which exhibited high stiffness with 12 percent fly ash and no lime.

2. For very low PI coarse sandy soil, stabilization with fly ash only was effective and resulted in substantial stiffness gains in the base layers of all the sections.

3. In comparing the test sections constructed on the low PI clayey soils, the optimum lime-fly ash ratios (yielding the highest stiffnesses) were found to be in the range of 0.10 to 0.50, using a minimum of 2 percent lime.

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The Effect of Deicing Salt on Aggregate Durability

WENDELL DUBBERKE and VERNON J. MARKS

ABSTRACT

Since 1962, the Iowa DOT has been using the methods of rapid freezing in air and thawing in water to evaluate coarse aggregate durability in concrete. Earlier research had shown that the aggregate pore system was a major factor in susceptibility to D-cracking rapid deterioration. There are cases in which service records indicate that on heavily salted primary roads, concrete containing certain aggregates show rapid deterioration while the same aggregates show relatively good performance on secondary roads with limited use of deicing salt. A five-cycle salt treatment of the coarse aggregate before durability testing has yielded durability factors that correlate with aggregate service records on heavily salted primary pavements. X-ray fluorescence analyses have shown that sulfur contents correlate well with aggregate durabilities with higher sulfur contents that produce poor durability. Trial additives affecting the salt treatment durabilities would indicate that one factor in the rapid deterioration mechanism is an adverse chemical reaction. The objective of the current research is to develop a simple method of determining aggregate susceptibility to salt-related deterioration. This method of evaluation includes analyses of both the pore system and chemical composition.

Iowa has 12,800 miles of Portland cement concrete (PCC) pavement including some roads 50 yr or older that have not been resurfaced or rehabilitated. On the other hand, some PCC pavement that exhibited high strength and quality immediately after construction deteriorated rapidly and required extensive rehabilitation at an age of less than 10 yr.

D-cracking, a type of PCC pavement deterioration attributed to the coarse aggregate in the mixture, was first recognized on Iowa's primary road system in the late 1930s. In general, the first sign of D-cracking is a discoloration or staining at the intersection of transverse and longitudinal joints. D-cracking will be used in reference to a rapid deterioration characterized by fine parallel cracks along joints, random cracks, or free edges of the pavement slab (see Figure 1). Except where noted, any mention of durability in this paper will be in reference to the effect of the coarse aggregate.

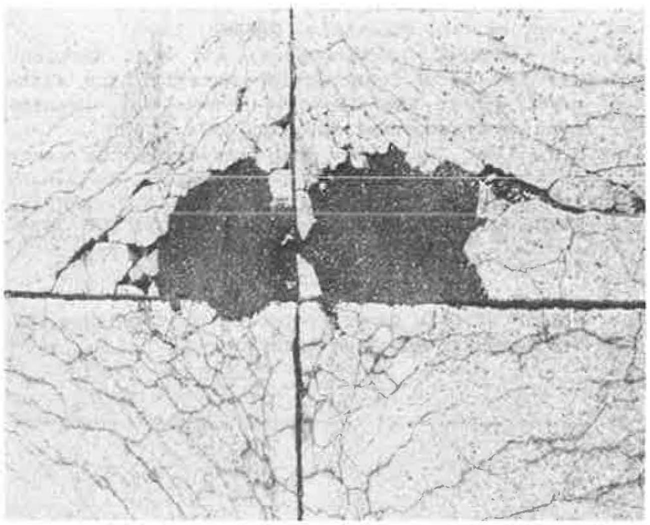


FIGURE 1 A close-up of D-cracking at the intersection of the transverse and longitudinal joints.

Extensive research into the mechanism and methods of preventing or reducing D-cracking has been conducted since 1960. This research has yielded substantial benefits in identifying the mechanism of D-cracking. Earlier Iowa research revealed that most D-cracking in Iowa is a distress that results predominantly from freeze-thaw failure in the coarse aggregate (1). In 1962, based on these findings, Iowa began using ASTM C666 Method B, Freezing in Air--Thawing in Water to evaluate the durability of concrete. Continual testing of Iowa carbonate coarse aggregates with a 90-day moist-cure, modified ASTM C666 Method B test correlated moderately well with performance of PCC pavements. The basic Iowa tests for quality of coarse aggregate for concrete are abrasion by AASHTO T96 and a 16-cycle water-alcohol freeze-thaw test (1).

Since 1978, much research has been conducted in regard to the pore systems of limestones used as coarse aggregate in PCC and their relationship to freeze-thaw aggregate failure (2,3). This research has shown that with some exceptions, most nondurable aggregates, when analyzed, exhibit a predominance of pore sizes in the 0.04-0.2-micron radius range. The Iowa Pore Index was adapted as a standard test in 1978 (2). It is a very simple test utilizing a modified pressure meter as a test apparatus. A known volume of oven-dried coarse aggregate is immersed in water in the base of the pressure meter. The amount of water injected into the aggregate under a constant 35 psi pressure is recorded. The volume of water injected in the period between 1 and 15 min after application of the pressure is the pore index. A pore index of 27 ml or more generally indicates a limestone susceptible to freeze-thaw D-cracking deterioration. Coarse aggregate pore sizes have been determined by using a quantichrome scanning porosimeter and using pressures from 0 to 60,000 psi. (It should be noted that current specifications restrict the use of nondurable stone and require higher quality aggregate.)

PROBLEM STATEMENT

These tests and specifications have been relatively effective in yielding durable PCC but exceptions continue to occur that result in rapid deterioration (12-15 years) of recently constructed pavement. These exceptions support the idea that there is at least one other major factor aside from freezing and thawing that contributed to rapid deterioration.

The normal concrete mix for Iowa primary pavement construction contains approximately 6.6 bags of cement/yd. The concrete mix normally used for secondary pavement contains approximately 5.2 bags/yd. Earlier Iowa research has shown that with all other factors equal, a higher cement content will produce a concrete with better durability than a concrete with a lesser cement content. A primary pavement with a higher cement content should provide better durability than a secondary pavement with a lower cement factor if the same aggregates are used in both. In Iowa, there are some aggregates that do not exhibit consistent service records. In 1962, a pavement containing a Pennsylvania crushed limestone from the Exline quarry was incorporated into a pavement on US-34, a primary highway in southern Iowa. Today, it exhibits severe D-cracking. A secondary road constructed in 1964 and containing the same Exline aggregate exhibits only staining and no D-cracking deterioration. In 1965, a D-cracking-susceptible gravel containing 70 percent carbonate was used in the construction of US-30, a primary highway in central Iowa. Today, it exhibits severe D-cracking. A secondary road containing the same gravel aggregate was constructed in 1966 and exhibits no indication of D-cracking.

Major differences in the winter maintenance practices of secondary roads and primary roads may explain the difference in performance of these two pairs of roadways. A substantial amount of sodium chloride deicing salt is used on primary roads, whereas there is limited use of deicing salt on secondary roads. Earlier research has documented the adverse effect of deicing chemicals and salts (4,5). Additional research is needed to define and explain the mechanism that accelerates the D-cracking deterioration on the primary roadways.

OBJECTIVE

The objective of this research is to develop simple, rapid test methods to predict the durability of aggregate in PCC pavement. The test method includes an analysis of the pore systems and chemical compositions of all aggregate sources.

SALT TREATMENT RESEARCH

A salt treatment preparation was developed in an effort to duplicate the observed accelerated deterioration on primary roads as opposed to secondary

roads. In Iowa, the coarse aggregates have historically exhibited the most influence on the resulting durability of PCC. For this reason, it was theorized that the salt may be adversely affecting the coarse aggregate. A salt treatment of the coarse aggregate was developed to be used before adding the coarse aggregate to the concrete mix. The salt treatment consists of five cycles of drying in an oven at 230°F for 24 hr, followed by immersion in a 70°F saturated solution of sodium chloride for 24 hr. The 70°F salt brine is poured over the aggregate immediately after it is removed from the 230°F oven. After the five cycles of salt treatment, the coarse aggregate is rinsed with clean tap water just before being incorporated into a concrete mixture.

The 90-day moist-cure modified ASTM C666 Method B testing of concrete mixtures with and without sodium chloride coarse aggregate pretreatment before being incorporated into the concrete has correlated very well with field performance. The durability of high-quality coarse aggregates such as those from the Alden or Mohs quarries (see Figures 2 and 3) have not been adversely affected by sodium chloride pretreatment. Even though the resulting durability may be somewhat below the concrete mix without sodium chloride pretreatment, it is not significant. Salt treatment of the limestone fraction of the Ames gravel (see Figure 4) results in an extremely rapid deterioration of the concrete under freeze-thaw testing. The Smith and Garrison quarries (see Fig-

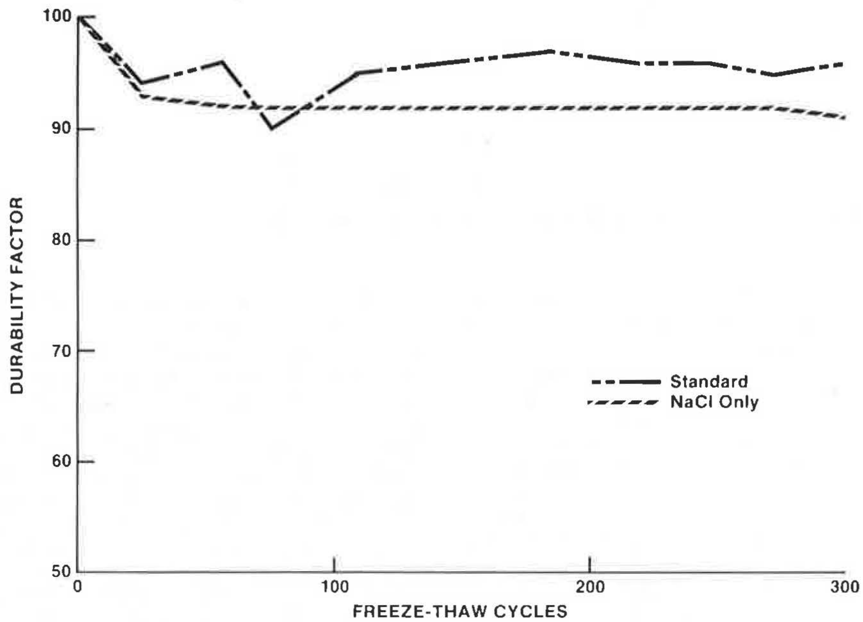


FIGURE 2 Alden durability factors.

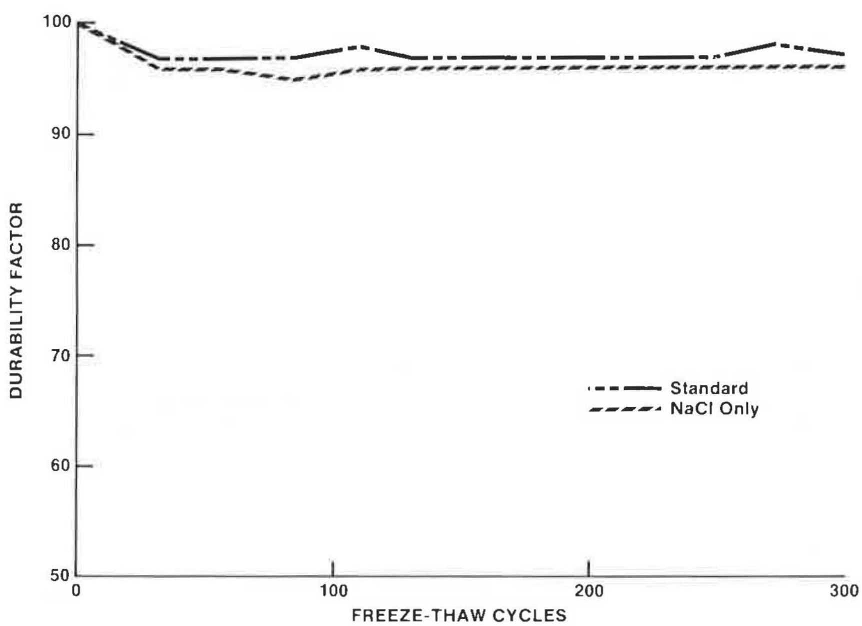


FIGURE 3 Mohs durability factors.

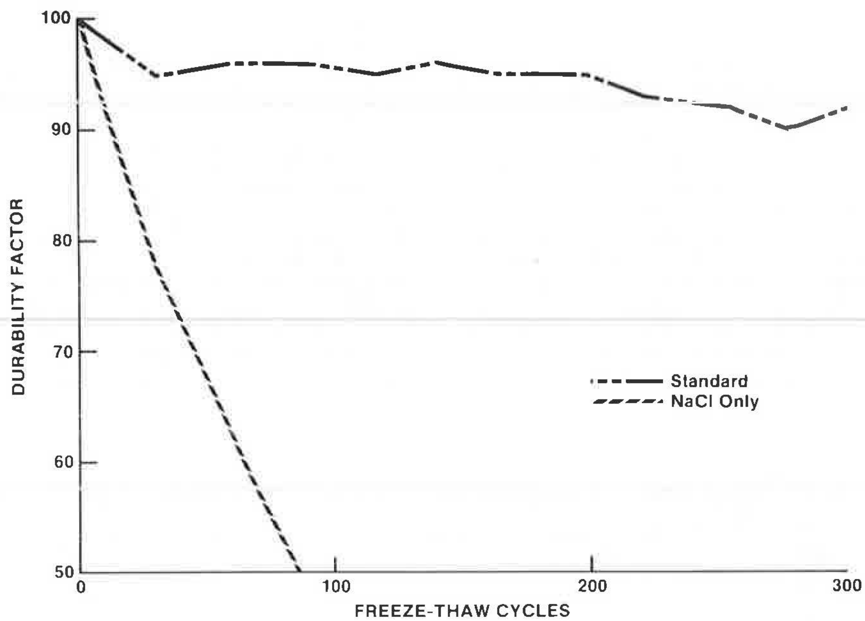


FIGURE 4 Ames Pit durability factors—carbonate fraction only.

ures 5 and 6) exhibit extremely accelerated deterioration after salt treatment. This again correlates very well with field performance.

Chemical analysis of the coarse aggregate has been conducted both with and without salt treatment to determine the amount of deicing salt retention. The sodium content increased from 0.05 percent without treatment to 0.09 percent after salt treatment on a Stanzel limestone and from 0.05 to 0.44 percent on a very porous Garrison dolomite. This salt treatment testing has generated much speculation as to the mechanisms involved. The most immediate reaction is that the salt would render the aggregate hydrophilic. The aggregate would thereby retain the water longer and contain more water at the time of freezing. The salt would also lower the freezing temperature slightly.

The Iowa standard ASTM C666 Method B freeze-thaw test on concrete made with a low-porosity, fine-grained Farmington Stone yielded a durability factor (DF) of 97 and a growth of 0.008 in. Concrete made with salt-treated Farmington stone had a DF of 28 and a growth of 0.164 in. After completion of the test, a slice was sawed through the 4-in. x 4-in. beams. Multiple fractures in the salt-treated aggregate particles are readily identified by visual observation (see Figure 7). No cracking occurred in the comparative aggregate without salt treatment. This cracking would appear to be a result of stresses generated by water freezing within the aggregate pore system or salt crystal growth. The salt treatment apparently alters the water-pore relationship to allow substantial damage from freezing.

In Iowa, the concrete beams are moist-cured for

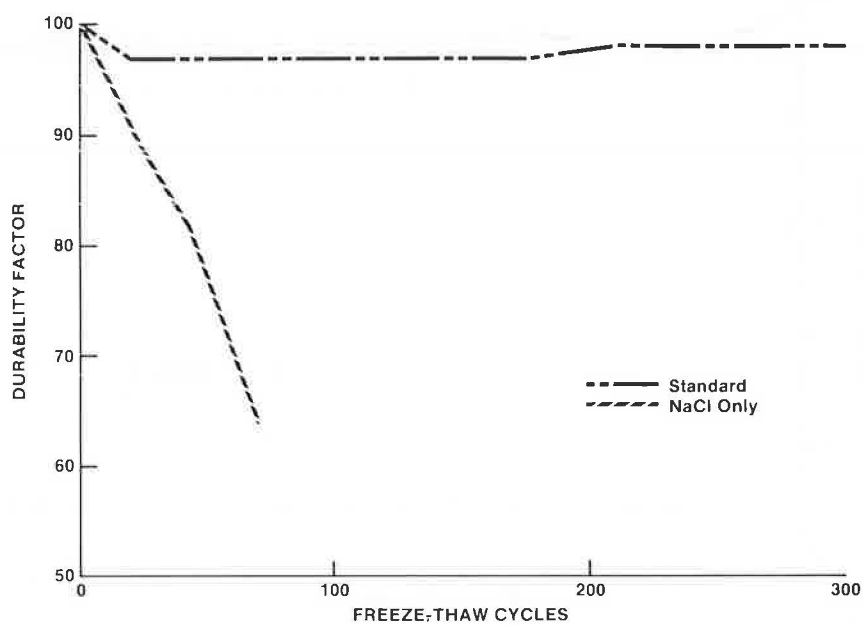


FIGURE 5 Smith durability factors.

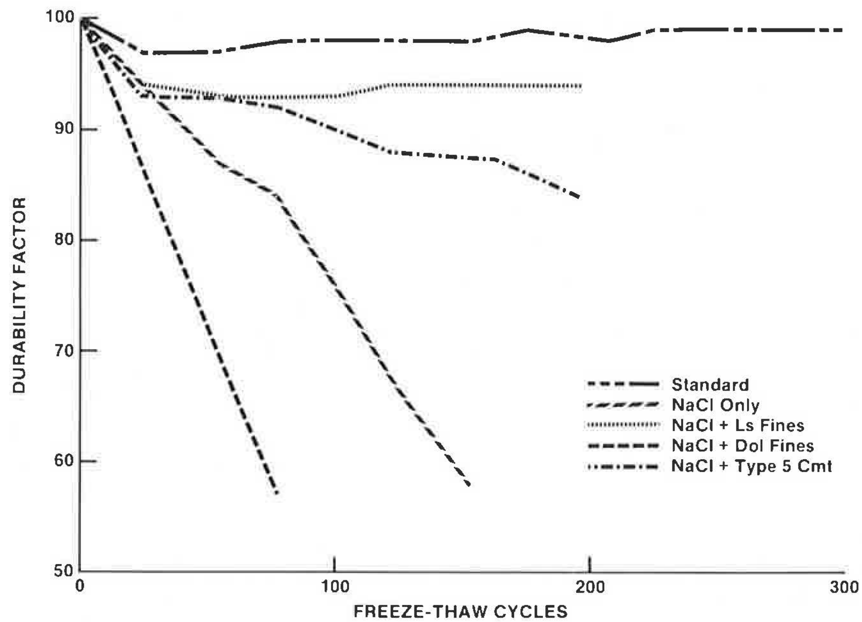
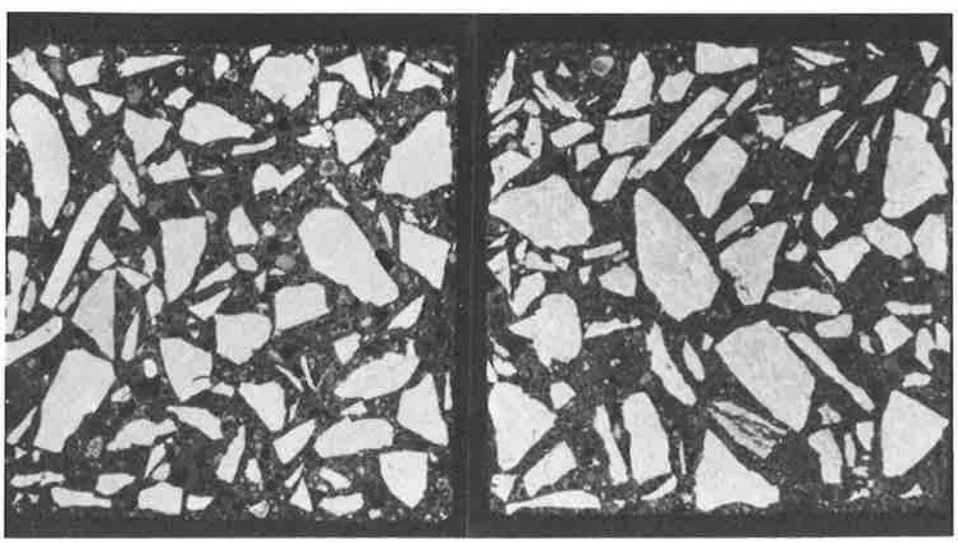


FIGURE 6 Garrison durability factors.

90 days before the ASTM C666 Method B freeze-thaw testing. The average results for testing of three beams constitute a sample on a particular concrete mix. Beams have been made where the only variation is the untreated coarse aggregate in comparison with concrete beams made with salt-treated aggregate. The nondestructive testing of the concrete is based on the dynamic modulus, which according to ASTM C-215, is intended to detect significant changes in the concrete because of freeze-thaw cycles. The initial sonic modulus of many untreated aggregates have been compared with those of treated aggregates. The beams made with untreated aggregates (15 samples) yielded an average initial sonic modulus of 1,800 and the beams made with treated aggregate yielded an average modulus of 1,750. There was no significant difference in the weight of the beams. This would indicate that even during the cure period, the properties of the concrete made with salt-susceptible aggregate were detrimentally affected by the salt treatment.

X-RAY ANALYSIS OF AGGREGATE CHEMISTRY

There is a wide variation in the adverse effect of salt treatment on concrete durability as noted earlier and shown in Figures 2 through 6. This variation did not always relate to the pore system, so a further analysis of the aggregate chemistry was conducted by using x-ray analysis systems available at Iowa State University. The x-ray fluorescence system has been used to evaluate the elemental composition of various aggregates. X-ray diffraction techniques were used to determine the mineral compo-



Salt Treated Aggregate Beam Standard Beam

FIGURE 7 Sawed cross-sections of concrete beams made with Farmington Stone showing multiple fractures in salt-treated aggregates.

sitions of the aggregates. The scanning electron microscope has been used to observe both the pore sizes and crystal sizes in the aggregates in addition to elemental chemical identification, distribution, and analysis. X-ray fluorescence has been used to determine magnesium, sodium, iron, sulfur, silica, calcium, potassium, and aluminum contents of most coarse aggregates used in Iowa concrete. These chemical analyses have been compared with service records of pavements constructed with the various coarse aggregates. The sulfur content yielded the best correlation (inverse) with performance of the aggregates that had passed the standard Iowa specifications. The sulfur content correlates very well with aggregate durability in heavily salted primary pavements, especially when magnesium is present.

The scanning electron microscope has been used to further investigate the sulfur content in aggregates that exhibit accelerated deterioration on salted primary roads. Energy plots from the scanning electron microscope (see Figure 8) of the salt-affected aggregates exhibit similar distribution of iron and sulfur. This would indicate that iron-sulfur particles in the 1- to 2-micron range are uniformly dispersed throughout the nondurable aggregate. The iron and sulfur are very likely present as pyrite or marcasite. (These finely divided 1- to 2-micron black specks were identified as pyrite in some nondurable Iowa ledges in 1961 by Donald W. Kohls in a University of Minnesota thesis.) The adverse reaction of the pyrite and liberated sulfur has been cited in other research (6-11).

EFFLORESCENCE ON QUARRY FACE

Salt treatment testing of crushed stone from the Lillibridge Quarry of Cerro Gordo County in northern Iowa would indicate that it would be nondurable in concrete. The Lillibridge stone has an exceptionally high but widely dispersed sulfur content. Whitish efflorescent deposits commonly occur on quarry faces after a lengthy dry period. A chemical analysis of the deposit identifies this material as calcium sulphate and magnesium sulphate. It would appear that there is a chemical reaction where the sulfur is released from the iron sulfide. This deterioration of the stone may also occur after being incorporated into concrete and thereby reduce its durability.

ADDITIVES AFFECTING SALT-TREATMENT DURABILITY

After verifying that the salt treatment preparation did cause the ASTM C666 durabilities to correspond to field performance, it was decided to conduct research to determine if various ingredients would either adversely or beneficially affect the durability factor. Two additives and a special cement were used (see Figure 6) to ascertain their effect on concrete durability. The first was a Type V (sulphate-resistant) portland cement instead of the regular Type I. Type V cement (4.8 percent tricalcium aluminate) did exhibit a significant beneficial effect on the concrete durability after the coarse aggregate was treated with salt.

Five percent of fine porous limestone with very low magnesium content was added to a concrete mixture, which yielded a greater beneficial effect than did the Type V cement. The addition of 5 percent porous dolomite fines (high magnesium content) yielded an adverse effect on the salt-treated durability beams. The alteration of the durability of concrete produced with salt-treated aggregate by the addition of carbonate fines would indicate an effect on the concrete chemistry. From this research, it would appear that magnesium may be a substance that promotes an adverse effect in durability of concrete mixes containing porous, pyritic, carbonate coarse aggregate.

FINE AGGREGATE AFFECTING SALT-TREATMENT DURABILITY

The Iowa DOT began aggregate durability research with a Conrad automatic freeze-thaw machine in 1962. Aggregate service records at that time indicated that the coarse aggregate in the PCC pavement was a major factor. A limited investigation of the effect

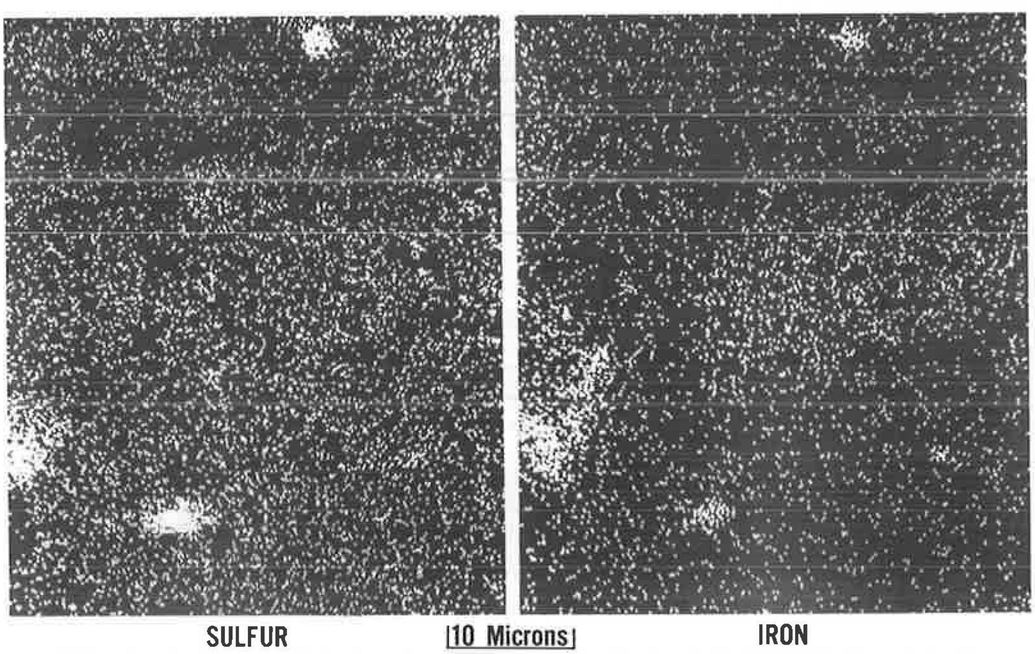


FIGURE 8 Scanning electron microscope energy plot of sulfur and iron.

of fine aggregate on concrete durability using the ASTM C666 Method B procedure produced insignificant differences, so a local, conveniently available sand was used as a standard.

Recent durability testing after salt treatment of the coarse aggregate has shown that fine aggregate can affect concrete durability. The effect of the fine aggregate has been masked by the normally much greater effect of the coarse aggregate and the limitation of ASTM C666 method to identify chemical problems. This is a possible explanation of some irregularities in ASTM C666 aggregate durability factors in past years. The Ames Pit in central Iowa, used as the standard fine aggregate until June 1984, can exhibit substantial petrographic variations. The coarse aggregate from this pit may contain as much as 70 percent carbonate particles, many of which are nondurable. A recent petrographic analysis of the fine aggregate from the Ames Pit identified over 60 percent carbonate particles in the material passing the Number 4 screen and retained on the Number 8 screen.

The more severe salt treatment durability testing has provided an opportunity to reevaluate the effect of fine aggregates. The Ames sand was compared to a Bellevue high quality, predominantly igneous Mississippi River sand. The Bellevue sand yields consistently and significantly higher durability factors. The Bellevue sand is now the Iowa standard fine aggregate for concrete for durability testing. This change should produce greater consistency in coarse aggregate durability testing.

DISCUSSION

Current research findings have strongly confirmed that there are factors in addition to the pore system that are associated with the rapid deterioration of PCC pavement. Substantial research has shown that freeze-thaw action on aggregates with susceptible pore systems is a major cause of D-cracking of concrete in Iowa. This does not, however, explain why all premature deterioration of concrete as an aggregate may be durable in some pavements and result in rapid deterioration in others.

The five-cycle salt-treatment durability relates well to service records of aggregate use in pavement. It has enabled laboratory studies of other related variables to be conducted. The study of such variables in actual field trials, however, would require too much time to determine results. Research is continuing on many aspects of aggregate durability in PCC pavement. Those currently being studied are as follows:

1. The development of an ice porosimeter to study aggregate pore structures,
2. The effect of fly ash on salt-susceptible aggregates,
3. The effect of deicing-salt impurities on concrete durability,
4. The effect of clay type and amount on aggregate durability,
5. The effect of reducing the maximum size of the aggregate when the problem is chemical rather than related to pore size distribution,
6. The relationship of the total coarse aggregate pore system to the rate of chemical reactivity, and
7. The effect of fewer salt treatment cycles.

CONCLUSIONS

This research on aggregate durability supports the following conclusions:

1. Deicing salt accelerates pavement deterioration when salt-susceptible aggregates are used.
2. The salt treatment of coarse aggregate before freeze-thaw testing yields durability factors that exhibit a definite relationship with field performance.
3. The salt treatment detrimentally affects the quality of concrete before freeze-thaw action.
4. The durability of dolomitic coarse aggregate is inversely related to the sulfur content.
5. An adverse chemical reaction contributes to the rapid deterioration of concrete containing porous pyritic dolomite.

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Construction of a Highway on a Sanitary Landfill and Its Long-Term Performance

MICHAEL J. BURLINGAME

ABSTRACT

The short- and long-term (4-5 yr) settlements of the Interstate 85 roadway in New Jersey, which was constructed on a sanitary landfill, are presented in this paper. Published, long-term settlement behavior of other structures constructed on refuse landfills are also presented for comparison. Stabilization of the landfill was accomplished by placing a pad of granular fill between the landfill and proposed pavement and then surcharging. Measured short- and long-term settlements are compared to those calculated from formulas developed on the basis of the behavior of sanitary landfill materials elsewhere. These equations were used to make conservative predictions of the measured settlements. Stabilization of the landfill with a heavier surcharge than is minimally required appeared to greatly reduce long-term settlements. A recent visual inspection of the roadway showed that it had no structural damage and little observable differential settlement.

In recent years, virgin soils have become increasingly difficult to find in the densely populated area between Philadelphia and New York City. The high cost of land and its scarcity forces development over old building sites or on reclaimed lands, such as sanitary landfills, once believed to be too costly or even impossible to build on. These subjects are discussed in this paper. Sanitary landfills are constructed of compacted refuse that is covered with a soil layer at the end of each day's operation (1). Compaction is usually accomplished by a bulldozer, which spreads the refuse; however, a heavy trash compactor resembling a sheepsfoot roller could also be used. Dump-type landfills, by comparison, also consist of refuse but this refuse is deposited in an uncontrolled manner. In this paper, the short- and long-term behavior of a highway constructed on a sanitary landfill is presented. The methods used to determine the height of surcharge, magnitude of settlement, and rate of settlement of the landfill are also discussed.

LITERATURE REVIEW

Methods of stabilization of sanitary landfills have been quite varied; however, heavy compaction and surcharging are the most popular ones. Table 1 contains a summary of information from several selected articles that deal with sanitary and dump-type refuse fills including the methods of stabilization, landfill ages and thicknesses, and the long-term performance of the structures constructed on them. Many case histories of attempts to stabilize refuse fills have been published, but only a few were selected for presentation in Table 1. These articles show the long-term success or failure of the stabilization method.

Sowers' article (1) about construction on sanitary landfills contains an excellent overview of their behavior and the construction difficulties that may occur. It is not the purpose of this paper to repeat Sowers' work here; however, anyone involved with this type of construction should study his work as a prerequisite.

The New York State Department of Transportation (NYSDOT) has constructed at least two highways on refuse fills (2). Heavy rolling was used to stabilize the fill. First, a 30-ton compactor was used which then allowed a 50-ton compactor to move across the landfill without rutting and becoming stuck. Densification was observed to occur to depths of up to 10 ft as determined by electrical resistivity surveys made before and after rolling. The first