THE EFFECT OF GRADING ON LEAN-MIX CONCRETE

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Severe nontraffic-load-associated cracking of lean-mix concrete (cement-treated) bases in the highveld region of the Republic of South Africa led to a laboratory investigation into some engineering properties of this material. This paper covers the first part of the laboratory study in which the effect of grading on flexural strength, tensile strength, strain at break, and drying shrinkage strain were investigated. Three aggregate gradings using the same aggregate with varying cement and water contents were tested at approximately 96 percent modified AASHO density in beam flexure, direct and indirect tension, and drying shrinkage. A mix having a relatively low water-cement ratio and the coarsest grading yielded the highest flexural strength, static elastic modulus, and tensile strength and lowest short-term drying shrinkage strain. These findings point to a possible revision of current specifications for lean-mix concrete bases that could lead to an improved performance of this base material in practice.

•THE active implementation of a long-term rural freeway plan in the Republic of South Africa has not come without its attendant problems to the materials engineer. Predicted traffic volumes and loadings that will use these pavements during their design life have demanded materials of the highest quality. Because of the element of uncertainty that existed during the early 1960s with respect to the long-term performance of untreated crushed-rock bases under heavy freeway traffic, certain freeway pavements were constructed with lean-mix concrete bases under relatively thin bituminous surfacings. Lean-mix concrete bases in this paper are equivalent to cement-treated bases where crushed-rock aggregate is used. Under the climatic conditions of the highveld in the Transvaal, these pavements showed severe block cracking even before the freeways were opened to public traffic (Fig. 1).

Initial investigations into these nontraffic-load-associated cracks pointed to drying shrinkage and possibly temperature effects as being the principal causative factors. Material properties that were considered to be important in the formation of cracks were tensile strength, strain at break, and amount of short-term drying shrinkage.

A research program was therefore initiated to investigate the effect of aggregate grading on these material parameters. The research program is still in progress, and this paper constitutes a progress report of some of the initial findings.

LABORATORY STUDY

The laboratory study was divided into two phases: one involving materials recovered from actual in-service pavements and the other laboratory-prepared materials. The first phase of the study was necessary to establish the elastic properties of lean-mix concrete to analyze the traffic-load-associated stresses and strains that occur in practice. This aspect, although important in the overall performance of lean-mix concrete bases, will not be dealt with in this paper.

A number of laboratory testing techniques were used to measure the properties of prepared specimens of lean-mix concrete. These techniques are briefly described.

Beam Flexure Test

Prismatic beam specimens measuring 75 by 75 by 450 mm were subjected to a third-point loading test. The load was applied gradually and was measured throughout the test with a load cell. The resultant deflection of the beam was measured at the mid-point by two linear variable differential transformers (LVDTs). Compression at the points of load transfer was eliminated from the deflection measurements by measuring the deflection of the beam relative to a datum that was at a fixed distance from the initial top surface of the beam. A continuous record of the load and deflections was made, and the average deflection was used in conjunction with the applied load to calculate the flexural bending strength, static elastic modulus, and strain at break. The flexural bending strength was defined as the maximum bending moment divided by the section modulus (Z) of the beam. Using the load and deflection data and applying normal elastic beam theory, we obtained a stress-strain relation. The slope of the straight-line portion of this relation was taken as the static elastic modulus in bending. Figure 2 shows a view of the apparatus during a test.

Direct Tensile Tests

Direct tensile tests were performed on 75- by 75- by 215-mm prismatic beam specimens by applying a gradually increasing load to the ends of the specimen. Load transfer was achieved by gluing metal loading heads to the ends of the specimen with quick-drying synthetic polyester resin. So far as possible, eccentric loading was eliminated by using ball-and-socket joints between the platens of the testing machine. The tensile load was measured by means of a load cell, and the deformation, in the direction of the applied load, was measured by means of an LVDT fixed between the ends of the specimen as shown in Figure 3. The load and deformation were recorded simultaneously on the vertical and horizontal axes of an X-Y recorder.

From the trace obtained, it was possible to calculate the tensile strength, strain at break, and tangent elastic modulus in tension of the lean-mix concrete tested.

Indirect Tensile Test

Cylindrical specimens measuring approximately 100 mm in diameter and 65 mm high were tested in the Brazilian test by applying a gradually increasing load at diametrically opposite points on the cylindrical face of the specimen. Case-hardened loading strips 25 mm wide were used to spread the applied load as recommended by Hudson and Kennedy (1). The maximum load resisted by the test specimen was recorded on the dial of the testing machine. The indirect tensile strength was calculated from $S = (2P/\pi td)$ where S = indirect tensile strength (Pa), P = maximum load (N), t = average height of specimen (m), and d = nominal diameter of specimen (m).

Drying Shrinkage Test

Prismatic beam specimens, similar to those used for direct tensile tests, were used for continuous short-term drying shrinkage measurements. Both ends of each prism were capped with a 25- by 25-mm brass plate that was glued in position by applying the glue over a small area on the axis of the beam. A solid metal frame designed to hold two rows of six specimens in a vertical position provided a datum from which the shrinkage measurements could be made. The frame containing the specimens was placed in an environmental cabinet set at 25 C and 90 percent relative humidity. The humidity level was chosen to simulate, as accurately as possible, the drying rate pertaining to a lean-mix concrete base under the local environment. Expansion or contraction of the metal frame could be disregarded because all measurements were made at a constant temperature. Each specimen was supported on three pins and located directly below an LVDT fixed to the top of the frame. Shrinkage of each specimen was measured by the LVDT and automatically recorded on a data logger. Measurements were recorded at hourly intervals for the first 2 days and thereafter at 3-hour intervals throughout the testing period.

Shrinkage tests were continued until the shrinkage was considered to be negligible over a period of 2 days. It generally took at least 3 weeks before this stable condition developed.

TESTING OF MATERIALS RECOVERED FROM THE ROAD

The first phase of the laboratory testing program consisted of beam flexure tests on lean-mix concrete base materials recovered from various pavements. Major samples, consisting of slabs measuring approximately 600 by 700 mm, were recovered and thereafter cut by means of a diamond saw into six test specimens of the required dimensions. The span-to-depth ratio of the cut specimens was chosen to exceed the minimum value of five recommended by Pretorius (2). The ratio of the minimum specimen size to the maximum aggregate size used varied between two and four. Results of seven pavements sampled are given in Table 1. Values reported are the average of six results.

Current specifications for lean-mix concrete base material in South Africa generally impose an upper limit of 5 percent on the cement content and give an envelope within which the aggregate grading should fall (3). The water content used is that which provides maximum density under modified AASHO compaction. The specified envelope of aggregate grading is shown in Figure 4 as gradings B and C.

TESTING OF LABORATORY-PREPARED MATERIAL

One of the objectives of the laboratory study was to isolate the effect of aggregate grading on the engineering properties of lean-mix concrete. Laboratory-prepared mixtures were thus tested in gradings A, B, and C as shown in Figure 4. The inclusion of a finer grading than that allowed by the current specification envelope was based on the work of Johnson (4) who showed that, for concrete, both tensile and compressive strengths increase with a decrease in mean aggregate size.

Description of Material Used

The types of both aggregate and ordinary portland cement used during the laboratory investigation were kept constant. Domestic water was used in all the mixtures. The aggregate was a reef quartzite with typical physical properties as given in Table 2.

The cement, while still in a hot condition, was obtained directly from a local cement factory. Results of physical and chemical tests on the cement used are given in Table 3.

For the three gradings investigated, the cement content was varied between 3 and 7 percent; generally the water content used was that which gave a maximum density at modified AASHO compactive effort for 5 percent cement content. Results of these tests are given in Table 4, which include dry densities obtained at 5 percent content and optimum moisture content between 3 and 7 percent.

Test prisms were compacted in collapsible steel molds, on a vibrating table operating at 50 cycles per second, to approximately 96 percent modified AASHO density. It required approximately 2 min of compaction to attain the required density.

INFLUENCE OF GRADING ON TEST PARAMETERS

Beam Flexure Tests

Test specimens for beam flexure tests were compacted and then cured in a moist room at 25 C ± 3 C for a period of 28 days before testing.

Figures 5, 6, and 7 show respectively the results of flexural bending strength, static elastic modulus, and strain at break for gradings A, B, and C at cement content levels of 3 and 7 percent. The aggregate gradings were defined in terms of mean particle diameter of the aggregate or more simply mean aggregate size. According to Johnson (4), mean aggregate size is defined as $\Sigma(\sqrt{d_1 d_2}/f)$ (percentage of particles between sieve sizes d_1 and d_2) where d is the sieve size in mm and f is an angularity factor defined by Loudon (5) taken as 1.5 for the quartzite used. Grading C, having the largest mean aggregate size, gave the highest values of flexural bending strength, static elastic modulus, and strain at break, and grading A gave the lowest values.

Direct Tensile Tests

Direct tensile tests were performed on specimens that were cured at 25 C ± 1 C for 7 days in sealed plastic bags and thereafter dried at 90 percent relative humidity at

Figure 1. Pavement showing block cracking of lean-mix concrete base.

Figure 2. Beam flexure test apparatus.

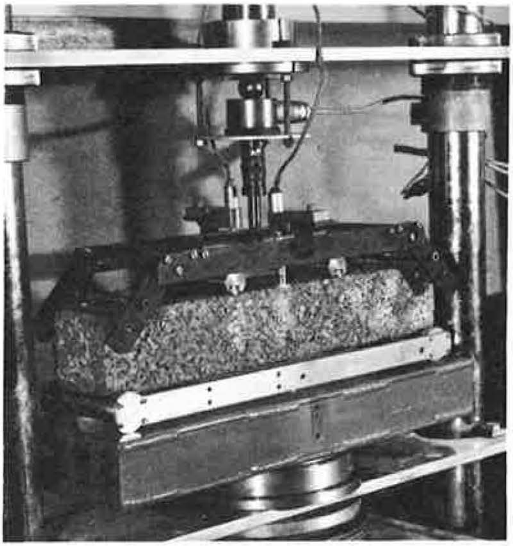


Table 1. Results of flexure tests on specimens of lean-mix concrete removed from existing pavments.

Contract	Flexural Bending Strength (MPa)	Coefficient of Variation (percent)	Strain at Break ($\mu\epsilon$)	Coefficient of Variation (percent)	Static Elastic Modulus (GPa)	Coefficient of Variation (percent)
A	1.39	6	113	4	18.5	10
B	2.68	9	181	11	23.8	11
C	3.07	15	145	12	27.9	12
D	2.05	19	134	19	20.6	14
E	0.78	7	114	23	16.4	17
F	4.38	9	148	11	38.9	18
G	0.45	20	182	10	5.9	23

Figure 3. Direct tensile test apparatus.

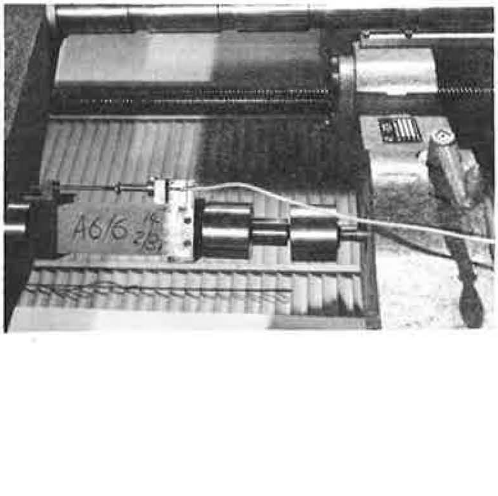


Table 2. Typical results of physical tests on aggregate used in study.

Property	Value	Unit	Coefficient of Variation (percent)
Elastic modulus	79	GPa	4
Uniaxial compressive strength	240	MPa	4
Uniaxial tensile strength	10.8	MPa	11
Poisson's ratio	0.13	–	–
Density	2,710	kg/m^3	–
Water absorption (ASTM)	1	Percent	–

Figure 4. Three aggregate gradings used in laboratory investigation.

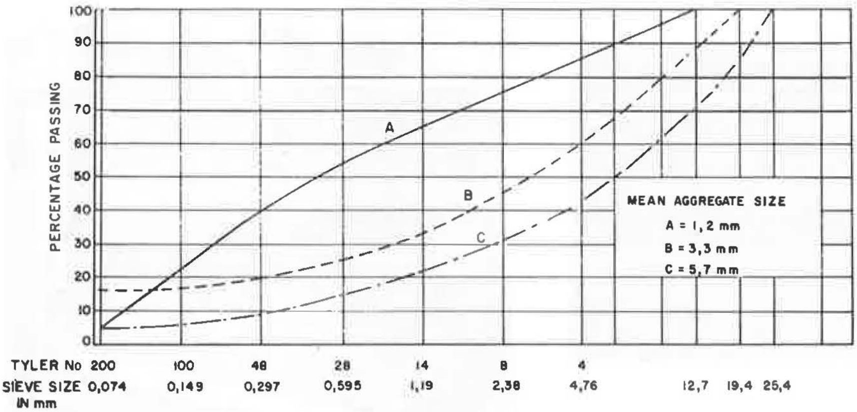


Table 3. Results of physical and chemical tests on concrete used in study.

Physical Test	Value	Chemical Analysis	Percent
Standard consistency (percent)	26.3	SiO_2	21.59
Initial set (min)	150	Insoluble residue	0.38
Final set (min)	195	Fe_2O_3	2.83
False set (mm)	1	Mn_2O_3	0.07
Expansion (mm)	1	Al_2O_3	4.68
Autoclave expansion (mm)	0.11	CaO	63.0
170 mesh residue (percent)	6.6	MgO	3.54
72 mesh residue (percent)	0.2	SO_3	2.47
Surface area (cm^2/g)	2,670	Loss on ignition (900 C)	0.80
Compressive strength	–	–	–
Vibration machine, 3 days (MPa)	28.9	Free lime	1.66
Vibration machine, 7 days (MPa)	38.8	–	–

Table 4. Results of water content and dry density tests.

Grading	Cement Content (percent by mass of aggregate)	Water Content (percent by mass of aggregate and cement)	Dry Density (kg/m^3)
A	3	7	2,115
	5	5	2,091
	5	7[a]	2,158[a]
	5	9	2,110
	7	7	2,126
B	3	6	2,270
	5	4	2,215
	5	6[a]	2,225[a]
	5	8	2,200
	7	6	2,259
C	3	5	2,345
	5	3	2,247
	5	5[a]	2,323[a]
	5	7	2,302
	7	5	2,339

[a]Optimum water content and maximum dry density at 5 percent cement content.

Figure 5. Relation between bending strength and mean aggregate size for lean-mix concrete.

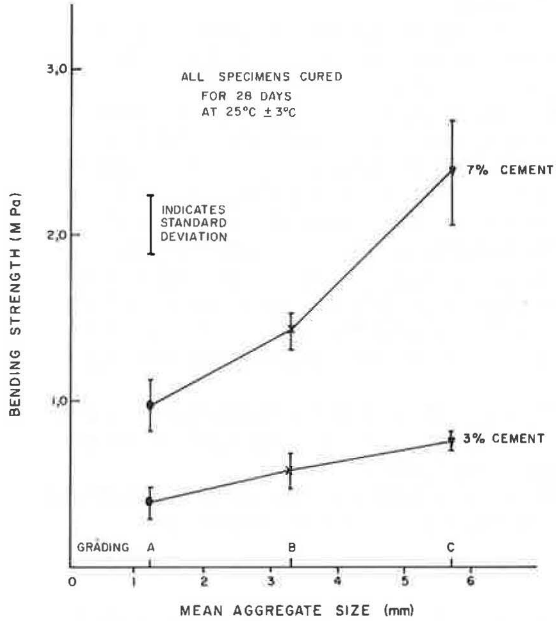


Figure 6. Relation between static elastic modulus in flexure and mean aggregate size of lean-mix concrete.

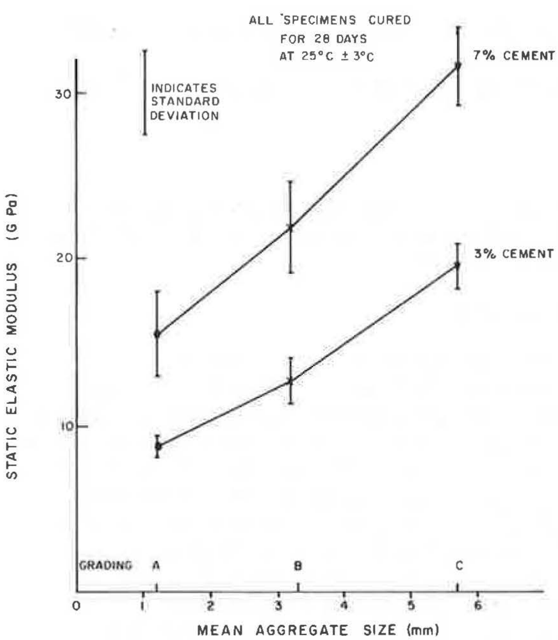
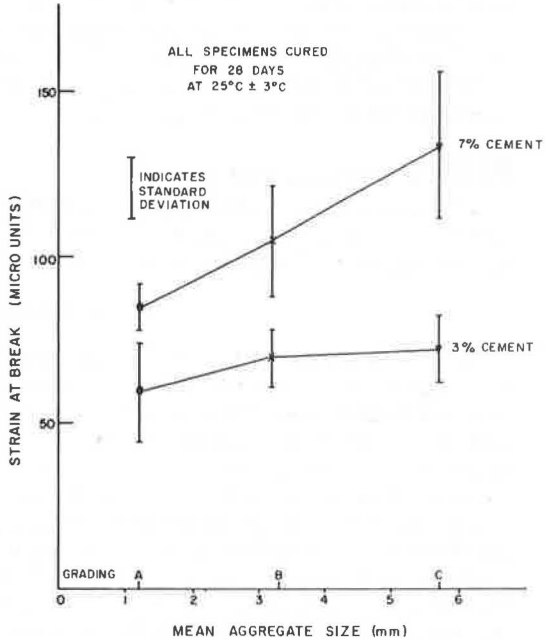


Figure 7. Relation between strain at break and mean aggregate size of lean-mix concrete.



25 C in an environmental cabinet for periods of 0, 7, 14, and 28 days. Gradings A, B, and C were investigated at cement contents of 3, 5, and 7 percent and at optimum water contents of 7, 6, and 5 percent respectively (Table 4).

To vary the water-cement (w-c) ratio, we made a second series of tests at a constant cement content of 5 percent where the water content was varied by 2 percent above and below the optimum value for gradings A, B, and C.

Certain difficulties were experienced in obtaining acceptable values of the strain at break. This was caused by the relatively weak material sometimes bending during the tensile test, thus giving completely meaningless strain values. So far as could be ascertained, this bending was not due to eccentric loading being applied. It resulted because, under tension, failure did not occur uniformly in a plane at right angles to the axially applied load, but rather microcracks formed on one or two faces of the prism and propagated slowly through the material. During this phase internal eccentric loading conditions prevailed, causing slight bending of the prism. This condition was immediately obvious from the load-deformation curve recorded on the X-Y recorder, and unacceptable results could thus be eliminated. An entirely satisfactory solution to this problem has not yet been found.

Values of strain at break varied considerably, and there was no meaningful statistical relation with respect to grading, w-c ratio, or drying period. However, average values and their coefficients of variation are given in Table 5.

The relation between direct tensile strength and w-c ratio for the various periods of drying for gradings A, B, and C are shown in Figures 8, 9, and 10 respectively.

Indirect Tensile Tests

Indirect tensile tests were performed on cylindrical specimens of lean-mix concrete compacted to approximately 96 percent modified AASHO density in a Hveem kneading compactor. Before testing, the specimens were cured for 7 days in sealed plastic bags at 25 C ± 1 C. For this series of tests the water content was kept constant at 7, 6, and 5 percent for gradings A, B, and C respectively, and the cement content varied over a wide spectrum of 3 to 12 percent.

Figure 11 shows the relation between indirect tensile strength and mean aggregate size for cement contents of 3, 5, 7, and 10 percent.

The relation between indirect tensile strength and w-c ratio for the three gradings investigated is shown in Figure 12.

Drying Shrinkage Tests

Shrinkage strains obtained at cement contents of 3, 5, and 7 percent are shown against mean aggregate size in Figure 13. The effect of w-c ratio on shrinkage strain for the three gradings investigated is shown in Figure 14.

DISCUSSION OF RESULTS

The first phase of this laboratory study, where specimens of lean-mix concrete were recovered from in-service pavements and tested in beam flexure, proved to be of great value in the planning of the subsequent study of laboratory-prepared specimens. Results of flexural bending strength and static elastic modulus obtained on the recovered specimens (Table 1) show variations by factors of 10 and 7 respectively. These large variations occurred in spite of the aggregate gradings used on the seven contracts falling within the envelope given by gradings B and C (Fig. 4) and the cement content being constant at the 4 percent level. An explanation of this large variation in properties could be that different curing, compaction, and construction techniques were used by the various contractors. It is important to note that the ratio of flexural bending strength to static elastic modulus is nearly constant, varying only by a factor of 1.6. This ratio is a function of the strain at break and is obviously much less affected by construction and curing techniques than the flexural bending strength and static elastic modulus.

Table 5. Analysis of strain at break under direct tension.

Material Composition	Average Strain at Break ($\mu\epsilon$)	Coefficient of Variation (percent)
All available results (all gradings, w-c ratios, and drying periods)	120.6	50
All results on grading A (all w-c ratios and drying periods)	129.7	43
All results on grading B (all w-c ratios and drying periods)	129.8	49
All results on grading C (all w-c ratios and drying periods)	99.3	56

Figure 8. Relation between direct tensile strength and w-c ratio of lean-mix concrete grading A.

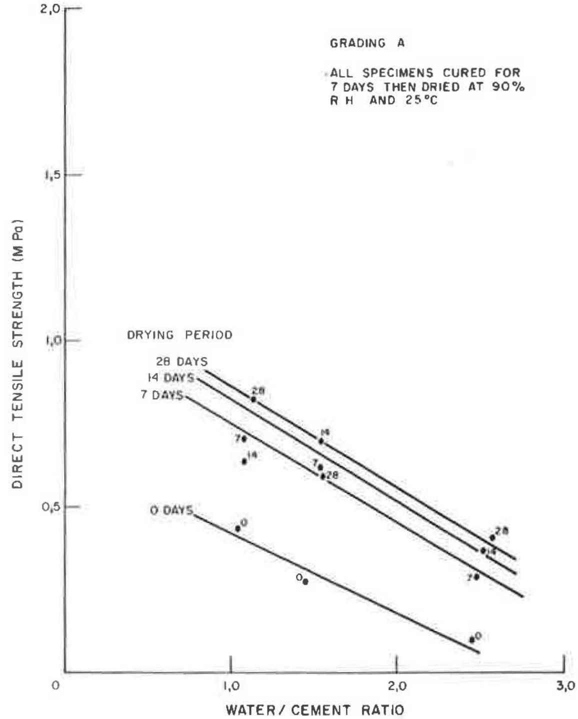


Figure 9. Relation between direct tensile strength and w-c ratio of lean-mix concrete grading B.

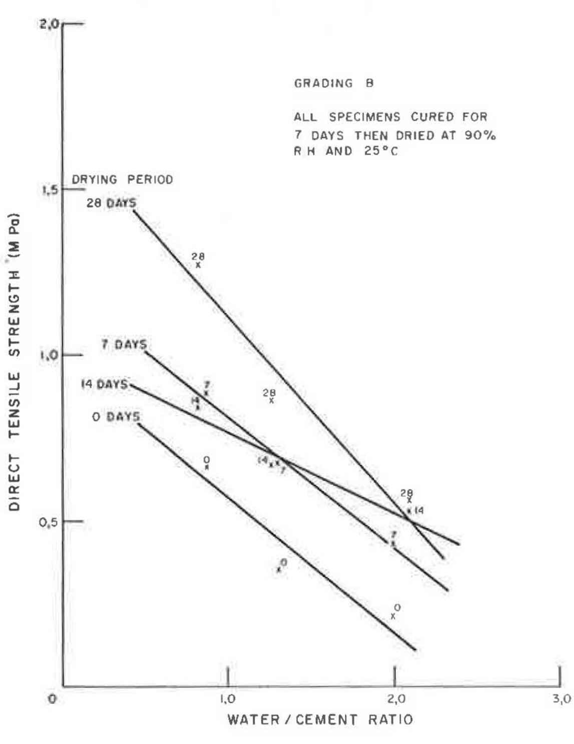


Figure 10. Relation between direct tensile strength and w-c ratio of lean-mix concrete grading C.

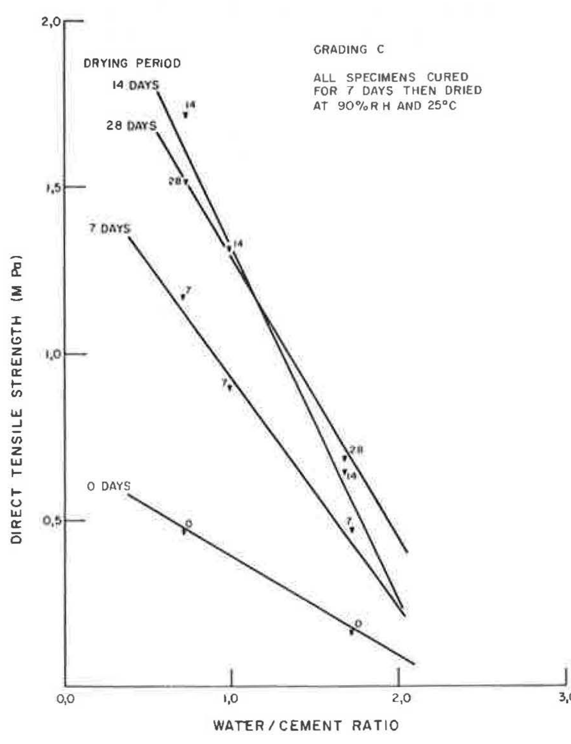


Figure 11. Relation between indirect tensile strength and mean aggregate size of lean-mix concrete.

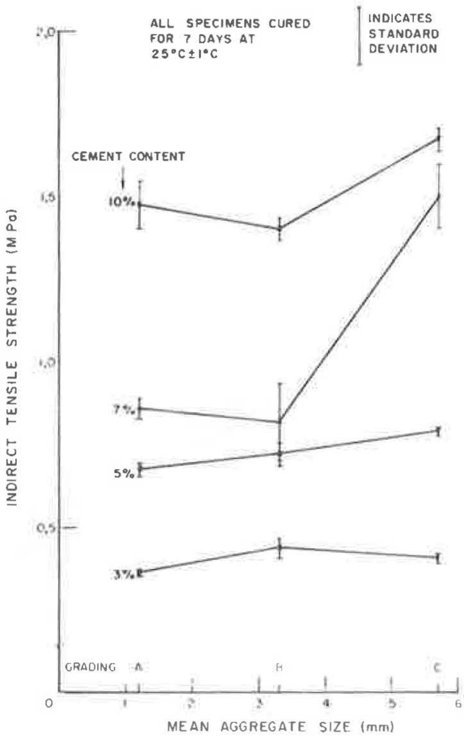


Figure 12. Relation between indirect tensile strength and w-c ratio of lean-mix concrete gradings A, B, and C.

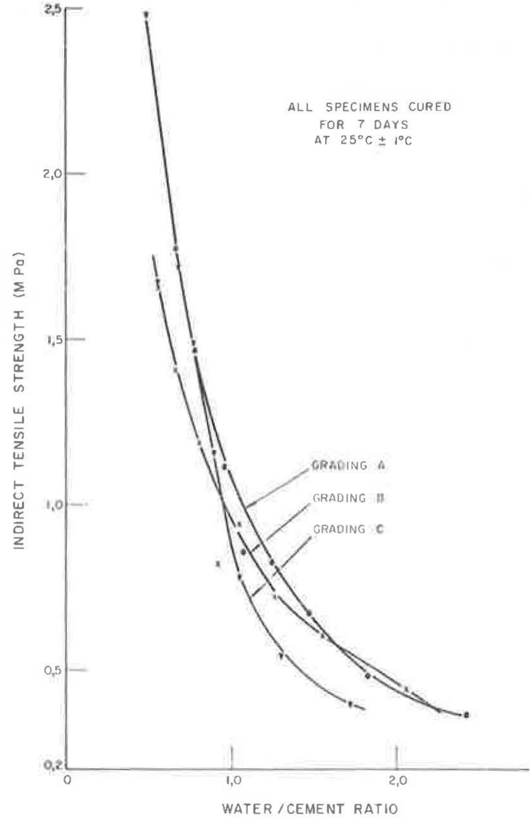


Figure 13. Relation between shrinkage strain and mean aggregate size of lean-mix concrete.

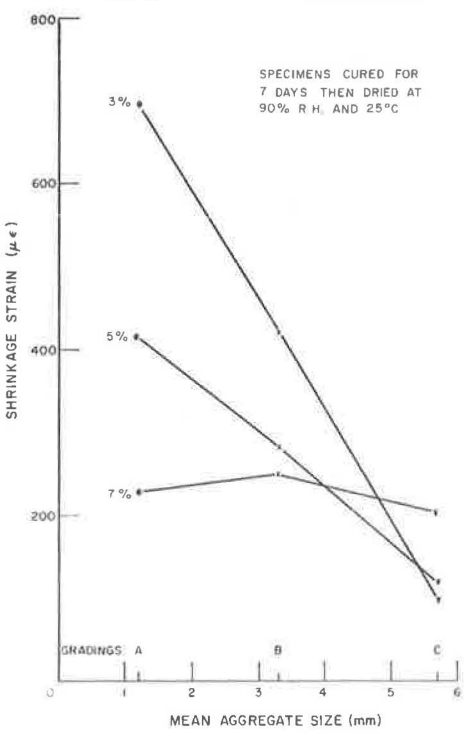
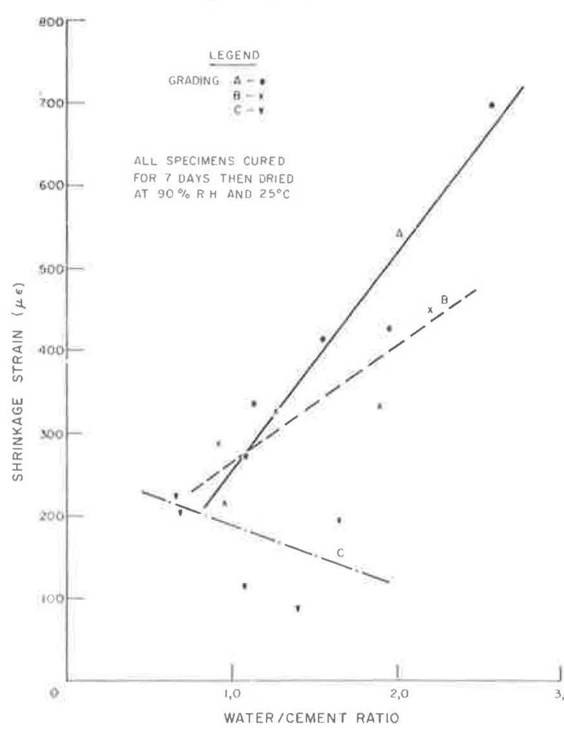


Figure 14. Relation between shrinkage strain and w-c ratio of lean-mix concrete gradings A, B, and C.



Because of the importance of the strain at break in the structural design of lean-mix concrete bases, part of the second phase of the laboratory study was aimed at investigating the effect of grading on this and other engineering properties of lean-mix concrete.

Results from the beam flexure test on laboratory-prepared specimens show that the strain at break for aggregate gradings A, B, and C at 3 percent cement content does not vary significantly; however, at the 7 percent cement content level, there is a significant difference among the strains for all gradings. Grading C gives the largest strain at break, approximately 130 $\mu\epsilon$ (Fig. 7). This value is not very different for the strain at break obtained from samples with an average age of about 1.5 years recovered from the in-service pavements that gave an average value of 145 $\mu\epsilon$ with a standard deviation of ± 28 $\mu\epsilon$. These results are important in terms of the structural design of lean-mix concrete bases under traffic loading and give a clear indication that improved performance will result from gradings that approximate grading C rather than gradings A or B. Grading C is the finest of the three gradings investigated when a cement content of at least 7 percent is used. Beam flexure tests also show a significant improvement in bending flexural strength and static elastic modulus for grading C, which has a mean aggregate size of 5.7 mm. This trend is more marked with the mixtures containing 7 percent cement than those of the 3 percent cement content level (Figs. 5 and 6).

Hughes and Ash (6), summarizing the findings of various researchers (7, 8), concluded that, when the workability of a concrete mix is kept constant by altering the w-c ratio, increasing the aggregate size results in a gain in strength for low cement contents; for high cement contents, however, a drop in strength results.

In these tests the cement content levels of 3 and 7 percent used may be regarded as low, and the workability of the mixes was kept constant by using the optimum water content, which gave a maximum density under modified AASHO compactive effort for mix gradings A, B, and C. From Table 4 it can be seen that the coarser gradings have lower optimum water contents, resulting in a decreasing w-c ratio at a constant cement content. The results obtained in this study therefore confirm the findings of the other researchers.

Direct tensile test results show a relation between tensile strength and w-c ratio; low w-c ratios give higher tensile strengths for all three gradings investigated (Figs. 8, 9, and 10). An improvement in tensile strength is also obtained on drying at 90 percent relative humidity; however, this is not very marked after 14 days. Here again, grading C has given the highest tensile strength, particularly after drying periods of 7 days and longer where the w-c ratio is below about 1.5.

Indirect tensile test results show a marked increase in tensile strength for grading C at cement content levels of 7 percent and above (Fig. 11). Below this level of cement content there is not a significant effect on indirect tensile strength with the three gradings investigated. The results of indirect tensile strength for various w-c ratios after a period of 7 days' curing, which is equivalent to specimens tested in direct tension without any drying, show the same trend; i.e., under these conditions a rapid increase in tensile strength is obtained for a decrease in w-c ratio. However, the variation of grading tested does not have a significant effect on the early tensile strength of the lean-mix concrete (Fig. 12). It should be noted that the indirect tensile strength values obtained are roughly two to three times the direct tensile strength values.

In terms of drying shrinkage cracking, the tensile strength and strain at break are of paramount importance. The strain at break values obtained in direct tension are very variable, there being no indication that either grading, cement content, or period of drying from 0 to 28 days has a significant effect on the level of strain at break.

Unrestrained shrinkage strain values vary considerably depending on grading and cement content; however, the effect of cement content is reduced as the mean aggregate size increases. For grading C, the effect of cement content is small as is shown in Figure 13. The w-c ratio has a significant effect on shrinkage strain, especially for gradings A and B; grading C is rather insensitive. It is of interest to note that, at a w-c ratio of between 0.8 and 1.0, the shrinkage strain is practically independent of grading and reaches a level of about 240 $\mu\epsilon$ (Fig. 14). From these results, it is obvious that grading C gives the lowest shrinkage strains for all cement contents and w-c ratios tested. The lowest strains obtained are in the order of 200 $\mu\epsilon$. From the results of both direct tensile and flexure tests, it is clear that, unless creep has a significant effect on the relaxation of tensile stresses during the drying shrinkage of lean-mix concrete, cracking will not be prevented but could be reduced by the correct selection of aggregate grading, cement, and water content.

CONCLUSIONS

Initial results from a laboratory study have been very interesting, and tentative conclusions may be made as follows:

1. The grading of the aggregate plays an important role in the strength and shrinkage characteristics of lean-mix concrete;
2. Of the three gradings investigated, grading C, having a mean aggregate size of 5.7 mm, has the highest strength and strain at break and lowest drying shrinkage strain values within the range of cement and water contents tested;
3. The levels of drying shrinkage strain are in excess of the strain levels that can be tolerated by lean-mix concrete, and it is therefore unlikely that cracking of lean-mix concrete bases can be prevented using ordinary portland cement and normal aggregate gradings suitable to meet the strength requirements demanded by heavy dynamic traffic loads;
4. From considerations of both flexural strength and the reduction of drying shrinkage cracking of lean-mix concrete, a coarse grading, such as grading C with a mean aggregate size of 5.7 mm, should be used at a cement content of about 7 percent with a w-c ratio of between 0.8 and 1.0; and
5. A revision of current South African specifications for lean-mix concrete should be considered with respect to grading and cement content requirements to increase the strength, elastic modulus, and bending strain at break and to reduce the potential drying shrinkage.

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