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SUMMARY REPORT

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South Carolina Dept. of
Transportation
955 Park Street
P.O. Box 191
Columbia, SC 29202

Permeability of Portland Cement Concrete (PCC) Structures in South Carolina –Volume II

M.F. Petrou, D.C. Rizos, K.A. Harries and J. Hanson

High performance concrete (HPC) is generally defined as a concrete with improved durability and/or higher structural capacity as compared to ordinary Portland cement concrete. It is currently being used for bridge construction to protect reinforcement from corrosion, to resist chemical and physical attack and to provide improved structural properties. The Federal Highway Administration (FHWA) developed HPC Performance Criteria pertaining to its mechanical properties and durability characteristics. The associated tests include compressive strength, modulus of elasticity, shrinkage, creep, freeze-thaw durability, scaling, abrasion and chloride penetration. The modulus of elasticity of the HPC (Class E) for bridge decks used in South Carolina is found to be very low. This has been attributed to the coarse aggregate used.

The objective of this work is to quantify the effects of coarse aggregate on the modulus of elasticity of HPC using Class E concrete and develop a model for predicting the modulus of elasticity based on known physical or mechanical characteristics of the constituent materials. A series of laboratory tests and analytical and numerical investigations have been conducted. The laboratory tests pertain to the experimental determination of the elastic modulus of HPC using coarse aggregates from various sources. Analytical and numerical models are calibrated based on experimental measurements and are used in some of parametric studies.

A number of tests were performed on twelve concrete mixes using twelve different aggregates from twelve different sources to determine the effect of the aggregates on the elastic modulus of concrete. The mix proportions, currently being used by SCDOT in the Class E HPC, were the same for each concrete mix. The only material varied was the coarse aggregate. The following conclusions are drawn from this portion of the research and apply to Class E HPC only:

- The extent to which crushed granite aggregate has weathered and the susceptibility of its source to the weathering process has a significant effect on the modulus of elasticity of high performance concrete. The weathered aggregate concretes are characterized by transgranular type of fracture, with the shear plane passing through the aggregates and cement mortar. The unweathered aggregate concretes are characterized by fracture mainly through the cement mortar and not necessarily through the aggregates. Weathered aggregates should not be used in HPC mixes.
- Of the three other rock types included in this study, the granite-gneiss aggregate concrete gave the highest elastic modulus, followed by marble-schist and then marine-limestone. It should be noted that this observation is true for these specific sources. However, no general conclusions can be drawn for other aggregates of the same rock type from different sources. Mineralogy of the parent rock has a significant effect on the concrete properties including elastic modulus.

The average concrete elastic modulus was compared with its average compressive strength and average permeability at 28 days and the following conclusions have been drawn:

- The average chloride permeability values ranged from 1660 to 2660 Coulombs, and falls into the low to moderate range according to ASTM C1202. An inverse relationship exists between the elastic modulus and the permeability of unweathered aggregate concretes. There is no correlation between the elastic modulus of concrete and the permeability of weathered aggregate concretes.
- For unweathered aggregate concretes as the concrete compressive strength increases the elastic moduli of the associated HPC increase. For weathered aggregates concretes there is little correlation between the concrete elastic moduli and the concrete compressive strength of the concrete.
- The ACI Building Code 318-02 equation for HPC gives a fairly good estimate of the concrete elastic modulus of unweathered aggregate concretes with an average variation of 17% but overestimates the concrete elastic moduli of weathered aggregate concretes by approximately 70%.

The effect of the modulus of elasticity of the aggregate on the concrete modulus was studied. A regression analysis was also performed on plots relating the LA abrasion and absorption percentage of the aggregates to the concrete modulus. The following conclusions are drawn:

- The elastic modulus of HPC increases as the elastic modulus of the rock increases.
- An inverse exponential relationship exists between the elastic moduli of the aggregates and their LA abrasion values. An inverse exponential relationship also exists between the elastic moduli of the concretes and their respective aggregate LA abrasion values.

A two phase finite element model (FEM) was developed for estimating the modulus of elasticity of HPC based on the elastic modulus of the aggregate and the concrete elastic modulus. Subsequently, some parametric studies were conducted in order to identify the way different properties of the individual phases of the composite material affected the overall stiffness of the composite model. The model is highly sensitive to the input data and can be used to effectively estimate the elastic modulus of concrete if the constituent material properties are known.

The following recommendations can be made to SCDOT based on the research observations and conclusions:

- The modulus of elasticity of HPC used for bridge design should be measured directly in the laboratory and not estimated based on the ACI Building Code 318-02 equation.
- When HPC is used in bridge construction it is desirable to use aggregates that have relatively higher modulus of elasticity, e.g. crushed granite from appropriate sources in North Carolina.
- Perform similar investigations on all the other sources of aggregates currently being used in HPC for bridge design in South Carolina, not included in this research.
- Aggregate from weathered sources or sources that give low modulus of elasticity should not be used for HPC.

The following future research is recommended based on the research presented in this work:

- Investigate the petrological, petrographical and mineralogical characteristics of all the aggregates in the SCDOT APPROVAL SHEET 2.
- Perform a microscopic investigation on the failure plane of HPC using different aggregates and determine its relation with the concrete elastic modulus.
- Develop a model incorporating the effect of the interfacial zone, thereby accounting for aggregates that are not inert.
- Determine the effect of the modulus of elasticity of fine aggregates on the elastic modulus of concrete.
- Develop a closed form analytical equation for predicting the elastic modulus of HPC

This research project was conducted at the University of South Carolina by Michael F. Petrou, Ph.D., Kent A. Harries, Ph.D. and Dimitris C. Rizos, Ph.D.
For further information, contact Terry Swygert at SCDOT: (803) 737 6652; swygertt1@dot.state.sc.us