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Behavior and Performance of Aggregate-Cement Pavements

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Field performance of six aggregate-cement pavements at the Pennsylvania Transportation Research Facility was evaluated based on their rutting and cracking behavior and values of present serviceability index. Three types of aggregate were used in the aggregate-cement bases: limestone, slag, and gravel. The results of an analysis of relative performance among the three types of aggregate-cement materials are presented. The pavement response to an 80-kN [18 000-lbf (18-kip)] equivalent single-axle load was analyzed by using an elastic-layer computer program. The pavement response was related with the field performance data to establish limiting criteria. Among the three types of aggregate studied, limestone possesses the greatest strength and performs best in terms of rutting, cracking, and change in serviceability index. Gravel possesses greater compressive strength but smaller resilient modulus and fatigue strength than slag. The pavement with a base of slag aggregate cement performs better than that with a base of gravel aggregate cement. The limiting criteria developed were a maximum compressive strain of 230 μm/m (0.000 230 in/in) for limestone aggregate and 180 μm/m (0.000 180 in/in) for both slag and gravel aggregates, a maximum tensile strain of 45 μm/m (0.000 45 in/in), and a maximum pavement surface deflection of 0.30 mm (0.012 in) for all three types of aggregate studied. With these limiting criteria, it would be possible to design aggregate-cement pavements to withstand 1 million 80-kN equivalent axle-load applications without significant surface cracking or excessive rutting.

The use of cement-stabilized material in pavement structures has increased steadily over the past decades. Most available procedures for thickness design of cement-stabilized layers are largely based on empirical rules. Recognizing the need for developing an improved method of thickness design, the Committee on Structural Design of Roadways of the American Society of Civil Engineers identified steps required for achieving this goal (1). Among the steps identified are the establishment of failure criteria and performance studies in the field. A number of studies have provided information relative to these steps, including those by Bofinger (2), Shen and Mitchell (3), Larsen and Nussbaum (4), Larsen (5), Mitchell and Freitag (6), and Nussbaum and Larsen (7). However, most of these studies dealt with cement-stabilized soils; very few studies on cement-stabilized aggregates are currently available.

An investigation of the field performance of various stabilized base-course materials was conducted at the Pennsylvania Transportation Research Facility at Pennsylvania State University. The stabilized materials studied were aggregate cement, bituminous concrete, aggregate-lime-pozzolan, and aggregate-bituminous. Three types of aggregate were used in the aggregate-cement material. The performance of bituminous concrete and aggregate-lime-pozzolan pavements has been discussed elsewhere (8, 9). This paper presents the results of a performance evaluation for pavements that contain aggregate-cement base courses. Limiting strain and limiting deflection criteria are developed from field performance data and pavement response. The results provide information that is useful in the steps identified above.

AGGREGATE-CEMENT MATERIAL

The aggregate-cement base material was composed of six percent by weight of type 1 portland cement and 94 percent by weight of aggregate. The mix design was determined by the Bureau of Materials, Testing, and Research of the Pennsylvania Department of Transportation (PennDOT).

Three types of aggregate were used: crushed limestone, gravel, and slag. The limestone and gravel are natural to central Pennsylvania. The slag was a blast-furnace slag obtained from Johnstown, Pennsylvania. Some basic characteristics of the slag are summarized below ($1\ kg/m^3 = 0.062\ lb/ft^3$):

Characteristic	Measurement
Specific gravity	2.34
Weight	1237 kg/m^3
Absorption	4.9 percent
Sodium sulfate loss	0.78
Los Angeles abrasion loss	35.2 percent
Loss by washing	0

The gradations of the three types of aggregate are about the same. The average gradation is given below (1 mm = 0.039 in):

Sieve Size (mm)	Percentage Passing
51	100
19	96
9.5	79.6
4.75	66.2
1.18	25.6
0.15	6.7

The strength and fatigue properties of the aggregate-cement materials were determined on specimens both compacted in the laboratory and taken from the test pavements. The laboratory-compacted specimens were 15.2 cm (6 in) in diameter and 25.4 cm (10 in) in height and were molded to the same moisture content and dry density as those in the test pavements by using the modified American Association of State Highway and Transportation Officials (AASHTO) compaction effort. Table 1 summarizes the moisture content and dry density of the test specimens. The compacted specimens were embedded in the soil near the test pavements to cure under the same environmental conditions as the pavements. Core samples were 10.2 cm (4 in) in diameter and 20.4 cm (8 in) in height. They were taken from the test pavement after about 1.1 million 80-kN [18 000-lbf (18-kip)] equivalent axle-load (EAL) applications (EAL, as used in this paper, indicates an 80-kN load). The 1.1 million EALs were achieved after approximately 20 months of traffic operation. Test results indicate that the laboratory specimens had practically the same strength property as the core samples.

Triaxial compression test results with confining pressures up to 0.21 MPa (30 lbf/in^2) showed no significant effect of confining pressure on the compressive strength of the aggregate-cement material. Tensile strength was determined by using the double-punch test (8). Table 1 gives some results of the compression and double-punch tests as well as the average resilient modulus of the aggregate-cement materials. The repeated loading used for the determination of resilient modulus had a load duration of 0.1 s and a frequency of 20 cycles/min. Test results indicate that the resilient modulus was practically independent of confining pressures up to 0.21 MPa, deviatoric stress up to 0.41 MPa (60 lbf/in^2), and number of load applications up to 2000. In addition, the resilient modulus did not vary significantly for specimens cured at different durations (from two months to one year).

The fatigue property was evaluated by using the repeated-load flexure test on beam specimens. The beam specimens, which were compacted in the laboratory, were 8.25 cm (3.25 in) square by 46 cm (18 in) long. The beams were simply supported and were loaded with two symmetrically placed interior concentrated loads. The repeated loading had the same duration and frequency as that used in the repeated triaxial compression test. It was found that the fatigue property remained almost constant for different specimen ages, from two months to one year. Test results are given in Table 1 in terms of K_1 and K_2 of the following fatigue equation:

$$N = K_1 (1/\epsilon)^{K_2}$$

where N = number of load applications to failure and ϵ = tensile strain.

The material properties given in Table 1 indicate that, among the three types of aggregate studied, limestone aggregate is superior to slag and gravel in terms of strength, resilient modulus, and fatigue property. A comparison between the properties of slag and gravel reveals that the gravel has considerably greater strength than the slag. The resilient modulus of slag, however, is significantly greater than that of gravel. The difference in fatigue property between the slag and gravel is small, although the slag appears to be better in this area than the gravel. Thus, it is rather difficult to rank the slag aggregate cement and the gravel aggregate cement based merely on their laboratory properties.

TEST PAVEMENTS

Six pavements containing aggregate-cement bases were constructed at the Pennsylvania Transportation Research Facility. Among the six pavements, two were constructed in the summer of 1972 and the other four were built in the fall of 1975. Each of the first two pavements contained a 20.3-cm (8-in) limestone-aggregate-cement base. One of the last four pavements had a 10.2-cm (4-in) limestone-aggregate-cement base, whereas the other three pavements contained a 15.2-cm (6-in) base made up of all three types of aggregate. One of the first two pavements was in a cut and the other in a fill section. In fact, the pavement in the fill section was removed after about 1.1 million EALs. At that time, the last four pavements were constructed at the site of the removed pavement. Each of the first two pavements was 67.1 m (220 ft) long, and each of the last four was 30.5 m (100 ft) long. All six pavements were 3.7 m (12 ft) wide and contained a 6.4-m (2.5-in) bituminous concrete surface course and a 20.3-cm subbase layer.

The materials for the aggregate-cement bases were mixed in a central plant. For the 10.2-cm (4-in) and 16.2-cm (6-in) base, the aggregate cement was placed in one lift; for the 20.3-cm (8-in) base, the aggregate cement was placed in two 10.2-cm compacted layers. The top of the first lift was scarified before placement of the second lift. Compaction was accomplished by using a roller with three steel wheels for the breakdown and compaction operation and a two-wheel roller for the breakdown and compaction operation and a two-wheel tandem roller for the finish operation. When the finishing operation was completed, a bituminous seal coat was

Table 1. Properties of aggregate-cement materials.

Property	Limestone	Gravel	Slag
Moisture content (%)	7.7	8.7	11.2
Dry density (kg/m^3)	2296	2152	2001
Compressive strength (MPa)			
7 days	10.34	9.65	6.20
4 weeks	13.79	-	-
1 year	21.18	16.79	13.50
Tensile strength[a] (MPa)	2.07	-	-
Resilient modulus[a] (MPa)	25 000	17 000	22 000
Fatigue[a]			
K_1	6.56×10^{-21}	1.83×10^{-8}	4.48×10^{-9}
K_2	6.05	2.93	3.08

Note: $1\ kg/m^3 = 0.062\ lb/ft^3$; $1\ MPa = 145\ lbf/in^2$.
[a]Average values for specimens cured between 2 months and 1 year.

applied to the surface of the aggregate-cement base course.

In addition to the aggregate-cement pavements, the research facility also contained several other pavements that had different base materials and layer thicknesses. The subgrade soil at the research facility was predominantly classification A-7. The first two pavements were subjected to traffic approximately two months after completion of the base-course construction. For the last four pavements, traffic was started about one month after the base course was completed. The traffic consisted of a conventional truck tractor that pulled a semitrailer and a full trailer. After about 1.5 million EALs, another full trailer was added to increase the rate of loading. The axle loading was within the range of 80-107 kN (18 000-24 000 lbf). Complete information on design, construction, material properties, and traffic operation is available elsewhere (9, 10).

FIELD EVALUATION

Field testing of pavement performance was conducted periodically. Rut depth was measured biweekly every 12.2 m (40 ft) in both wheel paths by using an A-frame that was attached to a 2.1-m (7-ft) long base channel. Surface cracking was surveyed and mapped biweekly. Surface roughness was measured in both wheel paths by using a MacBeth profilograph. The roughness factors obtained from the profilograph data were converted into pavement present serviceability index (PSI) by using Equations 1 and 2 given in the paper by Wang and Larson elsewhere in this Record. In addition, data on surface deflections, pavement temperature, depth of frost penetration, air temperature, wind velocity, precipitation, and subgrade moisture were collected.

Figure 1. Rut depth versus EAL applications for limestone-aggregate-cement pavements.

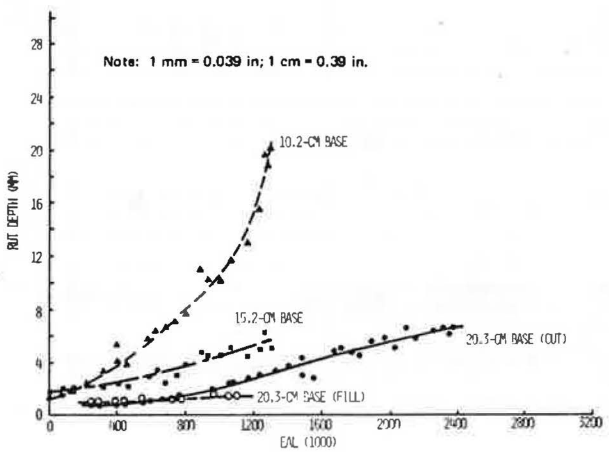
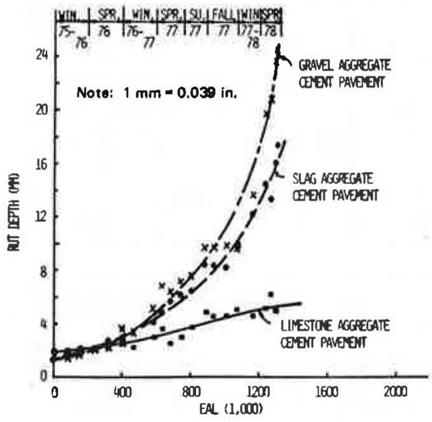


Figure 2. Rut depth versus EAL applications for three types of aggregate-cement pavement.



PAVEMENT DISTRESS

Rutting

Figures 1 and 2 show the variation of rut depth with number of EAL applications. The effect of base layer thickness on rutting for the pavements that contain limestone aggregate cement is shown in Figure 1. As expected, the pavement with a thick base course undergoes less rutting. The data on rut depth are quite consistent for the two 20.3-cm (8-in) base pavements, one in a cut and the other in a fill section. A comparison of the rut-depth data among the three types of aggregates under study is shown in Figure 2. Also shown in this figure are seasons within which the rut-depth data were taken. No clear indication is seen of significant seasonal variation in rutting. The figure indicates that, for the three types of aggregates studied, the limestone appears to have the greatest resistance and the gravel the least resistance to rutting.

It is generally recognized that rutting is primarily caused by the permanent deformation of each constituent pavement material. Because of the rigid and brittle nature of aggregate cement, permanent deformation in the aggregate-cement base is usually very small and can be neglected in the evaluation of rutting. Thus, for the three pavement systems that contain different types of aggregate but the same layer thicknesses, the difference in rutting would probably result from different permanent deformations in the subgrade. Permanent deformation in the subgrade depends greatly on the vertical compressive stress that is acting on the top of the subgrade. The vertical compressive stress decreases with increasing base-course modulus, other factors being equal. Since the resilient modulus of the aggregate cement decreases in order from limestone to slag to gravel, rutting would be expected to be smallest in the limestone, intermediate in the slag, and greatest in the gravel-aggregate-cement pavements.

According to Figures 1 and 2, for pavements that contain limestone-aggregate-cement bases, the number of EAL applications required for 6 mm (0.25 in) of rutting is approximately 760 000 for 10.2-cm (4-in) base, 1 800 000 for 15.2-cm (6-in) base, and 2 700 000 for 20.3-cm (8-in) base. For the pavements that contain 15.2-cm base, the number of EALs is about 900 000 for the slag aggregate and 800 000 for the gravel aggregate. These data will form the basis for the later development of limiting strain criteria.

Cracking

No cracking was observed in the fill section with the 20.3-cm (8-in) limestone-aggregate-cement base when the pavement was removed. In the cut section with the 20.3-cm limestone-aggregate-cement base, however, a transverse shrinkage crack developed across the entire pavement width about 3.2 m (10 ft) from one end of the pavement. This transverse crack was observed at approximately 1 million EALs, which was equivalent to about 16 months after construction. Figure 3 shows crack patterns mapped at about 2.4 million EALs. Longitudinal cracking appeared along the edge at approximately 1.4 million EALs. After about 1.8 million, some longitudinal cracks developed in the wheel path. The rate of growth of class 1 cracking is shown in Figure 4. All class 2 and class 3 cracking developed along the transverse crack. The total area of class 2 and class 3 cracking was about 3000 m^2/km^2 (3 $ft^2/1000$ ft^2).

In the pavement that contained 15.2-cm (6-in) limestone-aggregate-cement base, there was only one transverse shrinkage crack across the entire pavement width. This shrinkage crack was observed at approximately 1.27 million EAL applications. In the pavement that contained 10.2-cm (4-in) limestone-aggregate-cement base, the first transverse shrinkage crack developed about 3.2 m (10 ft) from one end of the pavement and was observed at approximately 84 000 EALs. The second transverse shrinkage crack developed at about the middle of the pavement at about 565 000 EAL applications. Longitudinal cracking appeared in both wheel paths after about 700 000 EALs. Class 2 cracking was not observed until about 1.07 million EALs. The length of class 1 cracking and the area of class 2 and class 3 cracking are shown in Figure 4. Figure 5 shows the crack pattern as it was mapped at three different times.

Figure 3. Crack patterns in pavement with 20.3-cm limestone-aggregate-cement base.

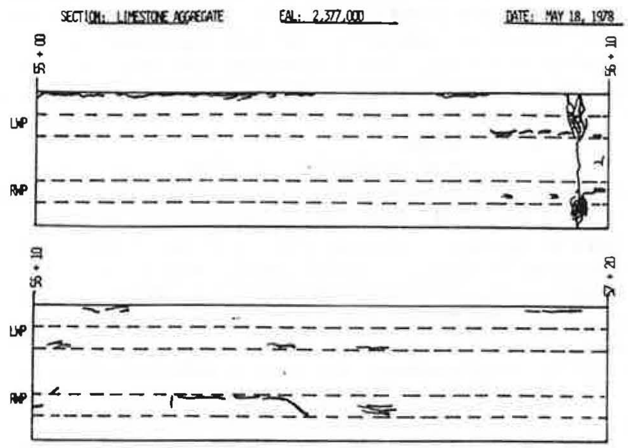
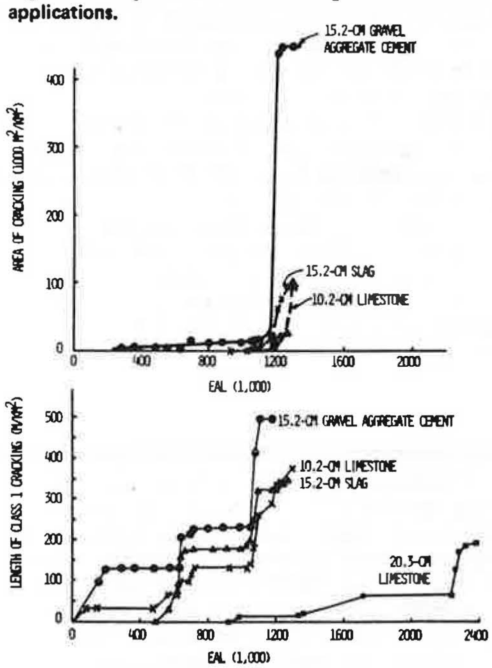


Figure 4. Length and area of cracking at various EAL applications.



Note: 1 m^2/km^2 = 0.001 $ft^2/1000$ ft^2;
1 m/km^2 = 0.0003 ft/1000 ft^2, and
1 cm = 0.39 in.

In the pavement that contained 15.2-cm (6-in) slag-aggregate-cement base, the first transverse shrinkage crack developed at about the middle of the pavement after approximately 565 000 EAL applications. At approximately 622 000 applications, a second transverse shrinkage crack appeared about 3.6 m (12 ft) from one end of the pavement. At almost that same time, longitudinal cracking developed in the wheel paths. Class 2 cracking appeared at about 1.2 million EAL applications. Figure 4 summarizes the length of class 1 cracking and the area of class 2 cracking. Figure 6 shows the growth of cracking.

For the pavement that contained 15.2-cm (6-in) gravel-aggregate-cement base, three transverse shrinkage cracks developed almost simultaneously during the early stage of pavement life. The locations of the three cracks are shown in Figure 7. The length of class 1 cracking and the area of class 2 cracking are shown in Figure 4.

Figure 4 shows that, for pavements of the same thickness that contained the three types of aggregate-cement base, cracking was greatest in the gravel-

Figure 5. Crack patterns at different EALs in 10.2-cm limestone-aggregate-cement pavement.

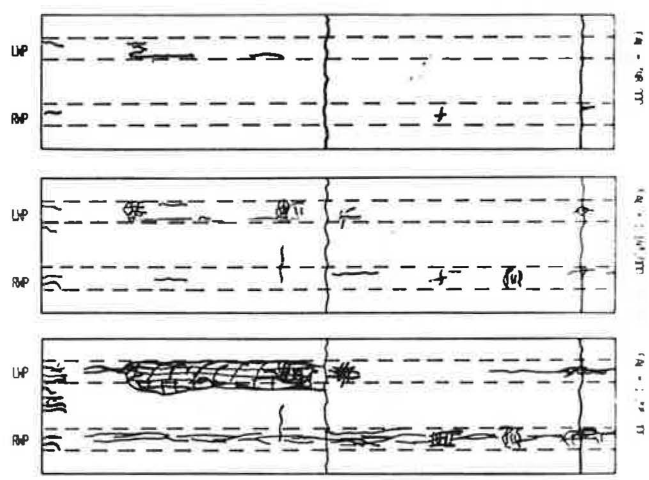


Figure 6. Crack patterns at different numbers of EAL applications in slag-aggregate-cement pavement.

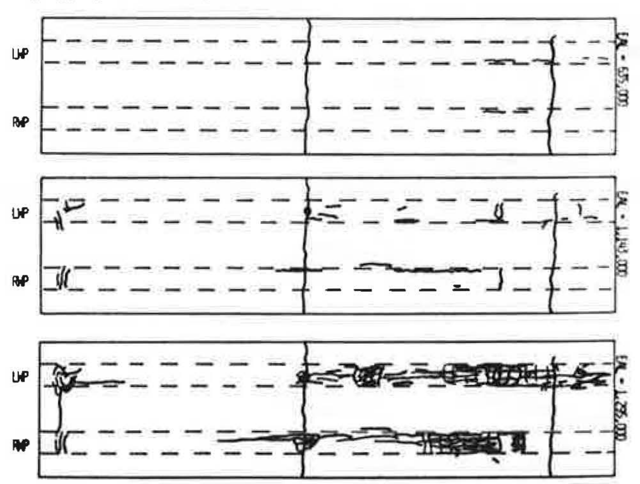


Figure 7. Crack patterns at different numbers of EAL applications in gravel-aggregate-cement pavement.

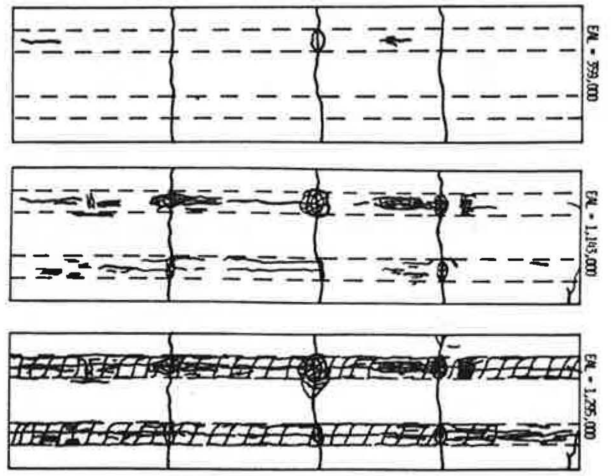


Figure 8. PSI versus EAL applications for limestone-aggregate-cement pavements.

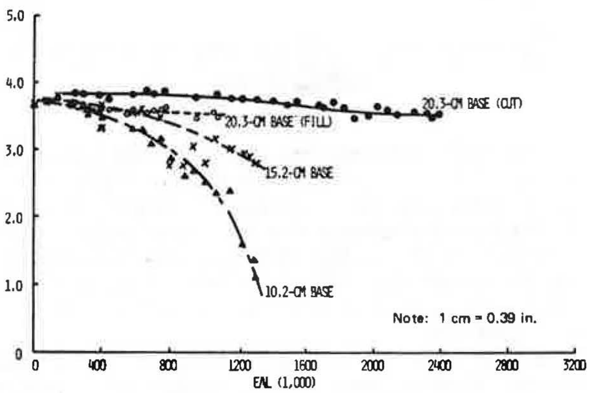
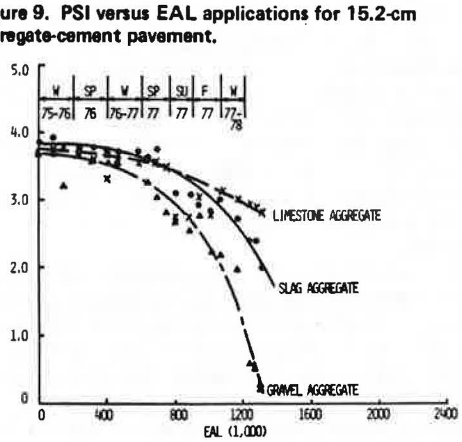


Figure 9. PSI versus EAL applications for 15.2-cm aggregate-cement pavement.



aggregate pavement, intermediate in the slag-aggregate pavement, and least in the limestone-aggregate pavement. Furthermore, the surface cracking appeared earliest in the gravel-aggregate pavement and last in the limestone-aggregate pavement. In addition, the rate of crack growth was fastest in the gravel pavement, intermediate in the slag pavement, and slowest in the limestone pavement.

These differences in cracking behavior among the three types of aggregate under investigation could be attributable to the difference in the fatigue and modulus properties given in Table 1. The fatigue life of a pavement system decreases exponentially with an increase in tensile strain at the bottom of the stabilized base course. The tensile strain decreases as the modulus of the base course increases. Since the resilient moduli of the three types of aggregate descend in order from limestone to slag to gravel, the tensile strain at the bottom of the base course will increase with type of aggregate in the same order and the fatigue strength will decrease with type of aggregate in the same order. Therefore, the combined effect of the difference in resilient modulus and fatigue strength would result in the observed cracking behavior.

Figure 4 also shows, as expected, that among the three limestone-aggregate pavements, more cracking developed in the pavement with a thin base course than the pavement with a thick base course. It is interesting to note that transverse shrinkage cracking developed in all aggregate-cement pavements except the pavement that contained a 20.3-cm (8-in) limestone-aggregate base, which was removed after about 20 months of traffic operation.

Transverse shrinkage cracking developed earlier than load-associated cracking. In most cases, the presence of shrinkage cracking aided to various degrees in the growth of load-associated cracking.

PAVEMENT PERFORMANCE

The variation of PSI with the number of EAL applications is shown in Figures 8 and 9. For all six pavements under study, the initial PSI values were almost the same, about 3.8. Figure 8 shows, as expected, that as the base-course thickness increased the rate of drop in PSI value decreased. For the 20.3-cm (8-in) base, the PSI values remained almost constant at 3.5 after about 2.4 million EAL applications. For the 10.1-cm (4-in) base, however, the PSI values dropped to 2.5 after only 1 million EALs.

Among the three types of aggregate studied, the drop in PSI value was fastest for the gravel aggregate, intermediate for the slag aggregate, and slowest for the limestone aggregate. This order of difference could be expected since development of both rutting and cracking was fastest in the gravel, intermediate in the slag, and slowest in the limestone pavements. The service life of the pavements to reach a PSI of, say, 2.5 was about 960 000, 1 200 000, and 1 400 000 EAL applications for the gravel, slag, and limestone aggregates, respectively. Thus, based on the performance data, the three types of aggregate can be ranked in the order limestone, slag, and gravel.

Both Figures 8 and 9 also show the seasons during which the PSI values were determined. It can be seen that, although the PSI values fluctuate within seasons, there is no apparent seasonal trend in the variation of PSI.

PAVEMENT RESPONSE AND LIMITING CRITERIA

The response of the test pavements to traffic loading was analyzed for the climatic condition that is most critical to pavement performance. The analysis was made by using an elastic-layer computer program and appropriate material properties. The computer program adopted was the BISAR program developed at Koninklijke Shell Laboratorium in Amsterdam. Material properties required were the modulus of elasticity and Poisson's ratio of each pavement constituent material. The elastic moduli of the aggregate cement are given in Table 1.

Table 2. Results of analysis of pavement response.

Type of Aggregate	Pavement Layer Thickness (cm)			Maximum Tensile Strain (μm/m)	Maximum Compressive Strain (μm/m)	Maximum Surface Deflection (mm)
	Surface	Base	Subbase			
Limestone	63.5	10.1	20.3	65.0	288.0	0.400
	63.5	15.2	20.3	42.2	171.5	0.301
	63.5	20.3	20.3	28.5	107.5	0.240
Slag	63.5	15.2	20.3	46.1	185.5	0.311
Gravel	63.5	15.2	20.3	54.4	216.0	0.330

Note: 1 cm = 0.39 in; 1 μm/m = 0.000 001 in/in; 1 mm = 0.039 in.

Figure 10. Maximum compressive strain at top of subgrade for EALs at 6.4-mm rutting.

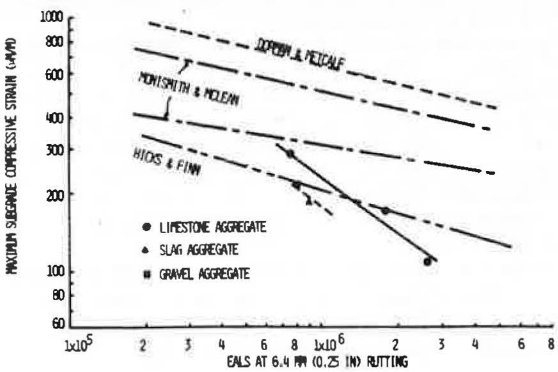


Figure 11. Maximum tensile strain at bottom of base course versus EAL applications.

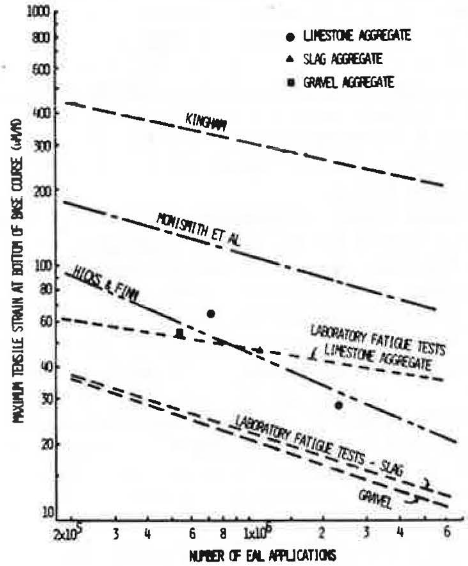
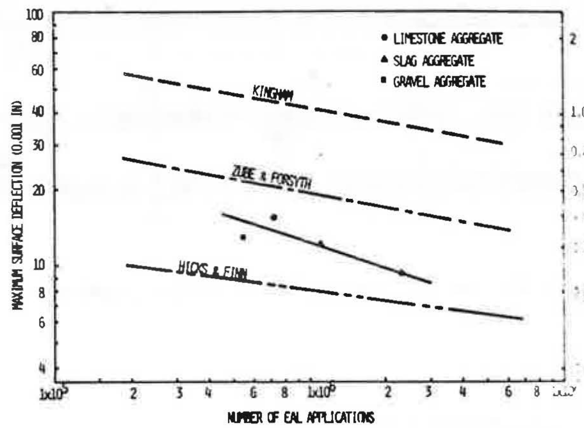


Figure 12. Maximum surface deflection versus EAL applications.



The Poisson's ratio of the aggregate cement was taken at 0.20, according to the results of other researchers (11, 12).

The subgrade moisture data indicated that the highest subgrade moisture content occurred around late spring and early summer. At this time of the year, the average subgrade moisture content was approximately 21 percent and the average pavement temperature was about 21°C (70° F). For these temperature and moisture conditions, the elastic moduli of the bituminous concrete surface, crushed-limestone subbase, and subgrade soil were 965 MPa (140 000 lbf/in^2), 331 MPa (48 000 lbf/in^2), and 69 MPa (10 000 lbf/in^2), respectively (13). Poisson's ratios were 0.40, 0.40, and 0.45 for the surface, subbase, and subgrade materials, respectively.

The traffic loading used was an 80-kN EAL on dual wheels with a tire pressure of 552 kPa (80 lbf/in^2). Results of the response analysis are summarized in Table 2. Pavement response was related to performance by using a base of 1 million EALs in order to develop limiting strain criteria. This level of EAL application was adopted because it is widely associated with 20-year pavement life.

In Figure 10, the number of EALs required to produce 6.4-mm (0.25-in) rutting for each pavement concerned is related to maximum compressive strain in the subgrade. A rut depth of 6.4 mm is used because it has been widely adopted for developing limiting strain criteria (14-16). According to Figure 10, the limiting compressive strain at 1 million EALs approximately equals 230 μm/m (0.000 230 in/in) for the limestone-aggregate-cement pavement. An extrapolation is needed for slag and gravel because only one test pavement for each of the two types of aggregate is available for analysis. It is estimated that the limiting compressive strain for slag and gravel equals about 180 μm/m (0.000 180 in/in).

The number of EALs at first appearance of significant cracking decreases with increasing maximum tensile strain at the bottom of the base course; this follows the trend of the laboratory fatigue curve shown in Figure 11. Among the four data points available, the data point for the pavement with the 20.3-cm (8-in) limestone-aggregate-cement base falls below the laboratory fatigue curve, which indicates that the laboratory fatigue test results overpredict the number of EALs required for fatigue failure in the field. Similar overprediction was also encountered at the San Diego test road (12) and in the performance analysis for the bituminous concrete pavements at the Pennsylvania research facility (13). Among the several possible reasons previously discussed in the literature (13), the effect of weathering could be a plausible one, since this pavement section had been exposed to severe weather conditions longer than the other three pavements. Figure 11 also includes the results obtained by other researchers (14, 16, 18) for different base materials. The data points scatter around the finding of Hicks and Finn (14), and the limiting tensile strain at 1 million EAL applications equals about 45 μm/m (0.000 45 in/in) for all three types of aggregate cement studied.

In Figure 12, maximum surface deflection is related to EALs based on the number of axle loadings at the first appearance of significant surface cracking. The test results are bracketed between the findings of Hicks and Finn (14) and Zube and Forsyth (19). The figure indicates a limiting maximum surface deflection of approximately 0.30 mm (0.012 in) for all three types of aggregate-cement pavement for a life of 1 million EAL applications.

SUMMARY AND CONCLUSIONS

The behavior and performance of six pavements that contained aggregate-cement bases were evaluated. Three types of aggregate were used in the aggregate-cement bases: limestone, slag, and gravel. Performance data were collected on PSI, rutting, and cracking. Pavement response to 80-kN EALs was analyzed by using the BISAR computer program and appropriate material properties. The response was then related to the performance data to establish limiting criteria.

Among the three types of aggregate studied, limestone possesses the greatest strength and resilient modulus. Pavement that contained limestone-aggregate-cement base performed much better in terms of rutting, cracking, and change in PSI than did pavements with the other two types of base materials. Gravel aggregate has greater compressive strength but lower resilient modulus and fatigue strength than slag aggregate. Pavement that contained slag-aggregate-cement base performed better than that with the gravel aggregate. The limiting criteria developed can provide a basis for designing aggregate-cement pavements to withstand 1 million 80-kN EAL applications without significant surface cracking or excessive rutting.

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