R-202

MICHIGAN
STATE HIGHWAY DEPARTMENT
Charles M. Ziegler
State Highway Commissioner

CRACKING EXPERIENCE OF CONCRETE PAVEMENTS CONTAINING SLAG COARSE AGGREGATE

Results of 1953 Survey

L. T. Oehler

E. A. Finney

Research Project 46 B-20

(An Investigation of Slag in Concrete Pavements)

Research Laboratory
Testing and Research Division
Report No. 202
December 31, 1953

CRACKING EXPERIENCE OF CONCRETE PAVEMENTS CONTAINING SLAG COARSE AGGREGATE
Results of 1953 Survey

This report contains the results of an authorized field condition survey to determine the crack experience of concrete pavements built with slag coarse aggregate in comparison with that of concrete pavements constructed with other types of coarse aggregates - for instance, gravel or limestone.

The survey was made between October and December, 1953 by personnel of the Research Laboratory at the request of W. W. McLaughlin, Testing and Research Engineer with approval of H. C. Coons, Deputy Commissioner-Chief Engineer. An earlier investigation concerned with the relative cracking of concrete pavements constructed with slag, gravel, and limestone aggregate is reported in Research Laboratory Report No. 96 dated May 2, 1947. The results of the 1947 report will be referred to in this study for the purpose of comparing the rate of cracking with age.

The results will be presented in the order in which the field condition surveys were made - namely:

1. All concrete pavement projects contained in the Willow Run and Detroit Industrial Expressway systems which were surveyed in 1946-1947 with the exception of those resurfaced in 1953.
2. Sections of parallel outside traffic lanes on Dix Highway, US-25 from US-24 to Ecorse.
3. An all slag aggregate project on Gratiot Avenue between 8 Mile and 13 Mile Roads, built in 1947.

In all cases, the condition surveys consisted of a visual observation and recording of all types of cracking in each slab of the projects surveyed.

Willow Run and Detroit Industrial Expressway Systems

The concrete pavement projects covered by this survey are designated by project numbers on the schematic diagram in Figure 1. The types of aggregate used in each project are identified by different colors. The pavement projects resurfaced in 1953 are also shown in Figure 1.

The 1953 condition survey of the two expressways included 11.447 miles of slag aggregate, 0.944 miles of limestone aggregate, and 24.767 miles of gravel aggregate concrete pavement including both roadways. Pavements at bridge projects and at certain intersections are not included in total mileage. These projects were all completed between 1942 and 1944, which makes them approximately ten years of age.

Four of the gravel aggregate projects had uniform pavement thicknesses of 10 inches; the balance of the gravel aggregate projects were 9 inches thick. All of the slag aggregate projects were built with 9-inch thick pavement. Both types of pavement projects were built with contraction joint spacing varying from 20 to 25 feet and expansion joints placed at 120-foot spacing. The projects contain no steel reinforcement, and load transfer devices at joints were omitted in all of the projects. Most of the gravel aggregates came from American Aggregates Corporation at Green Oaks. The slag aggregate all came from Great Lakes Steel Co. at Zug Island.

Increase in average daily traffic volume is as follows:

Year	Westbound	Eastbound
1946	4792	4875
1952	7386	6352
Percent Increase	54	30

A summary of 1953 cracking data will be found in Table I. For comparative purposes, the 1946 crack data is presented in Table II. The data in Table I has been summarized, separating the 9-inch thick gravel aggregate projects from the 10-inch pavement in order that all comparisons will be on a more nearly equal basis.

Results of Survey

1. There is an appreciable difference in the cracking experience of pavements constructed with the three types of aggregates, in both the passing lane, and in the heavy traffic lane, for the past 10 years. As shown below and in Figure 2, the cracking in slag aggregate pavement is on the average about 3.5 times the cracking in gravel aggregate pavement.

Average Cracking Experience for 9-Inch Pavements

	Traffic Lane (per lane mile)	Rank	Passing Lane (per lane mile)	Rank
Gravel	1152 ft.	1	446 ft.	1
Limestone	1633 ft.	1.4	213 ft.	0.5
Slag	3564 ft.	3.1	2042 ft.	4.6

Projects constructed entirely of limestone aggregates were so few that their cracking experience data will be shown for information only. They should not be used for comparative purposes. There are several projects containing both limestone and slag aggregates. These projects were surveyed but not reported here because of the difficulty in separating the areas containing the respective aggregates.

2. The influence of pavement thickness is shown below. The cracking in the 9-inch gravel aggregate projects is compared with that of the 10-inch thick gravel aggregate slabs.

	Traffic Lane (per lane mile)	Passing Lane (per lane mile)
9" gravel	1152 ft.	446 ft.
10" gravel	694 ft.	380 ft.
% Difference	66	17

The 9-inch pavement developed on the average for both roadways about 40 percent more cracking than the 10-inch pavement.

3. In order to show the rate of cracking between 1946 and 1953, it will be necessary to base the comparison on the number of cracked slabs rather than lineal feet of cracking per lane, since at the time of the 1946 survey, only the cracked slabs were counted. The comparison is shown below.

		Traffic Lane Cracked Slabs, in Percent			Passing Lane Cracked Slabs, in Percent		
		1946	1953	Diff.	1946	1953	Diff.
Gravel	(9)*	22	35	13	6	13	7
Limestone	(1)*	41	52	11	8	7	-1
Slag	(10)*	89	95	6	21	62	41

*Projects included

In the passing lane, the increase in cracked slabs of slag aggregate concrete has been approximately six times that of gravel concrete for the past seven years. In the traffic lane, it is evident that most of the slag aggregate slabs had cracked prior to 1946, with only an increase of 6 percent in the past seven years. In the case of gravel, only approximately one-third of all the slabs have cracked to date. The increase in cracked slabs is 13 percent for the past seven years. In the case of limestone aggregate, there has been an 11 percent increase in cracked slabs in the traffic lane while practically no change has taken place in the passing lane.

4. The influence of heavy traffic on pavement performance is clearly illustrated by the difference in crack experience for the traffic and passing lanes. Roughly, the cracking in traffic lanes is twice that of the passing lane as of this survey.

Dix Highway, US-25 from US-24 to Ecorse

This included a comparison of a slag aggregate concrete widening project F 82-3, C8 and C9, laid adjacent to and abutting a two-lane gravel aggregate concrete project (F 82-3, C5) constructed in 1928. The slag aggregate project was built in 1935. Only the two outside heavy traffic lanes were surveyed for comparative crack study. Construction information for the two projects will be found in Table III.

Aside from the type of aggregate used, the major differences in construction features of the two projects are: (1) the gravel aggregate project has 100-ft. expansion joint spacing and no intermediate joints, whereas in the slag aggregate project, expansion joints were placed opposite those in the gravel project and also one midway between, at 50-feet; and (2) plane of weakness joints were placed midway between expansion joints, thus creating a series of 25-ft. slabs throughout the slag aggregate project. The pavement thickness is the same for both projects.

TABLE III

Summary of Construction Information

	Gravel	Slag
Project	F 82-3, C5	F 82-3, C8 & C9
Year Constructed	1928	1935
Contractor	Wayne County	J. A. Mercier & Co.
Cement	Wyandotte 6 sacks/cyd	Wyandotte 6 sacks/cyd
Fine Aggregate	Greenville Gravel Corp.	Great Lakes Steel (Kelly Island)
Coarse Aggregate	Greenville Gravel Corp.	Great Lakes Steel (Kelly Island)
Reinforcement	5.4# per sq. yd.	5.4# per sq. yd.
Expansion Joint Spacing	100 feet	50 feet
Contraction Joints	None	None
Plane of Weakness Joint Spacing	None	25 feet (midway between expansion joints)
Pavement Thickness	10-8-10	10-8-10
Load Transfer at Expansion Joints	None	None
Modulus of Rupture 7 days	----	719 psi.
Modulus of Rupture 28 days	----	855 psi.
Compression Cylinders 7 days	3256 psi.	---
Compression Cylinders 14 days	3906 psi.	---
Compression Cylinders 28 days	5570 psi.	---

The survey included approximately 4.33 miles of pavement. A summary of comparative crack information is presented in Table IV. The data is shown graphically in Figure 3 together with pictures of surface condition.

Results of Survey

The survey brought out several interesting points:

1. Although the gravel aggregate pavement was eight years older than the slag aggregate pavement, the slag aggregate surface had approximately three times more lineal feet of cracks per mile-lane than the gravel aggregate pavement. This is significant because the gravel aggregate project was constructed with 100-ft. continuous slabs whereas the slag aggregate project was constructed with 25-ft. slabs. It is generally expected that the cracking of short slabs should be much less than that of long slabs but such is not the case here.

2. Roughometer measurements taken on the two types of aggregate pavement show that the roughness of the slag aggregate surface was approximately 36 percent greater than that of the gravel aggregate surface.

Roughness Data
Average inches per mile

Slag	278	
Gravel	204	Diff. 74, or 36 percent

Pictures showing the condition of both pavement surfaces are shown in Figure 3. Note cracking and faulting at cracks in the slag aggregate project (left) as compared with the gravel aggregate project (right).

Gratiot Ave., 8 Mile to 13 Mile Road, Project 50-27, C4

This project, built in 1947, was included in the study because it is of more recent design and is included in the Research Laboratory program for periodic condition surveys. Since we had the crack experience for 1948, it was not too difficult to make another survey in 1953 and include the project in this study to show the rate of cracking over the past five years. The summary of crack data is given in Table V. The data has been presented graphically in Figure 4.

This project is reinforced throughout and has contraction joints at 100-ft. spacing. Expansion joints were omitted except at intersections. The pavement is 10 inches thick. Slag aggregate is from Great Lakes Steel, Zug Island.

Results of Survey

1. The data show that the rate of cracking is increasing on the average of about 250 lineal feet per lane-mile, per year.

	1947	1948	1953	Increase
Lineal feet per lane-mile	0	286	1516	1230

2. Further, it is to be noted that in 1953, 85 percent of the slabs were cracked, whereas only 25 percent were cracked in 1948.

3. Cracking was uniformly distributed throughout the project. It has increased from a value of 0.4 cracks per slab in 1946 to 2.4 cracks per slab in 1953.

SUMMARY

1. In a study such as this, it is recognized that certain factors associated with the construction of the projects surveyed, other than the aggregate used, could affect their cracking experience to a certain degree. However, in view of the large amount of cracking of the slag aggregate concrete as compared to that of concrete made from other materials, it is believed that these factors are not significant in this comparison.

2. Cracking is the result of tensile stresses which exceed the ultimate flexural strength of the concrete. These tensile stresses are induced by wheel loads, warping of the pavement due to temperature and moisture changes, and subgrade resistance, acting either individually or in combination. In the determination of pavement thickness it is normally assumed that pavement concrete will be satisfactory provided it meets certain flexural strength requirements at 7 and 28 days and that the constituent aggregates and cement meet Department specifications. In Michigan, the required thickness for concrete pavement is based on the flexural strength properties of concrete made with natural aggregates. Aggregates which produce materially different flexural strength characteristics should receive special consideration in pavement design. On the basis of the cracking experience presented herein, slag aggregate is definitely one of these materials.

3. The problem of providing adequate flexural strength in pavements containing low strength aggregates may be approached in either of two ways -- first, by increasing the cross-sectional area of the pavement or, second, by possibly increasing the flexural strength of the concrete by the addition of greater amounts of cement per unit volume of concrete.

A. With respect to increasing the cross-sectional area of the pavement, the method set forth below may be used when designing a concrete pavement for a given service factor while permitting the use of constituent materials which, for normal cross-section, would result in pavement of inadequate strength.

Suppose, for example, that the flexural strength of concrete constructed with Material A (below normal) and Material B (normal) are f_A' and f_B' respectively. These values, divided by a suitable factor of safety (normally 2) will give the working stress for the two concretes as $f_A = \frac{f_A'}{F.S.}$ and $\frac{f_B'}{F.S.}$ respectively.

Then, using the corner load formula: $h = \sqrt{\frac{3\ W}{f}}$ (1)

h = thickness of slab in inches

W = one equivalent static wheel load, in pounds

f = the safe working flexural stress of the concrete, in pounds per square inch

it may be easily shown that the proper theoretical thickness of a pavement constructed, for example, with Material A can be related to the thickness of a pavement with Material B through the relationship of the flexural strengths of the two concretes in the following equation:

$$h_A = \sqrt{\frac{h_B^2\ f_B'}{f_A'}} \qquad (2)$$

Thus, the required thickness of a concrete pavement made with slag coarse aggregate (Material A) can be related to the thickness of a natural aggregate (Material B) concrete pavement through the flexural strength relationship between the two materials.

It is customary to assume the ultimate flexural strength for natural aggregate concrete to be 700 psi. which is reduced to a design working stress of 350 psi. by using a factor of safety of 2. This safety factor of 2 was established from fatigue tests on concrete beams made with natural aggregates a number of years ago by the

Illinois State Highway Department. To our knowledge, no such information on the fatigue properties of slag aggregate concrete is available. If we assume the design flexural strength of slag aggregate concrete to be about 15 percent below that of natural aggregate concrete, an approximate value obtained from recent studies at Ann Arbor involving Ford slag and limestone aggregates, see Table IV, then by means of equation (2), and for load conditions requiring a 9-inch thick pavement, we find that the thickness for the slag aggregate pavement should be 9.7 inches or, for practical purposes, 10 inches. In other words, we might logically increase pavement thickness at least one inch over normal requirements when slag aggregates are to be considered. This change would effect a 24 percent increase in flexural strength of the pavement.

B. Whether or not the addition of cement quantities in excess of 5.5 sacks per cubic yard to slag aggregate concrete will result in a material increase in flexural strength would have to be determined by controlled laboratory tests on the aggregate in question.

For normal air-entrained gravel concrete, data in the literature (Gonnerman, ACI Jr. June - Nov., 1944) indicates that a substantial increase in flexural strength with increase in cement content can be expected, amounting approximately to an increase of 10 percent per sack of cement within the range of 5 to 6.5 sacks. It would be logical to expect that a similar increase would result for slag aggregate concrete provided the strength of the aggregate was adequate.

With reference to Table IV, data furnished by Wayne County covering flexural strengths of field test specimens taken from Ford slag aggregate pavement projects laid in 1953, and containing 6.25 sacks of cement per cubic yard, shows flexural strengths less than those produced in 1953 laboratory tests at Ann Arbor on Ford

Table IV

Flexural Strength of Slag Concrete

Study	Type of Aggregate	Source of Aggregate	Cement Content	% A. E. Agent	Flexural Strength, psi 7 days	Percent	28 days	Percent
Ann Arbor Laboratory 1953	Limestone	---	5.5 sacks/cyd	5.2	706	0	783	0
	Slag	Ford	5.5 sacks/cyd	5.3	609	-14	680	-13
W. J. Worth Wayne Co. 1953 Field Beam Strengths	Gravel (27)*	Green Oaks	6.25 sacks/cyd		559	0	708	0
	Dolomite (95)*	---	6.05 sacks/cyd	5 to 7	648	+16	766	+8
	Slag (30)*	Ford	6.25 sacks/cyd		561	0	648	-8

*Number of specimens

Study	Mix	Grade	Slump, inches	Cement Content	7 days Reg.	A. E.	Percent Diff.	28 days Reg.	A. E.	Percent Diff.
Ann Arbor Laboratory 1953, Great Lakes Slag	1	B	1 - 2	5.00	647	532	18	734	641	13
	2	A	1 - 2	5.50	659	595	10	753	662	13
				Increase	+12	+63		+7	+21	
	3	B	3 - 4	5.45	612	550	10	716	629	12
	4	A	3 - 4	5.90	675	553	18	729	634	13
				Increase	+63	+3		+13	+5	

slag aggregate concrete containing 5.5 sacks of cement. The comparison can only be general, however, because the air content of the concrete represented by the Wayne County specimens varied from 5 to 7 percent, whereas the air content of the Ann Arbor specimens was controlled at about 5.3 percent. This difference in air content could account for the major difference in flexural strength reported by the two agencies.

Studies made at Ann Arbor in 1945, but with Great Lakes slag, indicate a slight increase in flexural strength with an increase of about 0.5 sacks of cement per cubic yard under comparable consistencies. See Table IV.

Unquestionably the overall durability of slag aggregate concrete would be improved to some degree by the addition of cement in access of 5.5 sacks per cubic yard. It can be demonstrated (see Figure 5) that for a 5.5 sack mix, the mortar in an uncrushed gravel concrete is richer in cement content than a corresponding mortar in a slag aggregate mixture consisting of 100 percent crushed particles. Due to the angularity of the crushed particles, there are more voids in a given volume, hence more mortar will be required to fill the voids in order to obtain a comparable workability. Further, this larger proportion of mortar in the mix, with the cement content unchanged, will in turn result in a higher water-cement ratio which would not be desirable from the standpoint of durability and flexural strength.

4. The fact that slag aggregate concrete is apparently sound even at the crack edges has given rise to the belief that the concrete, due to the inherent physical properties of the slag particles - namely, brittleness and softness, may fail more rapidly by fatigue than concrete made from other types of aggregate.

5. Another factor which might be associated with the unusual cracking characteristics of slag aggregate concrete is the relatively low thermal conductivity and high

moisture absorption of slag aggregates. It is logical to assume that these two properties under certain conditions may be instrumental in causing high localized tensile stresses in the slab. Such stresses, when combined with high load stresses, would no doubt influence cracking of the slabs at early ages.

Recommendations

When slag aggregates are approved for concrete pavement construction, it is recommended that the pavement thickness be increased over that which would normally be required for natural aggregates by a value of not less than 1 inch to compensate for apparent loss in flexural strength of slag aggregate concrete as manifested by high crack experience. Since the supporting ability of a concrete pavement varies as the square of the thickness, this one inch increase in thickness would compensate for an approximate loss in flexural strength of the concrete as follows: 8 to 9 inches - 27 percent; 9 - 10 inches - 24 percent; and 10 to 11 inches - 21 percent.

To augment the above recommendation, it is further suggested that the cement content per cubic yard be increased from 5.5 sacks to a minimum of 6 sacks to compensate for loss in mortar richness. This would offset to a certain degree the loss in mortar strength due to air entrainment and, in addition, it would impart greater durability to the concrete. The amount to increase the cement content should be determined from controlled laboratory tests.