except that vibration may shake out some of the voids and some of the excess water.

Objective 5

This is the icing on the cake. If all of the preceding work has been done well, the main voids are missing, and the materials are in place. It is now time to attack the micro-pores and micro-capillaries. This may be the time when re-vibration has its maximum effect, but any vibration can begin to fill the micro-pores of the aggregate which were not yet filled by the mixing and placing operations. It is during the vibration that the forces applied by the vibrator increase the dynamic, hydraulic pressures within the mix and are the last opportunity to fill the pores with paste and obtain the densest possible product. Curing isn't going to do it, inspection isn't going to do it, and praying or cursing won't do it.

The micro-capillaries are the last latent weakness. When the water departs the concrete during the bleeding process, re-vibration accomplishes breaking up of the naturally formed channels of the bleeding. During the drying process the water works its way out through its own system of capillaries. If the finished concrete has a neatly defined river and tributary system of capillaries running through the work, the concrete has its own, built-in system ready for its own destruction. Tearing up the capillaries by diligent, dynamic vibrator work is the last chance before curing to achieve the quality that someone paid for.

Need we ask further, "Why vibrate?"?

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Effect of Degree of Consolidation on Some Important Properties of Concrete

By D. Whiting, G.W. Seegebrecht, and S. Tayabji

Synopsis: Concretes were prepared at degrees of consolidation varying from 100 to 85 percent. Mixtures were typical of those used for pavement applications with cement factors ranging from 520 to 610 pounds per cubic yard (308 to 360 kg/m^3) and air contents ranging from 5 to 9 percent. Additional concretes were intentionally overvibrated to the point of incipient segregation. Test specimens were cast for determination of compressive strength, bond of reinforcing steel to concrete, permeability of concrete to chloride ions, and resistance of concrete to freezing and thawing in water.

Results show that compressive strength is reduced by about 30 percent for each 5 percent decrease in degree of consolidation. Bond stress is reduced even more dramatically, suffering a loss of approximately 50 percent for 5 percent reduction in degree of consolidation. Overconsolidation has little apparent effect on compressive strength, and may increase bond strength by virtue of displacement of air in these air-entrained concretes.

Resistance to chloride ion permeability decreased at reduced degrees of consolidation, especially when aggregate with higher water demand was used and where high air contents were employed. In most cases, resistance to freezing and thawing in water was not appreciably affected within the range of variables studies.

Keywords: aggregates; air entrainment; bond (concrete to reinforcement); cement content; compressive strength; concretes; consolidation; freeze-thaw durability; permeability

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INTRODUCTION

Portland cement concrete (PCC) has proven to be a versatile, strong, and durable material for construction of highway pavements. The combination of traffic loading, wear, temperature stresses, freezing, and applications of deicing agents, however, results in a severe environment which requires the use of high quality concrete materials and practices if the pavement is to perform as designed over its service life. Inadequate consolidation is one very important factor which can lead to premature concrete deterioration requiring expensive rehabilitation or replacement. A knowledge of the effects of incomplete consolidation on various concrete properties is needed so that the relationship between such factors as strength and degree of consolidation can be quantified and used by state highway agencies in preparation of quality control specifications.

Concrete must be completely consolidated to realize its full strength potential and durability. Fresh concrete, when initially placed, is usually honeycombed with entrapped air. Consolidation, usually achieved through mechanical vibration, is needed to eliminate these voids which otherwise would result in a weak, porous, and non-durable material. Various studies (1, 2, 3) have demonstrated the deleterious effects that incomplete consolidation has on mechanical properties of concrete. The most widely documented effect is that of decrease of compressive strength. For a voids content of 5 percent, compressive strength is reduced by about 30 percent. At 10 percent voids, compressive strength is reduced by about 50 to 60 percent. Field data reported by McBride (4) indicated a loss of approximately 1,000 psi (6.9 MPa) in compressive strength of pavement cores for a reduction of 5 lb/ft^3 (80 kg/m^3) in density. These void contents are in addition to purposefully entrained air voids (generally 5 to 7 percent by volume) which fulfill a useful function in increasing freeze-thaw resistance of the concrete.

There is a lesser effect of void content on flexural and tensile strength. Kaplan (3) reports a flexural strength reduction of 24 percent for 5 percent voids and 45 percent for 10 percent voids. Burns and Saucier (5), in studies of roller-compacted concrete, obtained a reduction of 42 percent in splitting tensile strength for a 4 percent void increase.

The effects of incomplete consolidation on other properties of concrete are less well documented. It may be assumed, however, that voids due to incomplete consolidation have roughly the same effect on concrete properties as do entrained air voids, although of a greater magnitude. This does not include properties relating to freeze-thaw resistance, where entrained air offers beneficial properties and entrapped air due to incomplete consolidation may not. With respect to bond to reinforcing steel, Hognestad and Siess (6) noted a decrease of 10 percent in bond of reinforcing steel to concrete at 5 percent entrained air. The effects of entrapped air, especially if concentrated around the reinforcement in the form of large voids, may be considerably greater. In addition, large voids in the surrounding concrete as well as immediately adjacent to the reinforcement may promote corrosion of steel, due to combined effects of reduced alkalinity in water-filled voids and increased permeability of the incompletely consolidated concrete to chloride ions (7).

While entrained air increases the resistance of concrete to freezing and thawing (and the action of deicing agents), voids due to incomplete consolidation may have the opposite effect. Water can collect in large voids and exert significant pressure on the already weak concrete when freezing occurs. These pressures can then result in cracking and spalling of the concrete, especially in conjunction with repeated cycles of dynamic wheel loading due to vehicular traffic on the pavement. These effects, however, have not been well documented, and controlled studies are needed in order to quantify the effects of consolidation on durability of concrete.

RESEARCH SIGNIFICANCE

Concrete quality, and therefore pavement performance, is greatly affected by the degree of consolidation. Research described in this paper provides highway engineers, contractors, and specifiers with information concerning the effects of consolidation on properties directly affecting performance and service life of concrete pavements. The results of this study can be used to develop end-result type specifications on the degree of consolidation of concrete. These specifications, coupled with use of improved nondestructive quality control tests such as the Consolidation Monitoring Device (8), will allow for more efficient production of high quality concrete pavement.

OBJECTIVES AND SCOPE

This research had two primary objectives. The first objective was to determine the relationships between degree of consolidation of concrete and its compressive strength, bond to reinforcing steel, chloride permeability, and resistance to freezing and thawing. The second objective was to determine the influence of such factors as cement content, air content, and aggregate type on these relationships, and to develop quantitative expressions which could be used in development of statistically based quality assurance specifications.

The objectives were carried out within the following scope:

1. Air-entrained concretes were prepared using gravel and crushed limestone aggregates over a range of cement contents encompassing those currently used in highway pavement construction.

2. Concretes were consolidated using standard practice (100 percent consolidation) and at nominal levels of 92 and 85 percent. In addition, a series of concretes were deliberately overconsolidated.

3. Concrete specimens were prepared and tested for 28-day compressive strength, 28-day bond to reinforcing steel (bond stress at 0.01-in. (0.25 mm) loaded-end slip), chloride permeability (AASHTO T 277: Rapid Method), and freeze-thaw resistance (ASTM C 666-Procedure A).

4. Data were statistically analyzed in order to develop quantitative relationships between degree of consolidation and the properties investigated. Expressions were developed to allow prediction of properties based on degree of consolidation, air content, and cement content of the mixtures.

FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

Many important properties of concrete were found to be strongly influenced by the degree of consolidation. Compressive strengths decreased by as much as 30 percent for a 5 percent decrease in consolidation. Bond to reinforcing steel was even more severely degraded. The critical bond stress (stress at 0.01-in. (0.25 mm) slip) decreased by more than 50 percent for a 5 percent decrease in consolidation. Permeability to chloride ions was similarly affected, very high permeabilities being recorded for test specimens consolidated to less than 96 percent of their normally vibrated densities.

For compressive strength and critical bond stress, materials and mix design factors have only a secondary influence. Mixtures of higher cement content are somewhat more sensitive to decreases in consolidation, losing a greater percentage of their strength. Entrained air content has little effect on the relationship of these properties to degree of consolidation. Both crushed limestone and rounded gravel aggregates exhibit similar relationships.

Mixture variables play a more significant role with respect to chloride permeability. Limestone mixtures generally show higher permeabilities at all levels of consolidation; this is attributed to the higher water demand and resultant higher water to cement (w/c) ratio in concrete prepared with crushed stone aggregate. Increasing air content results in an increase in permeability. This is most pronounced in the higher w/c ratio mixtures.

Resistance to freezing and thawing was not appreciably affected by degree of consolidation in any of the limestone aggregate mixtures. In the gravel mixtures, only those specimens which were cast at a low degree of consolidation and high air content showed significant signs of deterioration. Even in this case, specimens were intact and had less than 5 percent weight loss after 300 cycles of severe exposure.

Overconsolidation, at least for the low slump mixtures utilized in this program, did not impair the properties studied and in fact, in many instances resulted in significant improvements. Compressive strength, bond stress, and resistance to freezing and thawing were promoted to varying degrees. Permeability to chloride ions was reduced by overconsolidation. It should be noted that segregation due to the extended external vibration used to simulate overconsolidation was very slight in these mixtures, and most of the improvements may be related to expulsion of entrapped and some entrained air from the concretes.

The effects of consolidation on these properties should be taken into account when specifications for concrete consolidation are developed. It is recommended that such specifications reflect both the variance inherent in test results as well as variance associated with any particular method of measuring consolidation. As more data is developed under actual field conditions, greater confidence in use of consolidation measurement as a quality control tool will be obtained.

EXPERIMENTAL

Materials

The cement used was a blend of three ASTM Type I cements available locally in the Chicago, Illinois area. Physical and chemical properties of the cement blend are given in Table 1.

Aggregates used were a predominantly dolomitic natural sand from Elgin, Illinois, a crushed sub-angular dolomitic limestone from Thornton, Illinois, and a partially crushed, rounded siliceous river gravel from Eau Claire, Wisconsin. Relevant properties are given in Table 2.

The only admixture utilized was an air-entraining agent consisting of a 2 percent solution of neutralized Vinsol resin.

Mix Design

Three mix designs were used in this study. The combination of these mix designs and two aggregate types lead to the six nominal mixtures summarized in Table 3. Data published by the Portland Cement Association (9) indicates that cement factors currently used by State highway agencies range from a low of 470 lb/yd^3 (278 kg/m^3) to a high of 630 lb/yd^3 (374 kg/m^3), with a mean of 556 lb/yd^3 (330 kg/m^3). These low and high points, however, represent only 1 State each. More practical upper and lower limits would be represented by levels of approximately 520 lb/yd^3 (308 kg/m^3) and 610 lb/yd^3 (360 kg/m^3), which encompass about 84 percent of the state mix designs and represent more typical cement contents. In a recent survey of air content specifications reported by Whiting (10), it was found that while many States retained conventional ranges such as 4-7 percent, a number of States were accepting air contents as high as 9-10 percent, partly in response to appreciation for higher air content requirements in severe freeze-thaw and deicing environments. For this reason, two air content ranges were chosen for the 610 lb/yd^3 (360 kg/m^3) designs, that is, 5-7 percent and 7-9 percent. Slump was nominally held to within the range of 1 to 2 inches (25 to 50 mm) to simulate mixtures typically used in slip-form pavement operations.

Mixtures as prepared differed in slight respects from the nominal designs given in Table 3 due to effect of measured air contents on yield. Actual mix analyses, including measured values of slump and air content for each batch, are given in Appendix A.

Batching and Mixing

Coarse aggregate was weighed and then inundated with water in a closed container 18 to 24 hr prior to mixing. Immediately before mixing, a measured amount of water was drained from the container, such that the water remaining (which was subsequently placed into a separate container) would satisfy the absorption of the aggregate plus the net amount of water required for the batch. Fine aggregate was weighed and batched in a moist condition. All mixing was carried out in a 1.75 cu. ft. (0.05 m^3) counter-current pan mixer. Charging sequence was coarse aggregate, cement, sand, and the remainder of the mixing water.

The mix cycle consisted of 3 min. initial mixing, 3 min. rest, and 2 min. final mixing, as specified in ASTM Designation: C 192 (Making and Curing Concrete Test Specimens in the Laboratory). Air entraining agent was added after an initial 20 sec. mixing. Immediately following the final 2 minute mix period, the concrete was tested for slump and air content.

Specimen Preparation

Four types of specimens were prepared in this project. These consisted of 6x12-in. (152x305 mm) cylinders for determination of compressive strength, 3x3x11.25-in. (76x76x286 mm) prisms for freeze-thaw testing, 2x4-in. (50x102 mm) discs for determination of rapid chloride permeability, and concrete cubes for determination of bond to reinforcing steel. These latter specimens were cast as 6-in. (152 mm) cubes with a centrally located No. 6 (19 mm) deformed 60 ksi (414 MPa) reinforcing bar located in a horizontal position during casting. Total length of the reinforcing bar was approximately 38-in. (965 mm) with 0.375 in. (10 mm) of the bar protruding from the opposite end of the cast specimen.

The first set of specimens cast from each concrete batch was consolidated using procedures recommended in ASTM C 192. This consisted of consolidation by external vibration using a table vibrator with a frequency of 7000 rpm (116 Hz) and an amplitude of 0.004-in. (0.1 mm). Vibration was applied to specimens held firmly (but not rigidly attached) on the vibrating table until the surface of the concrete had become relatively smooth. Cylinders and blocks were placed in two equal layers, prisms and discs in one layer. After filling with concrete, the weights of concrete contained in each specimen were determined so that subsequent calculations of amounts of concrete needed for additional sets could be made.

Knowing the initial volumes of each mold the amounts of concrete needed to fill 92 and 85 percent of the mold volume were determined for the second and third sets. These amounts of concrete were then weighed into each mold. It was not possible to consolidate these specimens by vibration as the slightest amount of vibration would result in densification above the desired target values. In lieu of vibration, the concrete was hand placed into the molds with only limited manipulation required to achieve the necessary target values.

The final (fourth) set of specimens was designed to represent a concrete which had been overconsolidated. Due to the low slump, good quality aggregates, and proper mix designs, however, this objective proved difficult to achieve. Extended periods of vibration using a "spud" internal vibrator did result in segregation of material in the immediate vicinity of the vibrator, but this was felt to be too heterogeneous to be used in test specimens. A vibration time of 5 min. on the table vibrator was finally chosen, it being determined that this amount of vibration led to incipient segregation of coarse aggregate from the mixture and would probably also represent an extreme limit for overvibration in the field of a mix of similar design and quality.

All specimens were finished with a wooden float and placed under moist burlap and polyethylene sheeting for a 24-hr period. Molds were then stripped and the castings placed in a fog room at 73°F (23°C) for the selected curing periods. Cylinders and cubes were cured for 28 days. Prisms were cured for 14 days (in saturated limewater). Discs were moist cured for 14 days, air dried 14 days, then tested.

Prior to testing, actual bulk densities of all specimens were determined by direct measurement of specimen volume and weight (in air). Percent consolidation was then determined as the ratios of densities of specimens in sets 2, 3, and 4 to the average of companion specimens in set No. 1. Due to such factors as; consolidation due to movement of molds into position for curing, shrinkage upon set, and slight variations in dimensions of molds used, actual percent consolidation deviated from nominally chosen values. Average standard deviation of the difference from nominal values was 2.5 lb/ft^3 (40 kg/m^3) for all specimens.

<u>Apparatus and Techniques</u>

All of the techniques used in this program followed standard test methods. Details concerning the apparatus and test procedures can be found in the appropriate standards. Only brief descriptions are included here.

<u>Compressive strength</u>--The 6x12-in (15x305 mm) cylinders were capped with a high-strength sulfur-based compound and tested using procedures described in ASTM Designation: C 39 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens).