

A NEW DEVELOPMENT IN THE MODIFICATION OF THE PROPERTIES OF CONCRETE FOR USE IN PAVEMENTS

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During the past several years, new mileage of rigid type of pavement has been declining steadily in favor of the flexible type. The greater load spreading capacity of the former, due to the high rigidity of the concrete, is accompanied by a relatively low tensile strength and low capacity to accommodate movements caused by climate variations. Demands made by the structure of the pavement on this multiphase material have been established, and modifications of material properties, so as to achieve an improvement in pavement slab properties, are proposed. Confirmation has been made of the predicted effects of this modification on workability, static flexural strength and deformation, reversed flexural fatigue strength, and free and restrained movements due to temperature and moisture variations. A comparison has been made between the predicted structural behavior of pavement slabs based on their behavior in laboratory tests. This comparison shows that significant improvement in a number of important respects can be expected from the use of the modified concretes. In addition it is considered that the modification proposed in this paper would also enable efficient use to be made of lower quality aggregates.

●One of the primary virtues of a concrete pavement slab is its capacity to distribute the loads over a relatively wide area of the underlying layers. This is due to the high flexural rigidity that the concrete slab possesses, with the result that the major portion of the structural capacity of the pavement has to be supplied by the concrete slab itself. Large horizontal stresses are induced in it under the action of traffic loads, climatic variations, and movements of the supporting layers. The tensile strength of concrete, as compared with its rigidity, is very low and its capacity to accommodate movements due to things such as climatic variations is poor. These necessitate the use of thick slabs as well as the provision of means, namely a joint system, frequently accompanied by a system of reinforcement and load-transfer devices to control the magnitude of stresses and the resulting cracks. The joints, apart from adding to the initial and maintenance costs (1), are often a cause of distress in the pavements. Psychological effects, occurrence of resonant vibrations, and effects on the riding quality are all too well known, although good current practice goes some way toward removing these objections. Continuous reinforcement (if present) itself exerts restraint to the contraction of the slab by inducing tensile stresses.

It follows that any means by which these stresses may be reduced would be desirable. Modified concretes, designed with the aim of reducing stresses due to the factors mentioned, have been subjected to a comprehensive series of laboratory tests for the purposes of practical and theoretical evaluation.

The modification proposed is that the aggregate be coated with a chemically stable soft medium before it is incorporated into the mix. Because of its low cost and availability, the coating medium used in this study has been a penetration grade bitumen.

STRUCTURAL BEHAVIOR OF A CONCRETE PAVEMENT

The major design factor in rigid pavements is the structural strength of the concrete slab. By this is meant the capacity of the concrete slab to endure the following stress-inducing factors:

1. Externally applied static and repeated loading;
2. Restrained temperature and moisture-induced movements including restraint due to incompatibility of the phases in the material, restraint due to continuity of the material, and restraint by the subgrade; and
3. Volume changes in the supporting material, including those caused by frost action, permanent deformation of the subgrade, and loss of support through pumping.

External Loading

In the design of a pavement it is recognized as desirable to know and control the stresses both in the slab and in the subgrade. In this study, use has been made of the analyses of Westergaard and Burmister for approximation of these stresses (2). These studies indicate that reduction in the ratio $E_{\text{slab}}/E_{\text{subgrade}}$ (Burmister) or E_{slab}/K (Westergaard) reduces the bending stresses in the slab. The increases in the subgrade due to the preceding are insignificant (3), even if the stiffness ratios are reduced to $1/10$ of their usual value.

For given values of slab thickness and load, there are 2 ways in which the stress in the slab can be reduced—by increasing E_{subgrade} (or K) or by decreasing E_{slab} . In the former case [but not forgetting the cost of increasing E_{subgrade} as given by Ghosh and Dhir (4)], although the traffic stresses in the ideal case of uniform support assumed in the Westergaard and Burmister analyses will be lower, stresses induced by warping effects and subgrade restraint will be greater. In the case where E_{slab} is decreased, not only is the effect of factor 1 reduced but also are the effects of factors 2 and 3.

Satisfactory behavior of a rigid pavement depends on the structural integrity of the concrete slab. Whether the slab will be able to sustain stresses with the required factor of safety (or load factor) depends also on the strength of the concrete in the slab.

In Figure 1 curve AB shows a generalized approximate relationship between the modulus of elasticity E of concrete and its bending strength. Curve CD represents the relationship between the E of the same concrete in a slab and the bending stress in it for given loading conditions, subgrade, and slab thickness. The zone to the left of F (where bending stress in the slab exceeds the bending strength of the material) is representative of the case of lean concrete, and the zone to the right of F represents conditions in which the slab behaves as a rigid pavement.

Let a comparison be made between a normal concrete, the properties of which are represented by point N on the curve AFB, and a concrete being modified, say, to give properties represented by point M. By virtue of the lower E value of the modified concrete, the bending stress in it is less than that in normal concrete by an amount PS. This gives it a factor of safety MQ/SQ , which is more than that of normal concrete NR/TR . This superiority will exist even if the strength of the modified concrete is less (by an amount LM) than that of normal concrete, up to a certain limiting value of LM (not necessarily equal to PS) beyond which the strength of modified concrete will not be enough to take advantage of the stress reduction provided by its low E .

The degree of benefit derived from the approach depends on (a) the extent of

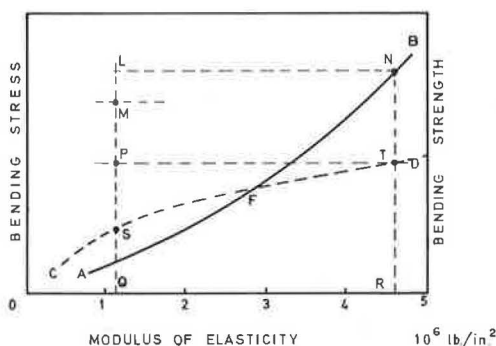


Figure 1. General relationships of bending stress, bending strength, and modulus of elasticity for concrete in road pavements.

modification in E , in which a reduction in E has considerably more effect in the lower range of E values below approximately 1×10^6 lb/in.² (7×10^4 kg/cm²); (b) the extent of modification in bending strength as compared with normal concrete; and (c) loading conditions, type of subgrade, and thickness of slab.

Restrained Temperature-Induced and Moisture-Induced Movements

The stresses induced in a concrete slab because of restraint against movements in response to temperature and moisture content fluctuations and gradients depend on the following:

1. The free (i.e., unrestrained) thermal and moisture coefficients of expansion and contraction of the concrete (larger values tend, other things being equal, to produce higher stresses);
2. Temperature and moisture diffusivity of the material (a lower diffusivity increases the gradients and hence increases warping stresses but also reduces the mean variation in temperature and moisture content and hence reduces longitudinal restraint stresses, and these stresses are more critical than warping stresses in the case of longer, > 100 ft or 30 m, slabs);
3. The E and creep characteristics of the concrete (a lower value of E accompanied by greater creep reduces the bending stresses due to warping and the longitudinal stresses due to subgrade restraint); and
4. Characteristics of the subgrade or base including surface frictional characteristics, shear strength, load-deformation and creep characteristics, and effect of moisture and temperature variations on these.

Volume Changes in the Supporting Material

Volume changes such as the dilation of a granular subgrade, unequal subgrade settlement or compaction, pumping at joints, swelling and shrinking in the subgrade, and frost heave beneath the pavement produce nonuniform support, resulting in bending stresses. These stresses, in response to loading and self weight of the slab, are proportional to the stiffness of the slab. The reduction, therefore, of stiffness and provision of an increased creep facility provide a reduction and relaxation of stresses. The analysis of Richard and Zia (6)—who used elastic theory and parameters E for slab and K for subgrade, confirms that a reduced value of E provides reduced stress in the slab. The analysis also shows that there are very large pressure concentrations on the subgrade at the boundaries of any such discontinuity in support and that these are also effectively relieved by a reduction in E and an increase in the creep facility in the slab.

MECHANICAL AND PHYSICAL CHARACTERISTICS OF CONCRETE

It is apparent from the discussion in the previous section that the effects of variation in the slab properties should be viewed not in isolation but with reference to the pavement as a structural system, performing under the action of traffic, under climatic variation, and under varying conditions of subgrade support.

The modification in concrete composition proposed, namely the coating of a proportion of the aggregate with a soft medium before it is incorporated in the mix, is here examined in the light of its probable effects on the performance of the structure as a whole.

If other factors are assumed to be constant, the proposed modification can be expected to influence concrete properties as follows:

1. **Workability**—For most aggregates the roughness of the surface texture and angularity of major projections will be reduced by coating. Hence workability is improved, with the usual consequences that for a given workability the water-cement ratio can be reduced, leading to an increase in paste-mortar strength, or a leaner mix may be employed.
2. **Average strength**—For many types of aggregate, the coating will produce a drop in bond strength, and this will lead to a fall in average strength as measured in

conventional laboratory tests in compression, tension, indirect tension, flexure, and fatigue. In other cases it is possible that the average strength, for a given water-cement ratio, may be increased because, in normal concrete, parasitic stresses due to thermal, moisture, and modules of elasticity incompatibility between the phases present invariably produce cracks that extend during the life of the structure because of climatic and loading fatigue. Introduction of a soft medium between the aggregate and paste will tend to reduce these stresses.

3. Statistical strength—An important aspect of the Griffith theory is that the fracture strength of materials such as concrete is statistical in nature and depends on the probability that, for a given applied stress, a flaw of sufficient size to propagate further is already present. On the assumption that the bitumen coating will eliminate or tend to reduce the occurrence of random parasitic cracks, the soft coating itself acting as a system of controlled and uniformly distributed flaws, it can be expected that the scatter of results of observed fracture strength will be reduced.

4. Low-quality aggregates—Aggregates that are generally considered to have rather low quality, with respect to high water absorption or potential adverse chemical reactivity, will be rendered innocuous by bitumen coating, and their use will thereby be made more feasible.

5. Modulus of deformation and creep—The effect of coating the aggregate will be to reduce the stiffness of the concrete and to increase the creep facility. These changes of the material properties will enter into any rational design of concrete pavement structures.

6. Coefficients of thermal expansion—In most cases the coefficient of thermal expansion of the concrete will be slightly increased as a result of coating because normally the value of the coefficient for the continuous phase of paste is higher than that of the dispersed aggregate phase, and the coating will allow greater freedom to the independent movements of the 2 phases. Coating may have the reverse effect of lowering the coefficient of expansion of the concrete in those rarer cases where the rigid phase of aggregate particles has a higher coefficient than the paste continuum. The causes of this would be (a) the reduced stiffness of the coated aggregate and (b) the greater opportunity for independent movement that would facilitate internal creep in the form of particle reorientation. In addition, there would be movement of the fluid phase into and out of the pore structure of the paste or mortar phase in response to volume changes in the aggregate. The latter action would also take place with respect to volume changes within the coating itself. These latter effects mean that, in spite of the fact that bitumen has a higher coefficient of expansion than any of the other phases present in the concrete, this in itself could be of minor significance in affecting the coefficient of the composite as a whole.

7. Thermal conductivity—In addition to the effects on thermal coefficients, the coating of the aggregate can be expected to affect the thermal conductivity. This would probably be of minor importance because the modification affects the dispersed phase only.

8. Coefficients of volume change with moisture movement—For reasons similar to those given in item 6, if an aggregate is used that possesses greater dimensional stability in the presence of moisture variations than the paste, then the coating of the aggregate and consequent reduction in bond stiffness will give a concrete with lower stability (i.e., showing higher coefficients of volume change) than normal concrete. On the other hand, if an aggregate is used that has lower dimensional stability than the paste, then the coating will render the mix more stable than the corresponding normal concrete.

9. Moisture diffusivity—The plugging of voids in the concrete by the progressive migration of bitumen toward these sites will reduce its permeability and water absorption. Both resistance to the establishment of moisture content gradients, leading to warping, and resistance to water absorption, leading to the swelling effects just discussed, will be favorably increased. Frost resistance also will be increased by the decrease in water absorption.

EXPERIMENTAL INVESTIGATIONS

Materials Used and Mixes Tested

Because of their common use in concrete mixes, a crushed quartzite gravel and natural sand (Weeford Pit, Staffordshire) were chosen. This type of aggregate has an above-average value of coefficient of thermal expansion (6) but is reasonably stable to moisture variations. Details of grading, concrete mix design, and type and quantity of bitumen used are given in the Appendix.

The investigation has involved the study of the following 3 types of concrete: (a) normal concrete; (b) concrete with coarse aggregate coated, i.e., retained on British standard sieve $\frac{3}{16}$ in. (4.76 mm); and (c) concrete with 92 percent by weight of all aggregate coated, i.e., all fractions except those passing B.S. sieve No. 52 (0.295 mm).

In the remainder of this paper, these types of concrete will be designated M_0 , M_1 , and M_2 respectively. In all cases the water-cement ratio was adjusted to give a selected workability of 20 sec (vebe time).

Curing was effected under water during 28-day periods for static tests, 28 to 48 days for fatigue tests, and 14 days for temperature and moisture-movement characteristic tests.

Results of Investigations

1. Flexural testing was done of beams 1.58 in. (40 mm) \times 2.47 in. (62.5 mm) \times 10.5 in. (265 mm). A third point loading system on a span of 9.3 in. (236 mm) was used for the flexural tests.

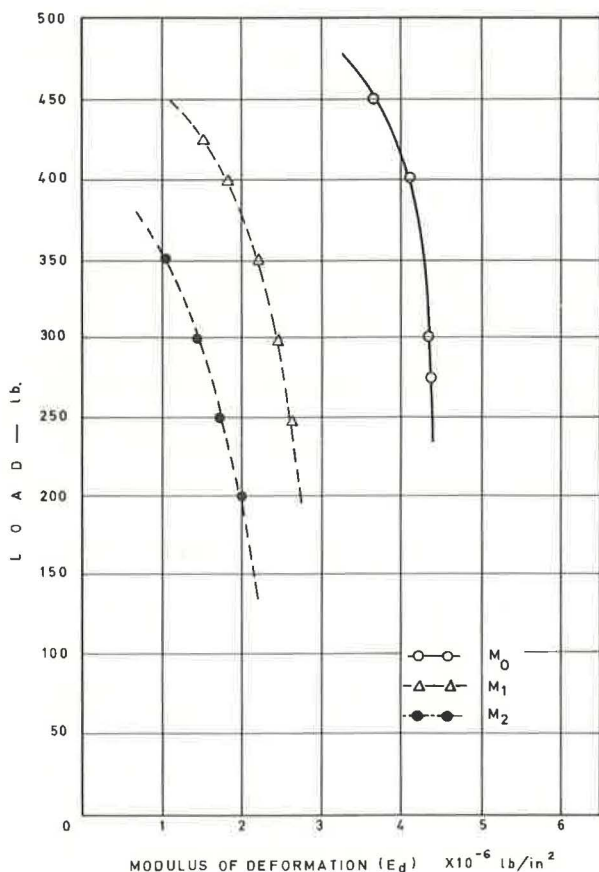


Figure 2. Load versus modulus of deformation for normal and modified concretes.

The modulus of deformation in flexure shown in Figure 2 is seen to be considerably reduced for the modified concrete as compared with the normal concrete, the difference being greater at the higher load levels. This modulus is the effective modulus that should be considered in the design of a pavement and has been used in calculations of expected performance discussed in the concluding section of this paper.

The average flexural strength is also reduced as a result of modification (Fig. 3). This reduction, as compared with normal concrete, is 5.8 and 24.2 percent for concretes M_1 and M_2 respectively. The reduced scatter in the results for the modified concretes means, however, that the difference in strength tends to decrease at lower probabilities of failure. For example, at a probability of failure level of 0.022 (2 standard deviations), M_2 is only 9.5 percent weaker than M_0 , and M_1 is 8 percent stronger.

2. In reversed flexural fatigue testing, the average strength (in terms of number of cycles to fracture failure) is, as in the case of

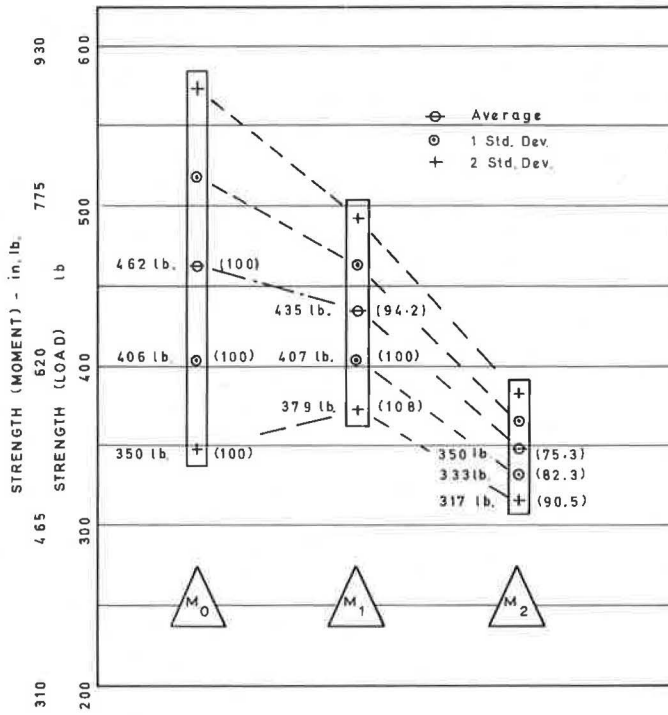


Figure 3. Flexural strength values for normal and modified concretes.

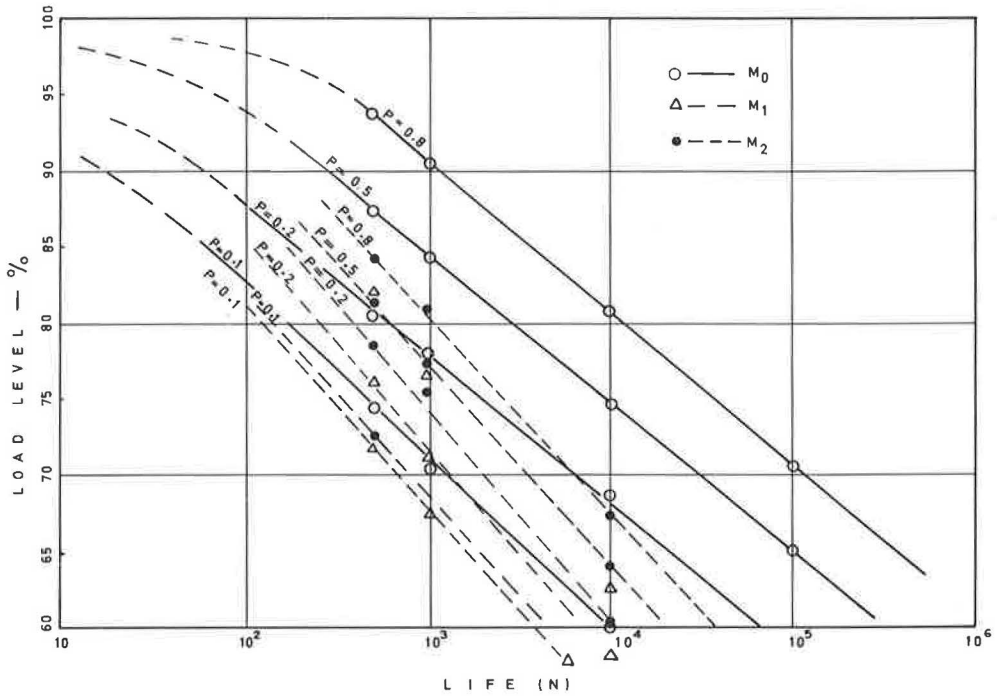


Figure 4. Fatigue lives of normal and modified concretes.

simple flexural testing, lower for the modified concretes than for normal concrete (Fig. 4). This difference, within the measured range, is greater at lower load levels.

In these results also, a reduced scatter was observed in the modified concretes, with the consequence that, at lower levels of probability of failure, the difference in strength is considerably less. This is shown by the proximity of the lines for the 3 concretes at $P = 0.1$.

It is also to be noted that the fatigue tests were of a constant bending moment type. As discussed in the section on external loading, however, it is important to recognize that, under actual service conditions, the bending stresses experienced by any slab will be a function of the slab's own stiffness. It follows that, under more simulative loading and support conditions, the merits of the modification would appear to considerably greater advantage.

With regard to results 1 and 2, a further point should be added based on the consideration of the scatter of the results and on the assumption that the weakest link theory is applicable. This point is that the average flexural strength (static and fatigue) of the modified concrete will be considerably improved, relative to that of the normal concrete, when measured on specimens of full slab thickness and when tested under realistic conditions such that the volume of the concretes subjected to near maximum bending moment is relevant to their individual stiffnesses.

3. The linear coefficients of thermal expansion (unrestrained) of M_1 and M_2 have been found to be increased by 8.8 and 13 percent respectively as compared with M_0 . (Coefficients of expansion are 12.4, 13.5, and 14.0×10^{-6} C for M_0 , M_1 , and M_2 respectively.)

4. The free drying shrinkage (unrestrained) of M_1 and M_2 are 16 and 25 percent respectively, greater than that of M_0 (Fig. 5). These comparisons refer to a drying period of 23 days at 10 C and 20 percent relative humidity.

5. Under restrained test conditions (Figs. 6 and 7), which are more simulative of the pavement slab conditions, the stresses induced in M_1 and M_2 because of temperature

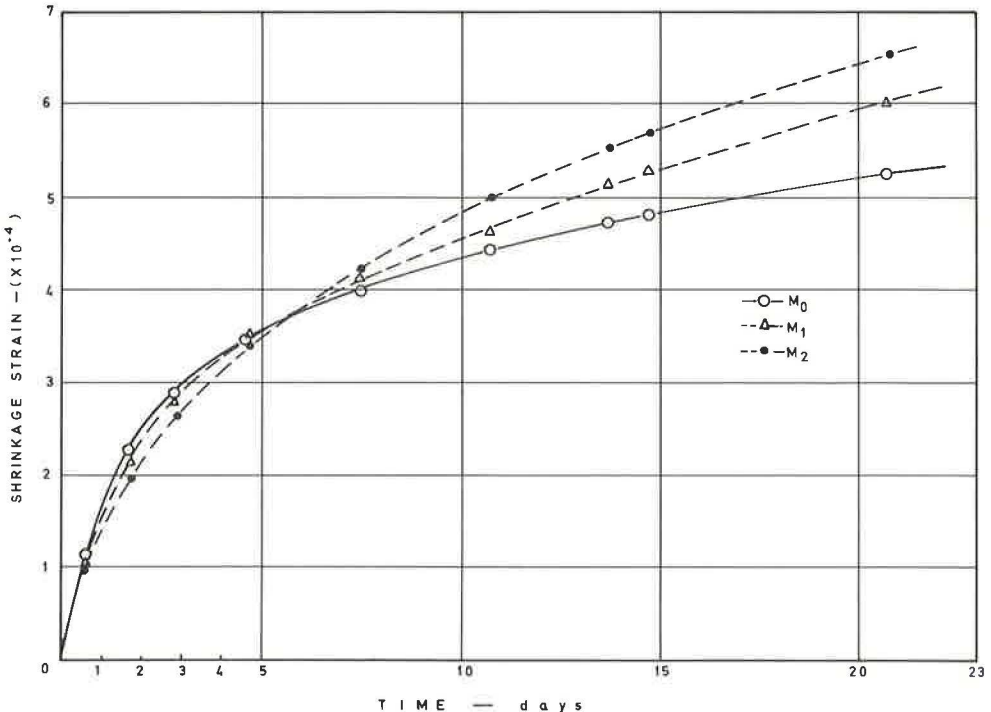


Figure 5. Strains due to unrestrained shrinkage in normal and modified concretes.

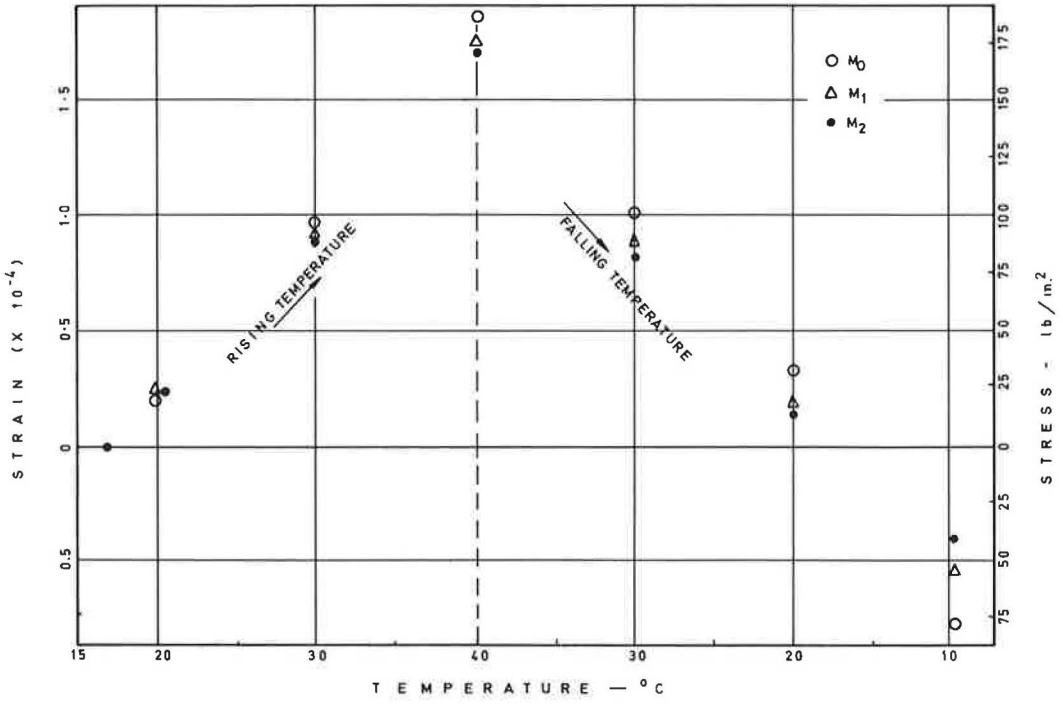


Figure 6. Thermally induced strains and stresses in normal and modified concretes.

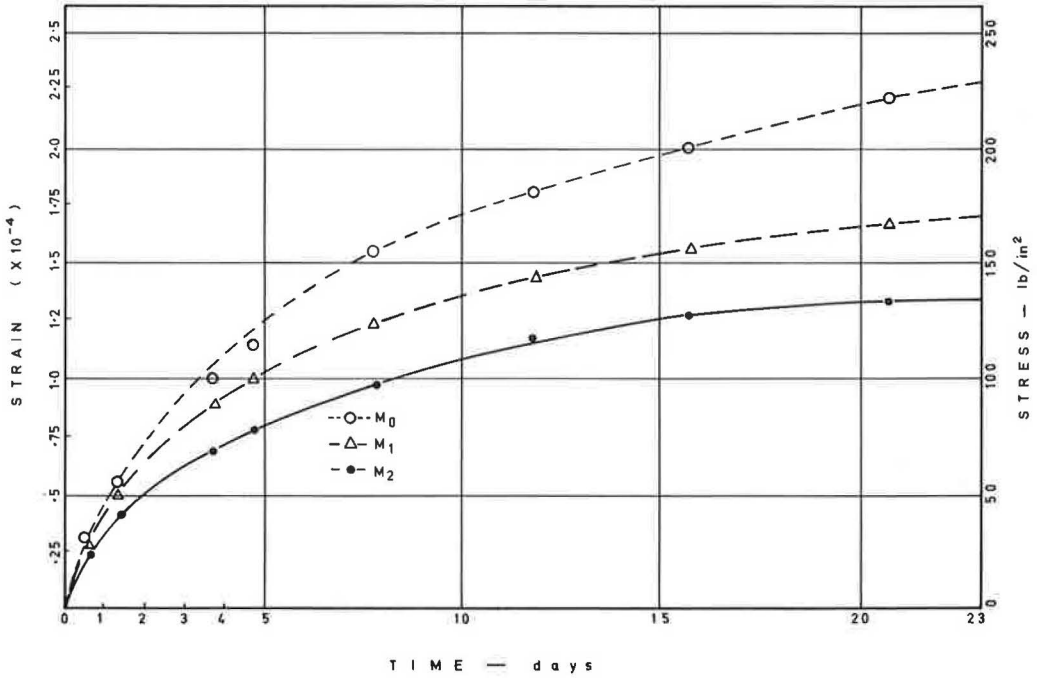


Figure 7. Strains and stresses due to restrained shrinkage in normal and modified concretes.

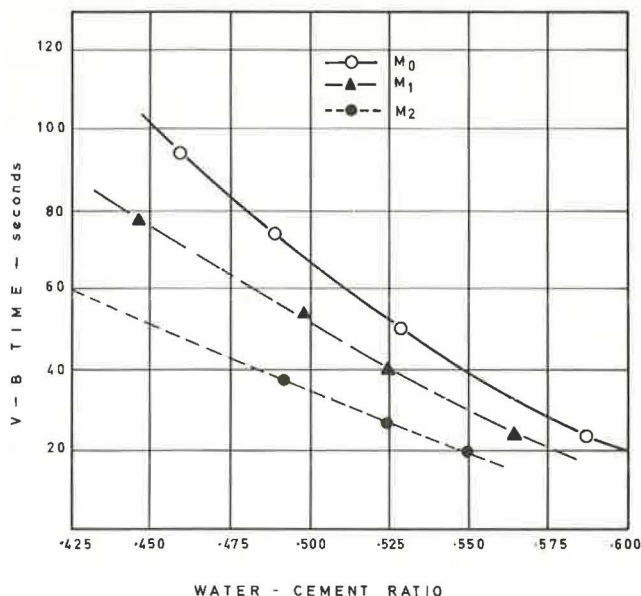


Figure 8. V.B. workability for normal and modified concretes at various water-cement ratios.

and moisture variations are very significantly lower than those in M_0 . The corresponding movements are also less in M_1 and M_2 . The orders of merit shown in these tests are hence the reverse of those in unrestrained tests (results 3 and 4).

6. The thermal conductivity does not seem to be affected by the modification.

7. As shown in Figure 8, the workability of the mixes M_1 and M_2 is considerably increased as a result of surface texture and shape modification of the aggregate particles by coating.

CONCLUSIONS

A theoretical comparative analysis of the structural behavior of pavement slabs of the 3 concretes based on the experimental results obtained shows the following:

As computed from Meyerhof's (7) method of analysis, the expected ultimate load-carrying capacity of the slabs of modified concretes is considerably greater than that of the slabs of normal concrete (Table 1). This is despite the lower average strength of the former and without taking into account size effects and the statistical probability of failure. This superiority of the modified concrete slabs is more marked for lower slab thicknesses, H , and lower values of the modulus of subgrade reaction, K .

Despite the bias against the modified concretes introduced by the method of fatigue testing (result 2) the data given in Table 1 show that on the whole the modified concretes can be expected to perform better under the fatiguing action of traffic, particularly for low values of H and K . The only cases where the normal concrete showed higher calculated life are marked in Table 1.

The calculated lives given in Table 1 are based on a probability of failure level of 0.1. There is in this analysis an additional bias against the modified concrete because it is certain that a rational method of pavement design should consider levels of probability of failure several orders of magnitude less than the one taken here. In a design based on such lower levels of probability of failure, the superiority of the modified concretes would be apparent over an even wider range of support, thickness, and loading conditions than that given in Table 1.

TABLE 1
COMPARISON OF STRUCTURAL BEHAVIOR OF CONCRETE

Slab Thickness H (in.)	Value of Modulus of Subgrade Reaction K (lb/in. ² /in.)	Ultimate Load Capacity (lb)			Value of Load Applied (lb)	Expected Life (no. of load cycles)		
		M ₀	M ₁	M ₂		M ₀	M ₁	M ₂
4	50	8,380	17,300	16,800	5,000	10,500	800,000	960,000
					7,000	77	105,000	114,000
					8,000	13	40,000	40,000
					9,000	>1	15,000	14,000
	100	15,600	27,000	26,000	9,000	34,000	365,000	410,000
					10,000	4,300	195,000	200,000
					12,000	290	54,000	51,000
					14,000	26	15,300	13,400
	300	27,950	48,000	44,000	15,000	36,000	520,000	450,000
					18,000	4,200	180,000	130,000
					21,000	410	62,000	38,500
					25,000	28	14,700	8,200
8	50	46,100	64,500	57,200	24,000	51,000	185,000	105,000
					30,000	3,300	38,500	17,000
					35,000	360	10,000	11,000
					40,000	40	2,510	770
	100	62,100	81,100	70,500	35,000	21,500	68,000	63,000
					40,000	3,900	23,000	8,300
					45,000	720	8,000	2,300
					50,000	140	2,750	640
	300	88,700	106,500	93,000	45,000	62,000 ^a	80,000	28,000 ^a
					50,000	21,500 ^a	41,000	13,400 ^a
					55,000	6,550 ^a	15,500	5,400 ^a
					60,000	2,000	7,000	2,100

^aOnly cases where normal concrete showed higher expected life.

The stresses in the modified concrete slabs due to all other stress-inducing factors will also be reduced very significantly. The possibility of greater spacing or elimination of joints (including contraction joints) is obvious.

Quantification of the exact relative overall merits of the 3 concretes is extremely difficult and, as is usual in such cases, calls for full-scale pavement tests together with further laboratory investigations.

The indications are clear, however, that concretes designed to have properties relevant to their place in the pavement structure are desirable if a rational method of rigid pavement design is to be used to its maximum effect and that such concretes, either as described or similar, are capable of being designed.

ACKNOWLEDGMENTS

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APPENDIX

DETAILS OF GRADING, CONCRETE MIX, AND BITUMEN

Grading

Figure 9 shows the grading of the aggregate used. The aggregates were first dried in the laboratory and then screened into separate sizes by using $\frac{3}{8}$ -in. (9.52-mm), $\frac{3}{16}$ -in. (4.76-mm), No. 7 (2.38-mm), No. 14 (1.41-mm), No. 25 (0.59-mm), No. 52 (0.295-mm), and No. 100 (0.152-mm) British standard sieves. These fractions were kept separately in closed bins until required; the separate sizes were weighed up to give the same grading for each batch of concrete.

Coating

Fraction sizes of $\frac{3}{8}$ to $\frac{3}{16}$ in. (9.52 to 4.76 mm) and $\frac{3}{16}$ in. to No. 7 (4.76 to 2.38 mm) were coated with 90 to 110 penetration bitumen. The aggregate was heated on a hot plate to about 150 C and transferred to an electrically heated mixer drum maintained at about the same temperature. The aggregate was thoroughly coated by being mixed for about 5 min with a precalculated amount of bitumen. The coated aggregate was then tipped into a cold water bath to prevent the aggregate particles from sticking to one another. The aggregate was dried in the laboratory air before being used in the concrete mix.

Aggregate fractions passing the No. 7 (2.38 mm) British standard sieve were coated with an emulsion of 190 to 210 penetration bitumen. Laboratory dried material from

the bins was weighed and transferred to the mixer drum, and a precalculated amount of emulsion was added. A mixing time of about 3 min was found to be sufficient to obtain an adequate coating, but mixing was continued in some cases to aid evaporation of water.

The quantity of bitumen used for coating of the $\frac{3}{8}$ - to $\frac{3}{16}$ -in. (9.52- to 4.76-mm) size fraction was 3 percent by weight. This amount was about the maximum quantity of bitumen that could be added without leading to excessive adhesion between the particles in a cooled state. The criterion for deciding the amount of bitumen or of bitumen emulsion for any of the

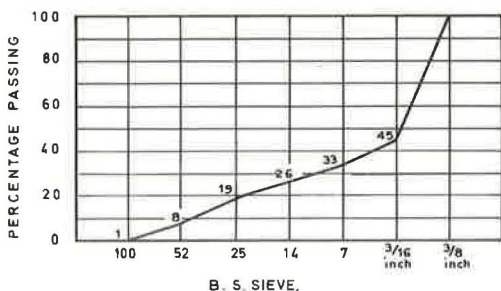


Figure 9. Grading of concrete aggregate used.

finer fractions was the ratio of mean diameter of the particles of the size fraction under consideration to the average thickness of the coating film. This ratio (122.5) was maintained constant for the various fraction sizes, and it was first determined for the $\frac{3}{8}$ - to $\frac{3}{16}$ -in. (9.52- to 4.76-mm) sized aggregate. The average thickness of the coating was calculated by dividing the volume of the bitumen used by the surface area (8) of the aggregate coated. This thickness was 0.0583 mm for the largest and 0.001715 mm for the smallest fraction sizes.

Aggregate-Cement and Water-Cement Ratios

An aggregate-cement ratio of 6:1 was used for all mixes. Water-cement ratios of 0.60, 0.575, and 0.55 were used for M_0 , M_1 , and M_2 respectively to give a workability of 20 vebe degrees. Further details of the characteristics of the test specimens and of the results are contained in the thesis submitted by Singh (9) to the Department of Transportation and Environmental Planning, University of Birmingham, England.