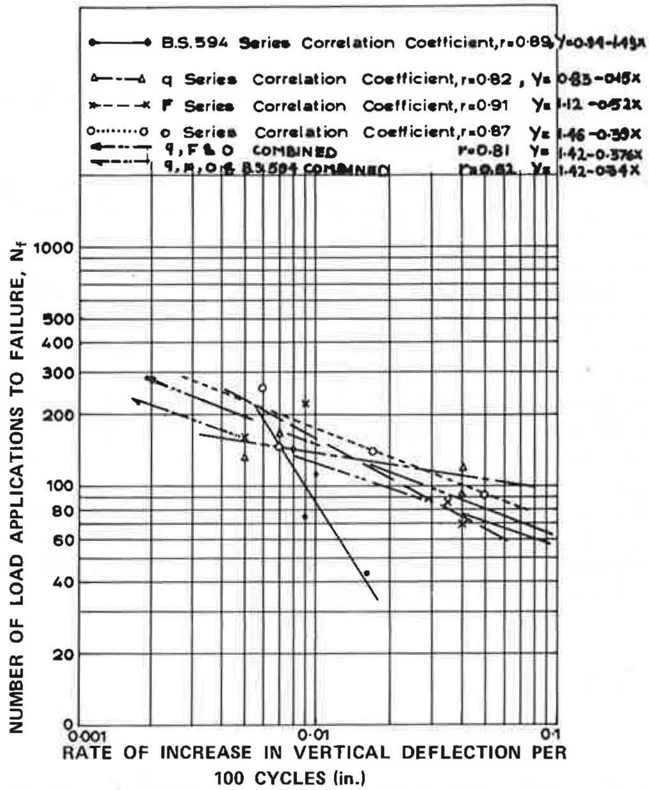


Figure 6. Number of load applications to failure versus rate of increase in vertical deflection.

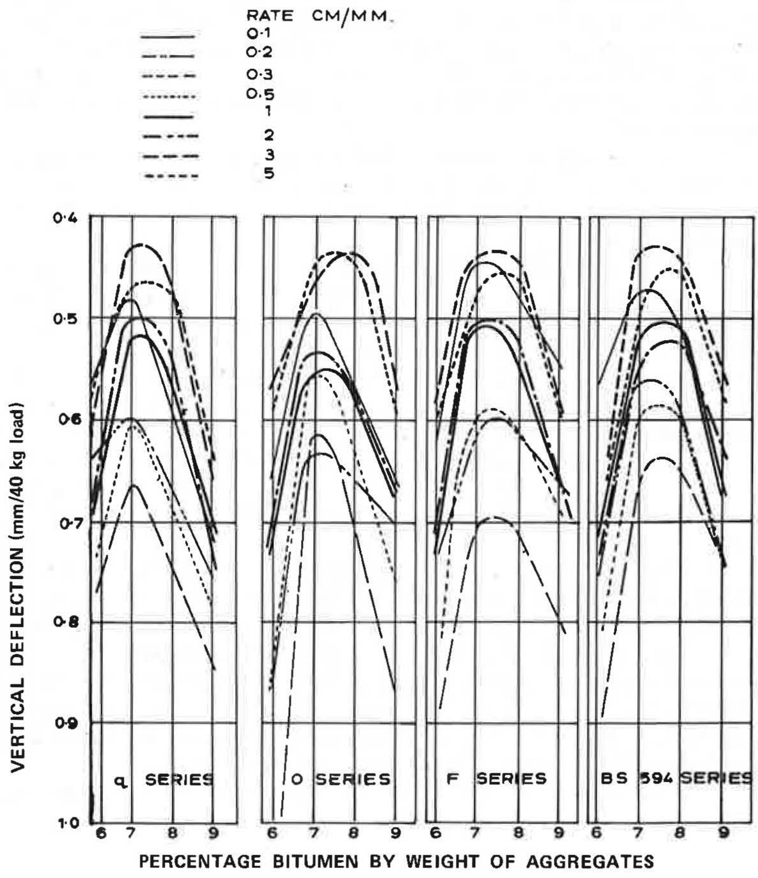


Figure 7. Vertical deflection versus binder content.

SLAB DEFLECTION VERSUS BINDER CONTENT AT DIFFERENT RATES OF MACHINE DEFORMATION

As mentioned earlier, each slab was first subjected to eight cycles (70-kg load) at 5, 3, 2, 1, 0.5, 0.3, 0.2, and 0.1 rates of deformation, after which the load was applied repeatedly at 3 cm/min until failure.

Slab deflections at each rate versus the corresponding binder content are shown in Figure 7. Minimum values of slab deflection at different OBCs are shown for each rate. The OBC shifted to the dry side as the rate was decreased. An average total decrease in OBC between the two extremes of rates was 0.4, 0.5, 0.4, and 0.3 percent for mixes F, O, q, and B. S. 594 respectively.

It is suggested that high rates of deformation would not give the binder as much time to flow and be mobilized as would low rates. Consequently, more binder was needed at high rates than would be needed at low rates to produce the minimum slab deflection, and this was observed in the OBC shift.

High rates produced sharper curves than low rates, suggesting that the former would be more appropriately used in comparing mixes at different binder contents. Lower rates, on the other hand, appear to be more suitable to investigation of the behavior of the mixes at one binder content than the OBC.

CONCLUSIONS

The results can be summarized as follows.

1. The failure in a slab tested under a repeated load of constant magnitude was defined as the number of cycles at which both the elastic and cumulative permanent deformation curves drawn on a semilog scale deviate from the straight line.
2. A peak value of fatigue life was obtained for each of the four mixes, O, F, q, and B. S. 594, at OBCs of 7.2, 7.2, 7.5, and 7.7 percent by weight of aggregate. The maximum fatigue life at the OBC was exhibited by mix O followed by mixes F, B. S. 594, and q, which suggests that it is beneficial to use a limited amount of flaky particles in the mix. Results also revealed the inferiority of the B. S. 594 mix to the two dense mixes O and F.
3. A minimum value of initial vertical deflection (70-kg load and 3-cm/min rate of deformation) was obtained for each mix; the lowest minimum initial deflection was exhibited by mix q followed by mixes O, F, and B. S. 594 at 7.3, 7.5, 7.4, and 7.5 percent OBCs respectively.
4. For each mix a minimum value of rate of increase in vertical deflection (increase in deflection at 70-kg load and 3-cm/min rate of deformation) was observed, the lowest of which was exhibited by mix F followed by mixes q, O, and B. S. 594 at 7.6, 7.2, 7.3, and 7.7 percent OBCs respectively.
5. There is no one unique OBC that gives the maximum density, maximum fatigue life, minimum initial vertical deflection, and minimum rate of increase in deflection. In the design of a mix, the binder content should comprise all these requirements as well as other properties such as skid resistance and Marshall stability.
6. In a simple linear regression analysis, initial vertical deflection and rate of increase in vertical deflection (increase in deflection) correlated very well with the fatigue life.
7. Mix life could roughly be predicted from either initial deflection or increase in vertical deflection. Increase in deflection can also be used to predict the life of a group of mixes and to compare these mixes without fatigue testing to failure.
8. In a multiple linear regression, life correlated very well with both initial deflection and increase in deflection combined. Correlation coefficients obtained were higher than the corresponding coefficients obtained in a simple regression analysis, indicating that the combination of initial vertical deflection and increase in deflection predicted life better than either of the variables individually.
9. The three rationally designed mixes were generally superior with regard to

fatigue strength to the B. S. 594 wearing course mix made of the same type of stone.

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