JOINT TRANSPORTATION RESEARCH PROGRAM

Principal Investigator: Jan Olek, Purdue University, olek@purdue.edu, 765.494.5015

Program Office: jtrp@purdue.edu, 765.494.6508, www.purdue.edu/jtrp

Sponsor: Indiana Department of Transportation, 765.463.1521

SPR-2864 2012

Optimization of Mixture Proportions for Concrete Pavements—Influence of Supplementary Cementitious Materials, Paste Content and Aggregate Gradation

Introduction

The initial part of this research project involved optimization of the composition of paving concrete mixtures with respect to the amount and type of supplementary cementitious materials and the volume of paste while keeping the type and gradation of aggregates constant. Once the optimized mixtures were selected, they were further evaluated with respect to the influence of aggregate gradation, the aggregate packing density, and aggregate type on their performance. The research plan consisted of three distinctive phases: Phase I was dedicated to statistical optimization of concrete binder; Phase II consisted of evaluation of aggregate gradation, type and aggregate packing density on properties of optimized mixes selected in Phase I; and Phase III covered statistical optimization of the paste requirement for concrete mixtures with different gradations and packing densities.

The statistical approach utilized in Phases I and III involved Response Surface Methodology (RSM), which is a group of statistical techniques typically used for optimization of industrial processes. The RSM methodology consists of three major steps: experimental design, statistical analysis, and numerical optimization. In the experimental design step, the Central Composite Design (CCD) approach was utilized in order to establish the number of concrete trial bathes, as well as the required combination of research variables (mixture designs). The CCD approach is typically used when up to five variables are included in the experimental program and allows for easy fitting of response surface (through a simple polynomial equation) into collected data. During the statistical analysis step the collected data were reduced using least-square and analysis of variance (ANOVA) techniques, a process which resulted in the development of predictive models for concrete properties measured. Finally, the numerical optimization step involved conversion of predicted outcomes for each concrete property studied into desirability values and determining the maximum (optimum) desirability value for the group of concrete properties selected for the optimization process.

While performing the optimization in Phases I and III of the project, it was assumed that the optimized mixture would be that which meets target values for the selected performance criteria (strength, sorptivity, shrinkage, scaling) at a minimum cost. In case of Phase I, a total of 10 concrete properties (performance responses) were selected in the optimization process. These responses included 7 and 56 days flexural strength, 7, 28, and 90 days compressive strength, scaling resistance, sorptivity, absorptivity, free shrinkage, and the combined cost of all materials used during mixture production. For Phase III, the number of selected responses was reduced to 8 and included 7 days flexural strength, 7 and 28 days compressive strength, scaling resistance, freezing and thawing resistance, absorptivity, free shrinkage, and the cost of component materials.

Phase I of the research plan included optimization of two binary (cement + fly ash and cement + ground granulated blast furnace slag (GGBFS)) and one ternary (cement + fly ash + GGBFS) binder systems. For the fly ash system, the variables studied included the total volume of paste in the mixture (21% to 25%) and the level of cement replacement by fly ash (14% to 30% of total weight of cementitious materials). For the GGBFS system, the variables studied included the total volume of paste in the mixture (21% to 25%) and the level of cement replacement by GGBFS (20% to 40% of the total weight of the cementitious materials). Finally, for the ternary system the paste content was varied from 21% to 25%, fly ash content was varied from 10% to 20%, and GGBFS content was varied from 18% to 30%. A total of 33 different concrete mixtures (all containing supplementary cementitious materials) were produced in Phase I. In addition to that, two plain (cement only) mixtures, one with 515 lb and the second with 565 lb of cement per cubic yard, were produced to serve as the control mixes. All concrete mixtures produced in Phase I of the research project were designed at a constant w/cm 0.44, with target slump and air contents of 2±1 in. and 6.5±1%.

The main goal of Phase II was to investigate the effect of different aggregate gradations on the fresh and hardened properties of optimized concrete mixtures developed in Phase I, as well as to identify the most desired aggregate gradations for paving mixtures. Different aggregate gradations were prepared by blending two, three, or four different aggregates based on the concept of Shilstone's Coarseness Factor Chart. A total of six different combined gradations were developed. These varied with respect to: value of coarseness and workability factors, proportion of fine aggregate in the total aggregate mass, packing density of combined aggregate gradation, and maximum particle size of coarse aggregate. These six gradations were utilized to produce concrete mixtures using the near-optimum binder system identified in Phase I. The binder systems selected included the following: 22% of fly ash and 22% of paste; 32% of GGBFS and 23% of paste; and 16% of fly ash, 26% of GGBFS, and 22% of paste. A total of 18 concrete mixtures were produced and tested for the same properties as those used in Phase I.

In Phase III, the concept of air free paste–aggregate void saturation ratio (k") was investigated in relation to aggregate packing density (Φ). An optimum fly ash concrete mixture (containing 28.5% fly ash) was modified in order to produce a total of 9 concrete mixtures with different combinations of k" and Φ variables. The k" values ranged from 0.869 to 1.081, whereas the Φ varied from 0.715 to 0.786. The testing plan utilized for Phase III was the same as that used for Phases I and II except that four selected concrete mixtures were also tested for cracking potential.

Findings

The paste content optimization part of the research (Phase I) revealed that it is difficult to produce concrete paving mixtures if the paste content is below 22%, especially when relying only on mid-range water reducing admixtures for workability control. For that reason, mixtures with paste content below 22% (corresponding to a total content of cementitious materials in a cubic yard of concrete of about 475 lbs) are not recommended for pavement applications. The numerical optimization of binders resulted (upon adjustments for concrete workability) in the following optimum values of variables: 22% of paste and 29% of fly ash; 23% of paste and 27% of GGBFS (for binary systems); and 15% of fly ash, 27% of GGBFS, and 22% of paste (for ternary systems). Research performed in Phase II indicated that aggregate gradations having the coarseness factor (CF) and the workability factor (WF) within Zone II of Shilstone's chart significantly affected concrete workability, placement, and finishability. However, the flexural strength, the compressive strength, and the freeze-thaw resistance values were similar for mixtures with different gradations and CF and WF values. In addition, it was found that aggregate packing density (Φ), along with air-free paste-aggregate void saturation ratio (k") (resulting from utilization of different aggregate gradations) were helpful in explaining observed differences in scaling, sorptivity (absorptivity) and shrinkage properties. The evaluations of the influence of Φ and k" factors on development of satisfactory paving mixtures were performed in Phase III. The results of the statistical optimization performed in Phase III revealed that the most desirable concrete mixtures were those with aggregate gradations characterized by Φ values ranging from 0.755 to 0.786 and k" values from 0.925 to 1.000. For these mixtures, the optimum total paste content ranged from 19.8% to 24.5%. Finally, the comparison of optimum paste contents resulting from Phase I and Phase III experiments allowed for the establishment of final recommended ranges of paste content for paving mixtures with different binders and aggregate gradations. For binary fly ash and GGBFS systems the recommended paste content is in the range of 21.5% to 23.25%, whereas for ternary systems (cement + fly ash + GGBFS) the paste content should be in the range of 21.5% to 22.75%.

Implementation

The ultimate goal of this project was to investigate the optimal ranges for paste content, amount of cementations materials, and aggregate gradation for concrete paving mixtures. As the final outcome from this study, the following recommendations are proposed for implementation into the existing specifications for concrete paving mixtures in Indiana:

- Although the analysis presented in Figures 7.2 and 7.3 of this report indicates that the minimum cement content required for production of satisfactory paving concrete mixtures can be even below 300 lb/yd^3, it is probable that such mixtures might be challenged to meet early age/opening to traffic strength requirements due to inherent variations in materials properties and curing conditions. In such cases, in order to ensure an adequate rate of strength gain it may be necessary to set the minimum cement content at levels higher than those indicated in Figures 7.2 and 7.3. The exact values of the minimum cement content should be established by the contractor during the trial batches by demonstrating that resulting mixtures will satisfy the minimum 7 days flexural strength and ensure adequate durability of concrete.
- The use of ternary concrete mixtures (incorporating PC + GGBFS + fly ash) should be allowed in pavement construction.
- The recommended paste volume should be in the range of 21.5% to 23.5% and the packing density of aggregates should be from 0.755 to 0.786.
- It is recommended to utilize up to three (one fine and maximum two coarse) aggregates to establish a well-graded combined gradation characterized by a CF of 60±5 and a WF of 36 to 40.
- The combined aggregate blends should have fine aggregate content from 35% to 42% of the total aggregate content by mass.
- Utilization of aggregate gradations with a maximum nominal aggregate size of 1 inch appears to be possible but requires further verification.

The benefits of this research include the following:

- Generation of optimal ranges for paste content, amount of cementitious materials, and aggregate gradation for concrete paving mixtures.
- Generation of information regarding the minimum cement requirements for paving mixtures in binary systems (i.e., containing Portland cement plus slag or fly ash). Figures 7.2 and 7.3 of this report can be used directly by mix designers to reduce the amount of cement, thus making the mixtures more economical
- Confirmation of the technical feasibility of using ternary mixtures in the construction of concrete pavements.

Recommended Citation

Rudy, A., and J. Olek. *Optimization of Mixture Proportions for Concrete Pavements—Influence of Supplementary Cementitious Materials, Paste Content and Aggregate Gradation*. Publication FHWA/IN/JTRP-2012/34. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2012. doi: 10.5703/1288284315038.

View the full text of this technical report here: http://dx.doi.org/10.5703/1288284315038

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