IDENTIFICATION OF COARSE AGGREGATES PRONE TO SURFACE DETERIORATION AND D-CRACKING IN CONCRETE PAVEMENTS

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Coarse aggregates have long been recognized as potential sources of deterioration of concrete exposed to freezing and thawing action. Deterioration of pavements may take place as pitting, pop-outs, and varying extents of D-cracking. The negative effects of deleterious aggregates can occur even if the cement paste is protected by an adequate entrained air system.

The negative effects of coarse aggregates on the durability of concrete pavements have been observed in several Indiana pavements in which argillaceous aggregates were used. Two distinctive features were observed: first, damage appeared as intense surface deterioration, and second, damage occurred in one to two years after the construction of the pavements.

In all the surveyed cases, inspection showed that the failure plane occurred through a coarse aggregate particle, and there was no apparent damage originating in the surrounding cement paste. Construction records indicate that the concrete was air entrained, which suggests that the paste was reasonably well protected against freezing and thawing action. But by no means is protection provided for the coarse aggregate by air entrainment. The same pattern of surface failure was observed in different locations, but it was particularly accentuated in a cross over that was opened early to traffic and exposed to large amounts of deicers.

The occurrence of the problem in such a short period, the fact that those aggregates were accepted from an approved source, and the fact that they may occur in different proportions in production samples, made it necessary to perform further studies regarding their response to freezing action.

The argillaceous aggregates involved in the present study gave rise to severe surface deterioration of both concrete and bituminous pavements. However, at the present time, it is not known if the aggregate performance is acceptable in the deeper layers of the pavements. Likewise, it is not known whether or not, and to what extend, D-cracking will take place in the future. It is important to identify the primary causes of this problem in order to formulate some recommendations for the future use and identification of these and similar aggregates.

STATEMENT OF OBJECTIVES

Unconfined freezing and thawing losses of these argillaceous aggregates, saturated with water and with 5% NaCl salt solution, are presented in reference (1). The percent losses of some of those argillaceous aggregates are listed in Table I. From the inspection of these results, the relative severity of freeze-thaw cycled in the presence of salt solution is obvious. On the basis of these results and the reported field performance, the hypothesis is postulated that significant osmotic pressure contributed to the failure of the aggregates under consideration.

The main objectives of this research were as follows:

1. To determine the existence of any osmotic effect and its possible influence as a contributing cause of surface deterioration.
2. To analyze the response mechanism due to freezing of one rock specimen vacuum saturated with salt solution.

BACKGROUND

A previous research conducted by Shakoor (1) included collecting field core samples of selected surface deteriorated pavements, and sampling of the corresponding quarries that supplied the coarse aggregate. He also included the results of petrographic analyses and the determination of physical properties of those samples. The findings reported in that reference indicate that the aggregates involved in this type of failure are highly argillaceous. The clay mineral was classified as Iillite, and it was uniformly distributed in the aggregate.

Because of the possible association between the present problem and deicer scaling, the discussion of the later seems appropriate. Scaling results when "Concrete mortar of poor quality will crumble away with repeated freezing and thawing cycles, gradually exposing the coarse aggregate particles" (2).

Cordon (2) presented a detailed discussion of several theories and mechanisms to explain salt scaling. Experimental determination and further observations seem to support more than one hypotheses (3, 4, 5, 6). Some of the various hypotheses proposed to explain the failure mechanisms, attribute salt scaling to:

A. Crystallization pressure
B. Chemical reactions
C. Osmotic and hydraulic pressure
D. Thermal gradients

The first two were not found to be significant during experimental observations (5, 7). Snyder (8) suggested that thermal gradients in combination with hydraulic pressure are the most significant causes of salt scaling.

In this research, the importance of the osmotic pressure mechanism is reaffirmed; specifically, the build up of osmotic pressure that eventually exceeds the tensile strength of the coarse aggregate. In this regard, in 1955, Powers (9) stated:

> Experimental work has not yet revealed the relative importance of osmotic pressure. It need not be a major mechanism in ordinary freezing and thawing tests, for all the effects of freezing have been observed when freezable water contains only a trace of alkali. However, osmotic pressure may be a major factor in "Salt scaling". When the normal solute content is augmented in regions near the surface of the pavement by salts applied for ice removal, osmotic pressure in partially frozen capillaries may be the dominant source of stress. This is an inference, not yet checked experimentally.

By definition, "Osmosis is the phenomenon whereby solvent permeates a semipermeable membrane separating two solutions of different concentrations. A net flow of solvent occurs from the less to the more

concentrated solutions" (10). A semipermeable membrane is one that permits the flow of solvent but not the flow of solute.

EXPERIMENTAL WORK

In order to accomplish the objectives of this study, two laboratory experiments were designed. The first experiment was designed to determine the existence of any osmotic phenomenon through the argillaceous aggregates under study. The second experiment consisted of recording the state of strains during freezing of a test specimen vacuum saturated with salt solution.

First Experiment

Materials and Apparatus

Three rock samples designated as P, G, and CC-1, were used for these determinations. The first materials, sample P, was sampled from a quarry that provided aggregate for some of the surface deteriorated pavements under investigation. The other samples were included for the purpose of studying the possible dependence of the osmotic phenomenon on different pore size distributions. The pore size distribution of each material was determined by mercury porosimetry, and the detailed results are included in reference (11).

For the purpose of determining whether or not each selected materials was able to perform as a semipermeable membrane, it was necessary to design a testing device. Such a device should contain the concentrated solution inside, the testing specimen in one end, and a volume measuring pipette in the other end. The equipment and relative dimensions are shown in Figure I.

Specimen Preparation

Cores 1-3/8" diameter and 1.60, 3.93, and 1.70 mm thicknesses were taken from rock samples designated as P, G, and CC-1, respectively. All the slices were oven dried at 105!C for 24 hours and, after cooling to room temperature in a desiccator, each specimen was bonded with epoxy cement to one end of the tube, as shown in Figure II. After curing the resin for 24 hours, the specimen was de-aerated for 2 hours and vacuum saturated with salt solution for 2 more hours. The vacuum pump was then turned off and the specimen was allowed to saturate for one week under atmospheric pressure.

The testing procedure consisted of completely filling the acrylic tube with 5% by weight salt solution, and fixing tightly the pipette in its position. No air bubbles were left in the tube. Then the whole apparatus was placed in contact with distilled water; the initial pipette reading was taken, and the flow of water through the specimen was monitored by recording pipette readings and elapsed time. A running test is shown in Figure III.

Results and Discussion

The experiment was repeated using each of the three selected samples. The osmotic phenomenon was observed in only one case, sample P, which is a highly argillaceous aggregate with very fine capillary pores. The experimental results taken during nine days, volume of solvent permeating toward the more concentrated solution and corresponding elapsed time, are plotted in Figure IV.

The fact that osmotic pressure was observed in only one case suggests that, for that sample (P), an additional detrimental mechanism may arise during freezing and thawing if a salt concentration gradient exists. However, it is not known how important the effect of osmotic pressure is with respect to the hydraulic pressure mechanism. For the other two samples, G and CC-1, there would be no such additional disruptive pressure.

The different responses observed between samples P, and G and CC-1, can be explained as follows. According to Kesting (10), osmosis occurs if the barrier material has pore sizes within the range from 6 angstroms to 0.06 mm, approximately. Therefore, it is evident that osmosis takes place whenever there is a significant amount of pore sizes smaller than about 0.06 mm, which is the limiting value proposed by Kesting. The relative volume of pores smaller than 0.06 mm diameter, computed from the pore size distribution of samples P, G, and CC-1, is given in Table II.

Based on the previous findings, further analysis of the results presented in reference (1) was performed. Two data sets are particularly important. First, those cases in which the presence of 5% weight NaCl solution made very severe the freezing and thawing action in comparison with the use of pure water. Some of those laboratory results are indicated in the first two columns of Table I. Except for one case, the percent losses in pure water after 50 unconfined freeze-thaw cycles were less than 4%; the same aggregates in the presence of salt solution showed losses up to 50%. For these samples, the volume of pores smaller than 0.06 mm diameter, $\subseteq$ V(%), was computed and it was found to be a significant fraction of the entire pore size distribution, Table I.

The second data set corresponds to cores taken from surface deteriorated pavements. From the top of each core, pieces of aggregates that experienced failure were obtained for mercury porosimetry determinations. The fraction of pores smaller than 0.06 mm is also indicated in Table I. In all cases a significant proportion of such capillary pores was found.

The results presented in Table II, in connection with those presented in Table I, seem to support the occurrence of an osmotic effect in laboratory and field conditions. In both cases, the increased severity of the freezing and thawing action in the presence of salt solution was evident.

Second Experiment

A second experiment was designed to quantify any possible contribution of osmotic pressure to the state of strains already produced by hydraulic pressure after an initial freezing stage. For this purpose, two cylindrical specimens 2 inches long and 1-1/8" diameter were taken 1/2" apart from each other from the rock sample previously designated as P.

One cylinder was instrumented with thermistors for measuring the temperature in the center and on the surface of the specimen; the second specimen was instrumented with strain gages for measuring the strain changes during the freezing process. Both cylindrical specimens were vacuum saturated with 5% weight NaCl salt solution, before they were subjected to freezing action.

The details of the materials, apparatus, specimen preparation, instrumentation, and data recording equipment are presented in reference (11).

This experiment was conducted in two stages. In the first stage, the temperature was steadily dropped at a rate of 4 to 5 degree C/hr until initial freezing occurred; then, after an additional temperature drop, further cooling was stopped at about -14°C. In the second stage, the specimen reach the uniform temperature of the freezing chamber, and it was kept in that condition for several hours. During all the stages, simultaneous readings of the state of strains and temperature were recorded. The results are presented in Figure V.

Results and Discussion

The results of the second experiment provide direct evidence to support the hypothesis that, for the argillaceous aggregates under consideration, there exists an additional osmotic effect that contributes to the surface failure mechanism. The state of strains recorded during the two stages of the experiment is shown in Figure V. The relative significance of the osmotic pressure is supported by the steady increase of tensile strains while the temperature of the specimen remains practically constant.

For a temperature change of approximately 2°C (from -15°C to -17.3°C) the strain increment was more than 300×10^{-6} in a less than three hour period. This strain increment by itself, even assuming that no strains are due to hydraulic pressure, may be large enough to produce failure. It should be pointed out also that such strains would have been larger if the test had lasted longer.

The response of the specimen in the second experiment shows an interesting characteristic: the NaCl solution saturated specimen becomes an osmotic cell by itself once freezing starts. It means that, after a selective water freezing occurs, there is an increment in the solution concentration

in the unfrozen capillaries in the specimen. This, and the internal flow taking place due to the volume displaced by the freezing water, seems to give rise to concentration gradients within the specimen. As a consequence of such concentration gradients, osmotic pressure starts to build up inside the specimen. It should be recognized that osmotic pressure and hydraulic pressure are simultaneously present once freezing starts; but, after the temperature remains constant, the effect of the former predominates over the effect of the latter.

CONCLUSIONS

The occurrence of the osmotic phenomenon in the argillaceous aggregates under consideration has been discussed and experimentally verified. Likewise, the significance of osmotic pressure as a contributing factor to aggregate failure has been experimentally verified.

On the basis of the findings presented, the following conclusions are pertinent:

1. The simple testing procedure used to detect the ability of coarse aggregates to perform as semipermeable membranes can be used to identify coarse aggregates prone to surface deterioration in the presence of deicers. This test could be used instead of the more elaborate procedures involving confined or unconfined freezing and thawing.
2. Quantitative estimations using the Poiseuille equation, reference (11), show that high hydraulic pressures can be generated in a porous matrix whenever there is a significant volume of pores smaller than 0.06 mm. Therefore, the same simple test might be used to identify and reject coarse aggregates giving rise to D-cracking by the internal failure mechanism. Further theoretical analysis and experimentation using selected samples is desirable in this respect.

ACKNOWLEDGMENT

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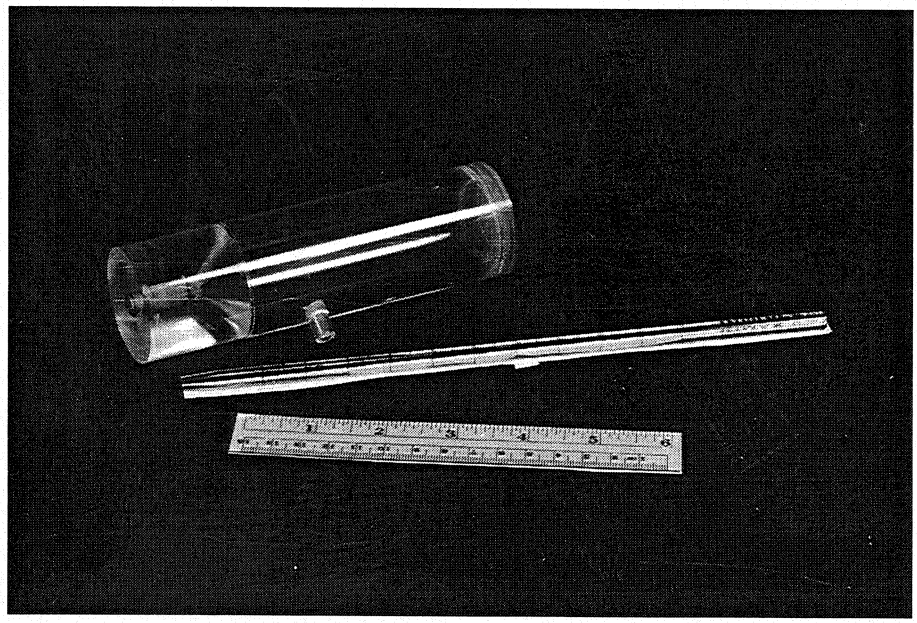


Figure 1. Apparatus Used for the Determination of the Osmotic Phenomenon

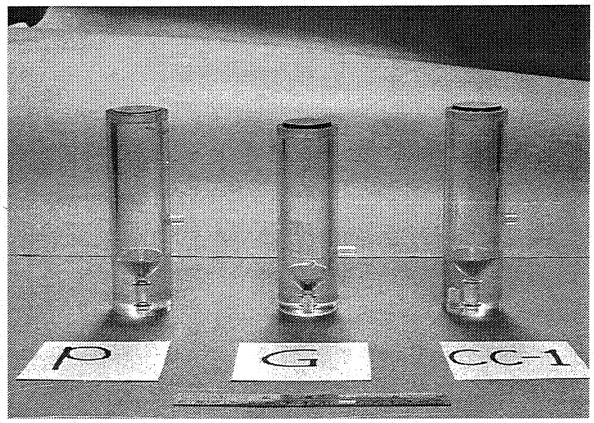


Figure 2. Test Specimens Bonded to Acrylic Tubes

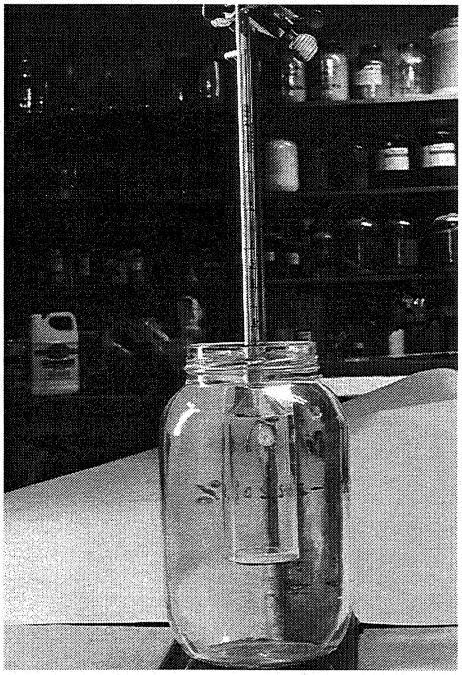


Figure 3. Test in Progress

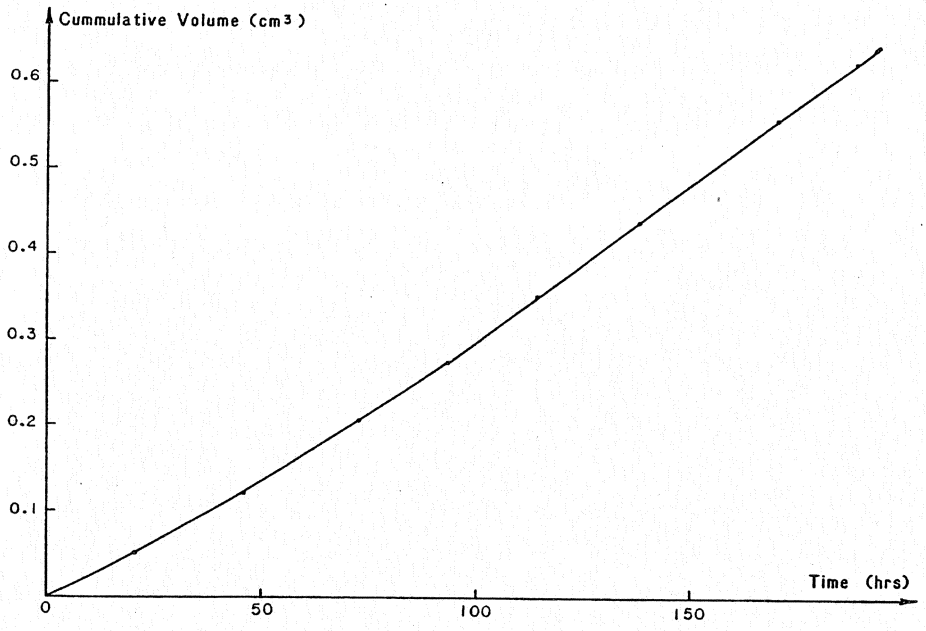


Figure 4. Volume of Solvent Permeating Toward Concentrated Solution, Against Time

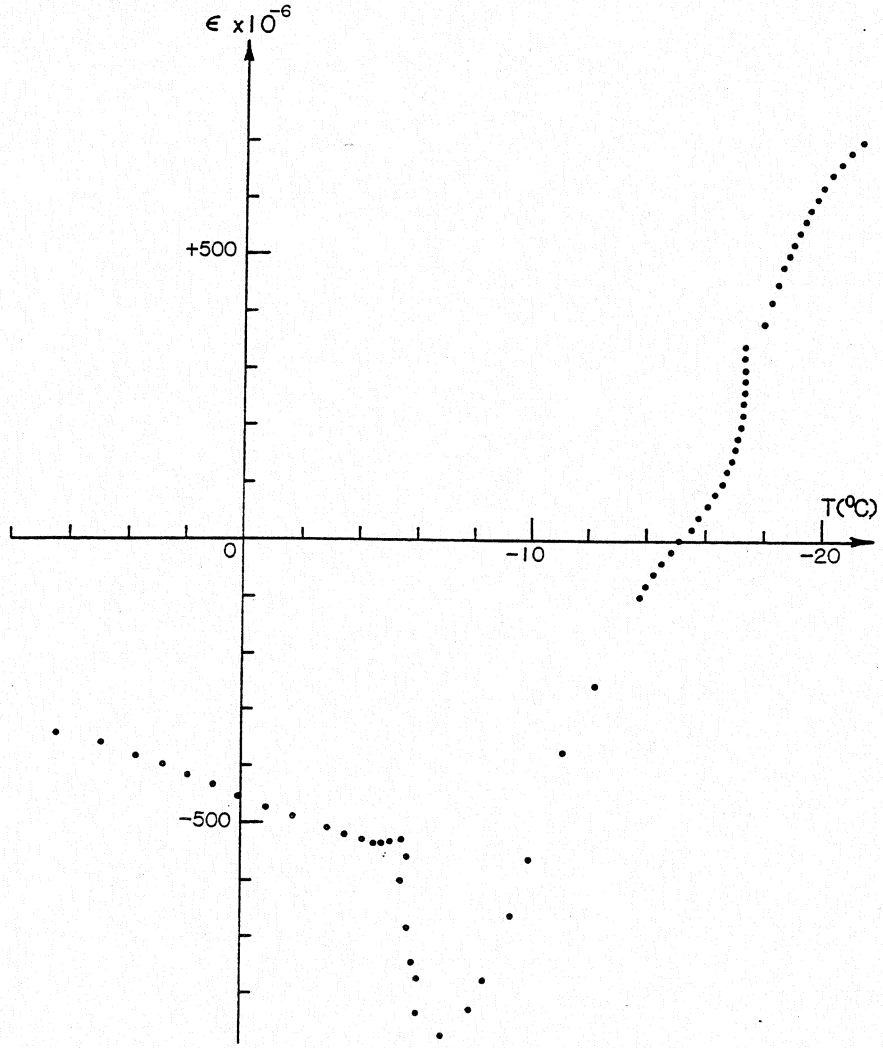


Figure 5. Strain Readings During the Two Stages of the Experiment

Table I Percentage of Pore Sizes Smaller than 0.06 m. Shakoor's data (24)

Sample	F&T Loss (%)** in water	F&T Loss (%)** 5% salt	ΔV(%)*
Laboratory Results			
T4	3.50	37.30	91.9
T7	3.68	47.37	90.0
K5	40.48	99.67	87.7
L2	3.53	43.23	76.4
L4	2.60	49.97	38.2
L5	1.56	36.25	38.5
L6	3.77	34.01	78.8
Field Cores			
I265-C2			36.1
I265-C3			59.9
I265-C5			85.0
US 24-SR115-C2			88.6
US 24-STN2-C3			76.2
US 24-STN2-C4			72.0
US 24-STN3-C6			79.1
US 24-STN4-C7			79.5
US 24-STN4-C8			77.9

* Volume of pores smaller than 0.06 μm diameter, expressed as percent of the total intruded volume.

** F&T losses after 50 cycles.

Table II Percentage of Pore Sizes smaller than 0.06 μm

Sample	V(%)*
P	85.0
G	6.0
CC-1	1.0

* Volume of pores smaller than 0.06 μm diameter, expressed as percent of the total intruded volume.

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US 24-STN2-C4			72.0
US 24-STN3-C6			79.1
US 24-STN4-C7			79.5
US 24-STN4-C8			77.9

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