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

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OPTIMIZATION OF MIXTURE PROPORTIONS FOR CONCRETE PAVEMENTS—INFLUENCE OF SUPPLEMENTARY CEMENTITIOUS MATERIALS, PASTE CONTENT AND AGGREGATE GRADATION

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16. Abstract

The main purpose of this research was to evaluate the influence of the type and the amount of supplementary cementitious materials, paste content and aggregate gradation on the results of statistical optimization of mixture proportions for concrete pavements. The research program was divided into three main PHASES.

In PHASE I, the influence of the amount and type of supplementary cementitious materials (as well as the paste content) on selection of optimum proportions for concrete pavement mixtures was studied. The Response Surface Methodology (RSM) was utilized to design test matrices of concrete mixtures consisting of three binder systems: the fly ash system, the GGBFS system and the fly ash plus GGBFS system. For each binder system, the paste content varied from 21 to 25% by mixture volume. The optimum composition of concrete mixtures was found to be 29% of fly ash and 22% of paste for the fly ash system, 37% of GGBFS and 23% of paste for the GGBFS system, and 15% of fly ash, 27% of GGBFS and 22% of paste for the ternary system.

In PHASE II, three concrete mixtures (each representing near optimum composition of variables studied in PHASE I) were selected and produced with six different aggregate gradations. These aggregate gradations varied with respect to coarseness (CF) and workability (WF) factors (as defined by Shilstone's chart), packing density and maximum aggregate size. The results revealed that the best performance was obtained for mixtures with CF of about 67 and WF of about 40. In addition, the paste-aggregate void saturation ratio (k"), which relates paste content to aggregate packing density, was found to be important in controlling scaling and drying shrinkage of concrete mixtures produced in PHASE II.

The focus of PHASE III of the study was on numerical modeling to determine the optimum combination of (k") and aggregate packing density (Φ) with respect to concrete performance. The results revealed that the most desirable concrete mixtures were produced with a (k") value ranging from 0.925 to 1.000 and with packing density in the range from 0.755 to 0.786. Finally, selected concrete mixtures produced in Phase III were evaluated with respect to their cracking potential. The mixtures selected for the cracking potential study were those which showed elevated level of drying shrinkage and were characterized by relatively high k" values and poor aggregate packing density. The cracking potential of these mixtures was evaluated using the modified AASHTO ring test procedure, which involved demolding of specimens immediately after the concrete reached the final setting time. The final setting time was determined using the time Domain Reflectometry (TDR) method.

17. Key Words aggregate gradation, cementitious materials, concrete, paste content, pavement, statistical optimization	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

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EXECUTIVE SUMMARY

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 $6.5 \pm 1\%$.

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.

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1. INTRODUCTION

1.1 Problem Statement

The quality and performance of Portland cement concrete (PCC) pavements is the joint outcome of proper design, construction and maintenance processes. Each of these processes effects (and is affected by) the other in ways that determine overall pavement quality and long-term performance (*1*). Among these three factors, the process of concrete mixtures design seems to be the most crucial, since it defines the base for proper construction and then the maintenance requirements.

The same author (*1*), indicated that the modern process of concrete mixture design become more complex and that it requires an interdisciplinary knowledge. The complexity of concrete mixture design is due the need of combining the number of different types of ingredients from diverse sources. Although, as mentioned by van Dam (*2*), the selection of concrete materials for durable concrete pavements is based on the idea of using only high quality materials, and utilizing the proportioning method which will allow sustaining specified performance, sometimes this selection results in incompatibility problems and most often gives not-optimized (overdesigned or underdesigned) mixtures. Utilization of not-optimized mixtures increases initial cost of construction projects and may lead to unexpected problems with long term performance of concrete pavement.

The problem of production overdesigned concrete mixtures or the use of underdesigned mixtures for specific projects is additionally exaggerated by state specifications. In these specifications, big emphasis is placed on quality control/quality assurance (QC/QA) protocols (in order to assure high concrete quality and to reduce the amount of concrete failures) with little attention being paid to an optimized concrete mix design. An example of such approach can be seen in the current Standard Specification for Concrete Pavement in Indiana (*3*), which significantly limits the potential to optimize materials and mixtures, thereby reducing opportunities to move further towards performance specifications.

Considering these limitations of the current approach, it is clear that additional research is required in order to set up the optimum limits for parameters used for concrete mixture design (i.e., amount of supplementary cementitious materials, water cement ratio, and paste content) as well as aggregate gradation. Many paving projects still use just two aggregate sizes (fine and coarse) along with basic air-entraining and water reducing admixtures (*4*). Much work is needed to study and define different blends of aggregates, admixtures, and cements to meet many needs (i.e., economy, recycling, and improved handling).

All considerations mentioned above lead to the general conclusion, that there is a need to develop guidelines on how to design low-slump concretes which will offer enhanced performance and thus extend the lifespan of concrete pavement and minimize the cost of maintenance. Such "enhanced" performance concretes should be designed at low water-cementitious materials (w/cm), should incorporate optimum amount of supplementary cementitious materials (SCMs), and properly selected set of chemical admixtures. Moreover, such mixtures should be designed and produced using optimized aggregate gradation which will allow for reduction of paste volume without negatively impacting the ease and quality of placement and finishing operations.

1.2 Objectives of The Research

The needs pertaining to optimization of concrete paving mixtures can be illustrated by examining current Specifications for Concrete Pavements developed by Indiana Department of Transportation (INDOT). In Section 500 of these specifications (*5*), INDOT lists the following QC/QA criteria for concrete pavements mixtures:

- minimum amount of cement at 440 lb/yd^3,
- maximum water to cementitious ratio of 0.45,
- minimum Portland cement/fly ash ratio of 3.2 by weight (mass),
- minimum Portland cement/slag ratio of 2.3 by weight (mass),
- target air content of 6.5% and
- minimum flexural strength at 7 day of 570 psi.

In addition, contractors may use aggregate gradation as specified in the Materials Section of 2008 INDOT specification or use an alternative aggregate gradation. However, the aggregate mixture shall include at least 35%, but not more than 50% of fine aggregate by total aggregate weight (mass). As far as the cementitious materials are concerned, the above mentioned specification allows the use of only one type of supplementary cementitious material (fly ash or slag) at the time. In practice, it means that even when blended cements are used, the addition of a third cementitious material would not be permitted to create so called "ternary" concrete mixture.

As can be seen, current specification for concrete pavements in Indiana substantially limits prospects of optimization of concrete proportions for pavements by requiring relatively high minimum amount of cement, by excluding potential application of ternary concrete mixtures and giving practically no guidelines on how to produce of well-graded aggregate gradations. Most of Midwest state specifications have similar drawbacks. For these reasons, it seems necessary to establish new criteria for the selection of concrete mixture proportions for pavements in Indiana and other Midwest states.

Using previously presented limitations of existing pavement mixtures specification, the following objectives were identified for the present research:

- to reduce the minimum required amount of cement in paving mixtures

- to investigate the optimum level of substitution of cement with fly ash and ground granulated blast furnace slag (GGBFS) in paving mixtures
- to develop ternary concrete mixtures with Portland cement, fly ash and GGBFS for potential application in paving operations
- to develop guidelines on how to proportion well-graded, optimized aggregate blend for paving mixtures, and
- to provide general guidelines on how to design optimized concrete mixtures for pavements.

1.3 Scope of the Research

The overall scope of the research was divided into three distinctive phases, each of which is described briefly below:

- Phase I: This phase consists of statistical optimization of the proportions of concrete binder. The Central Composite Design methodology (CCD) was used to design the experiment for the optimization of binder in three types of concrete mixtures: (a) cement + fly ash, (b) cement + GGBFS, and (c) cement + fly ash + GGBFS. The variables studied in each of these systems included: paste content (from 21 to 25% by mixture volume) and total content of supplementary cementitious material (SCM) in the mixture. This was expressed as weight percent of total binder, and varied depending on the binder system used.
- Concretes with cement + fly ash binder system consisted of nine different mixtures, in which fly ash content varied from 14% to 30% by the total mass of the binder. Cement + GGBFS concretes included mixtures in which GGBFS varied from 20% to 40% by mass of the total binder. Finally, the third system included 15 concrete mixtures that contained cement and both, fly ash and GGBFS. In this system the amounts of fly ash and GGBFS varied from 10% to 20% and from 18% to 30%, respectively. The total number of mixtures produced in Phase I was 35 (this included two control (cement only) mixtures with, respectively, 515 and 565 lb/yd^3 of cement). The results obtained from testing of hardened concrete were combined with estimated costs of the materials and used as an input in performance prediction models which were analyzed using Response Surface Methodology (RSM) techniques. Lastly, the numerical optimization methods were used to find optimal composition of concrete mixtures for each binder system.
- Phase II: The main goal of this phase 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 of 2, 3 or 4 different sizes of aggregates based on 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. A total of 18 concrete mixtures were produced and tested in Phase II. The main conclusion from this part of the study was that Shilstone's method of selection of aggregate gradations for paving mixtures was not precise enough to predict some negative effects of poorly graded aggregate on concrete performance and prevent high shrinkage values in mixtures with well graded aggregates. Additional data analysis revealed that the aggregate packing density (Φ), along with air-free paste-aggregate void saturation ratio (k''), can be helpful in understanding observed differences between concrete mixtures with different aggregate gradations.
- Phase III: The concept of air-free paste-aggregate void saturation ratio (k'') introduced in Phase II seemed to fairly accurate link the properties of concrete mixtures with their paste content. Thus, it was decided to further investigate this concept in connection with aggregate packing density (Φ). In addition, it was believed that defining optimum values of k'' will allow to revise the paste content ranges developed in Phase I for different systems, and thus define more general optimum paste ranges for paving mixtures. The research plan (which included nine concrete mixtures) was designed using the same statistical methods as used in Phase I. The concrete mixtures produced during this phase varied with respect to packing density of combined aggregate blends (Φ) and values of air-free paste-aggregate voids saturation ratio (k'').

1.4 Organization of the Report

This report consists of eight chapters. The first two chapters provide general information on previous work related to the research topic and the theory of experimental design. Specifically, Chapter 1 (Introduction) describes the problem statement, research objectives, and research scope. Chapter 2 (Background and Research Methodology), begins with the discussion of typical composition of paving mixtures with focus on the amount and type of cementitious materials used as well as an aggregate gradation. Next, the background on statistical experimental design utilized throughout the study is provided. Finally, it presents the performance criteria utilized in verification of the optimum proportions for concrete paving mixtures developed in the research.

Chapters 3 through 5 contain experimental plan, description of the concrete constituents, testing plan, results, data analysis and conclusions. Specifically, Chapter 3 (Research Approach) presents the information on materials, mixtures design and test procedures utilized for each of three Phases. Chapter 4 (Results of Laboratory Testing), presents the results obtained from all three Phases of the study. Chapter 5 (Discussion), includes detailed discussion of optimum combinations of research variables with respect to measured concrete properties.

Chapters 6 through 8 summarize the results of laboratory testing and optimization process. In Chapter 6 (Conclusions), the major findings from the research as presented. In Chapter 7 (Recommendations and Guidelines for Concrete Pavements), detailed guidelines on how to optimize mixture design for concrete pavements are presented. Lastly, Chapter 8

(Future Research) discusses future research needs in the area of optimization of concrete paving mixtures.

2. BACKGROUND AND RESEARCH METHODOLOGY

2.1 Typical Variables Influencing Properties of Paving Mixtures

The selection of research variables used in the study were selected following a detailed literature survey, including state specifications for concrete pavements from twelve (12) Midwestern and Atlantic states where the use of concrete pavements has been historically strong. The results from this survey were additionally supplemented by the guidelines for mixture proportioning published by American Concrete Pavements Association (*6*), Department of Defense (*7*) and typical mixture designs reported by major transportation agencies.

Based on these data, the following factors were identified as those which are likely to influence properties of pavement concrete:

- minimum cement and total cementitious materials contents
- water-to-cementitious materials (w/cm) ratio,
- amount of supplementary cementitious materials (SCMs) and,
- fine-to-total aggregate ratio.

In order to determine the typical values of these factors reported in state specifications and in the literature, several frequency plots were prepared. The data presented in Figure 2.1 include the minimum amount of cement used in concrete pavements from state specifications only. The data shown in Figures 2.2 to 2.6 were obtained from 97 different concrete mixtures used in various laboratory research projects related to concrete pavements, as well as from several

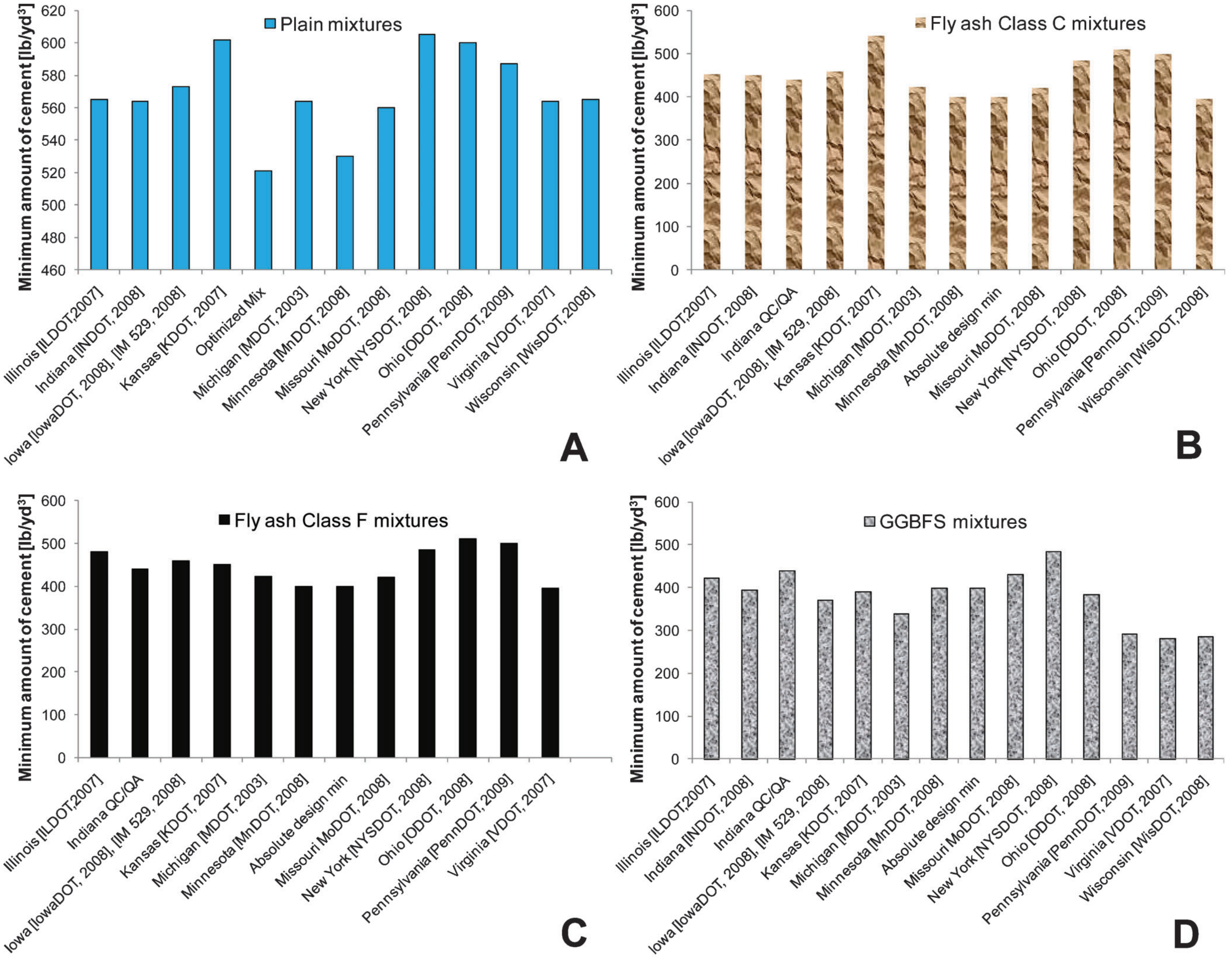


Figure 2.1 Minimum amount of cement content in paving mixtures in various state specifications: (a) plain cement mixtures, (b) Class C fly ash, (c) Class F fly ash, and (d) GGBFS.

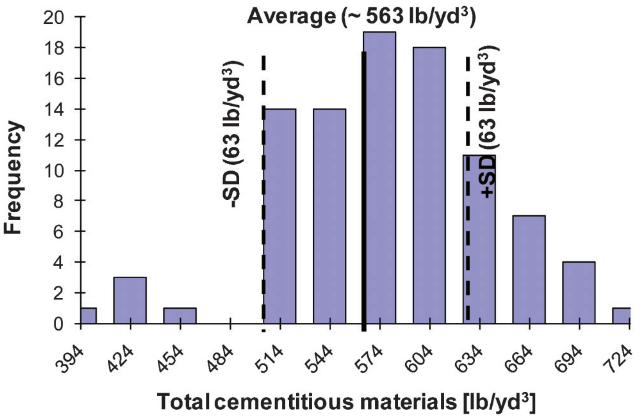


Figure 2.2 Distribution of total content of cementitious materials in 93 concrete paving mixtures reviewed in the study.

State DOT's. In addition, information provided by several contractors from Indiana and from other states is also included.

2.1.1 Minimum Cement and Total Cementitious Materials Content

The mimimum cement content for plain mixtures (see Figure 2.1 (d) varies across the states from 517 lb/yd^3 to 611 lb/yd^3, with the average value at about 550 lb/yd^3. On the other hand, the minimum amount of cement for mixtures containing SCMs is more uniform (see Figure 2.1 (b–d)). Among these mixtures, the lowest required amount of cement (about 380 lb/yd^3) was associated with GGBFS mixtures, whereas for Class C and Class F fly ash mixtures, the requirement for minimum cement content was about 450 lb/yd^3.

Minimum cement contents obtained from Figure 2.1 (a–d) are higher than those specified by ACPA (about 283 lb/yd^3 at maximum replacement level by supplementary cementitious materails) (*8*) and UFGS guidelines (about 235 lb/yd^3 for airfield pavement and 253 lb/yd^3 for marine concrete structures, if both produced with 50% replacement for GGBFS) (*7*). Such big descrepancies between these data sources indicates that the issue of minimum cement content for durable (optimized) paving mixtures must be included as one of the test parameters in the present study.

Figure 2.2 shows the variations in the total amount of cementitious materials obtained by analyzing the composition of 93 different pavement mixtures. The compositions of the analyzed mixtures were obtained from variety of sources, including state DOT's specifications and published reports from several research projects. The detail proportions of these mixtures are given in an Appendix A.

According to several sources (R. M. Newell, personal communication, 2005; (*8*), UFGS, 2004 (*7*)) the total amount of cementitious materials required to produce durable concrete paving mixtures should be in the range of 470–517 lb/yd^3. However, as can be seen from Figure 2.2, the average total cementitious materials content calculated for mixtures reviewed in this study was higher (~563 lb/yd^3), with standard deviation of ~63 lb/yd^3.

2.1.2 Water-to-Cementitious Materials (w/cm) Ratio

Figure 2.3 shows the distribution of w/cm values for the same group of 93 paving mixtures.

The average value of w/cm was found to be 0.46, with standard deviation of 0.07. When selecting w/cm value for the current study, several other (practical) factors were also considered. These included: desired workability of concrete mixtures, maximum recommended dosage of water reducing admixtures and maximum w/cm values required by various states DOT's. Based on combinations of these parameters, the single w/cm of 0.44 was selected for all mixtures used in this study.

2.1.3 Amount of Supplementary Cementitious Materials

The maximum allowable amount of supplementary cementitious materials is another important parameter that needs to be considered when evaluating composition of paving mixtures. Based on extensive literature review, fly ash and GGBFS were found to be supplementary cementitious materials most widely used in paving applications. There are two main reasons why these two materials are used to replace the cement in paving mixtures. First, significantly cheaper mixtures can be produced when these materials are used as cement substitutes. Second, significant improvements of several concrete properties (i.e., workability, long-term strength, and permeability) can also be achieved.

Figure 2.4 shows the distribution of percentages of fly ash used as replacement for cement. This graph was prepared based on the analysis of a total of 44 different concrete mixtures which were produced with either Class C of F fly ashes.

In general, the typical level of replacement of cement by fly ash is about 20% with the standard deviation of 5%. In addition, Figure 2.4 indicates that maximum fly

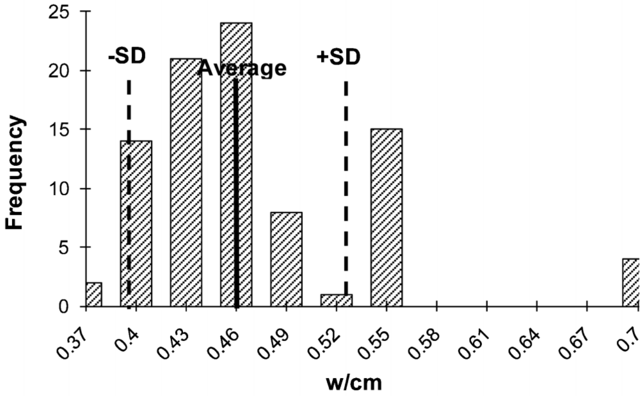


Figure 2.3 Distribution of typical with cm values for 93 concrete pavement mixtures reviewed in this study.

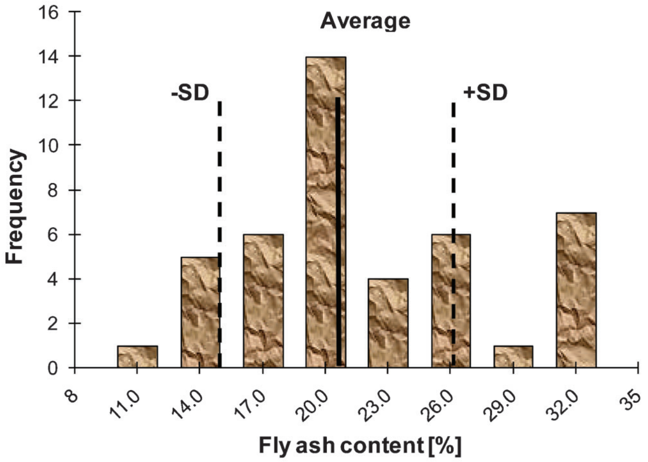


Figure 2.4 Distribution of percentages of fly ash used as replacement for cement in paving mixtures.

ash content for paving mixtures should probably not be higher than 32%.

Due to limited number of mixture proportions with GGBFS collected during the literature review, the histogram for typical replacement levels for GGBFS in paving mixtures cannot be prepared. Instead, the available data is summarized in the form of a bar graph in Figure 2.5.

As can be seen from Figure 2.5, the amount of GGBFS used in concrete paving mixtures can be as low as 15% and as high as up to 50%. Based on limited data presented in Figure 2.5, it seems that about 35% of GGBFS can be considered as a "typical" replacement level used in concrete paving mixtures.

2.1.4 Fine-to-Total Aggregate Ratio

The mass proportion of fine-to-total aggregate was also identified as another characteristic that influences the properties of concrete pavement mixtures. For such mixtures, the content of fine aggregate (typically sand) has to be high enough to obtain good workability, adequate air content and to allow for proper surface finishing. Paving mixtures with low content of fine aggregates can exhibit segregation, develop difficulties with respect to attaining required air content and may experience surface finishability problems. On the other hand, too high content of fine aggregate increases water and binder demands, may result is stiff mixtures and difficulties with proper consolidation (i.e., honeycombing or vibrator trials). The typical concrete distresses related to high fine aggregate content are pavement cracking, excessive scaling and spalling (*9*). Selection of the most efficient fine aggregate content, as well as that of total content of aggregate for particular concrete mixture, can be based on local experience, guidelines proposed by ACI 211.1 (*10*) or alternative methods (i.e., Shilstone's Coarseness Factor Chart, 0.45 Power curve or 8-to-18 Specification (*11*)). More extensive information related to selection of optimized aggregate gradation (including proportions of fine-to-total aggregates) will be presented later in this document. For the purposes of Phase I of this research project, the proportions of fine-to-total aggregates have been selected using data found in the literature and information about local practices (*12*).

Figure 2.6 shows distribution of typical values of fine-to-total aggregate contents for paving mixtures

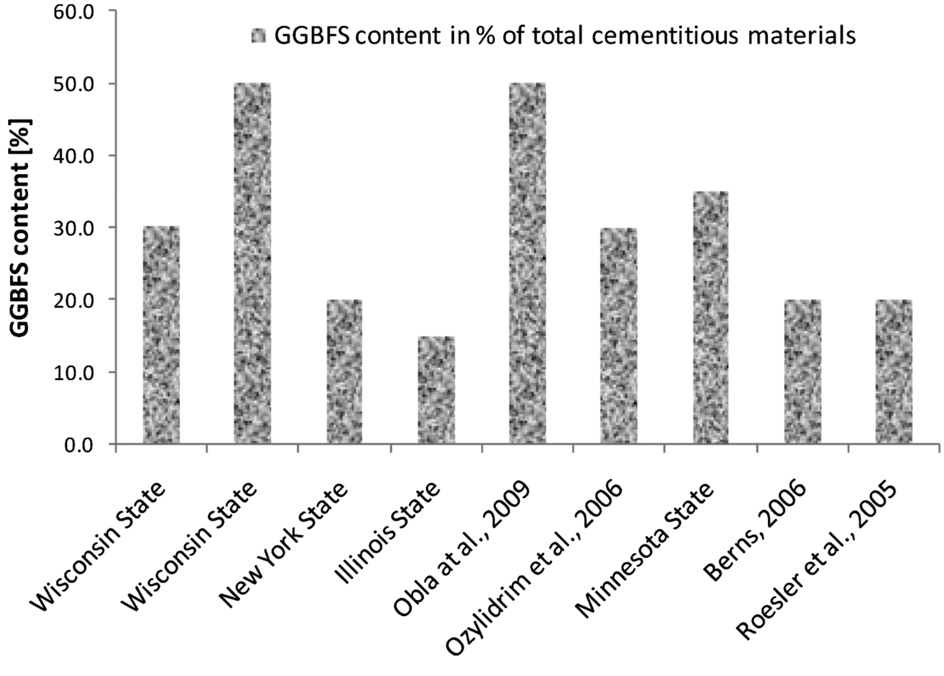


Figure 2.5 Experimental replacement of cement by GGBFS in concrete paving mixtures.

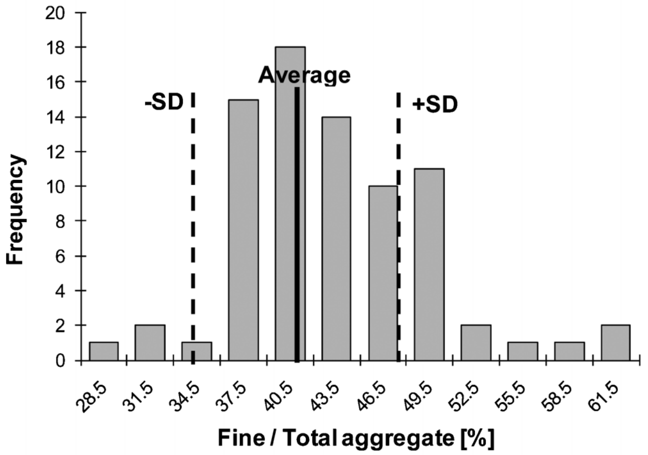


Figure 2.6 Distribution of fine-to-total aggregate contents for paving mixtures.

found in the literature. The average value was 42% with the standard deviation of about 6.1%.

2.2 Aggregate Packing Density (Φ)

Due to specific requirements for consistency, placement techniques, finish-ability and volumetric stability of pavement mixtures the aggregate packing density was introduced in this study to help with the optimization efforts. The packing density of aggregate (Φ) is the ratio of the volume of solids (V_S) to the bulk volume of solids (V_T) as illustrated in Figure 2.7.

In practice, the dry packing density of aggregates can be determined from the known values of apparent solid density of aggregate particles (ρ_{grain}) and bulk density of aggregates (ρ_{bulk}) as follows:

$$\Phi = \frac{\rho_{bulk}}{\rho_{grain}} = \frac{\frac{M_S}{V_T}}{\frac{M_S}{V_S}} = \frac{M_S}{V_T} \cdot \frac{V_S}{M_S} = \frac{V_S}{V_T} \qquad \text{(Eqn.1)}$$

Symbol M_S represents the mass of aggregate sample used to determine packing density of aggregates blend.

Packing density of aggregates (ϕ) calculated from Eqn. 1 can be further expressed as a function of the voids content (ε) (i.e., the fraction of the voids in the bulk volume to be filled by paste or V_V/V_T) as shown in Eqn. 2.

$$\Phi = \frac{V_S}{V_T} = \frac{V_T - V_V}{V_T} = 1 - \frac{V_V}{V_T} = 1 - \varepsilon \qquad \text{(Eqn.2)}$$

Where symbol V_V represents the volume of voids between the aggregate particles.

2.3 Modeling of Aggregate Packing Density

In order to fully evaluate the effect of aggregate packing density on concrete performance, a large number of aggregate blends would have to be produced and evaluated in the laboratory. This extensive amount of work can be easily reduced by utilizing mathematical models which can help to estimate packing density for given aggregate blends, and thus reduce the number of concrete mixtures required in the experimental program.

In 1976 W. Toufar, E. Klose and M. Born (*14*) created the model to calculate the packing density of multicomponent mixtures of particles. According to their model, the packing density of multicomponent system can be calculated as the weighted average of the total number of binary particle mixtures. The model can be applied to systems of particles with the ratios of their characteristic diameters (d_1/d_2) ranging from 0.22 to 1.0 (*13*).

Toufar et al. distinguished three limiting cases for a binary system, each characterized by the diameter ratio and the relative amount of the components:

Case 1:$d_1 >> d_2$ and $V_1 >> V_2$
Case 2:$d_1 << d_2$ and $V_1 << V_2$
Case 3:$d_1 \approx d_2$

Where, d_1 and d_2 are the diameters of small and large particles respectively, and the V_1 and V_2 are the volume fractions of small and large particles, respectively.

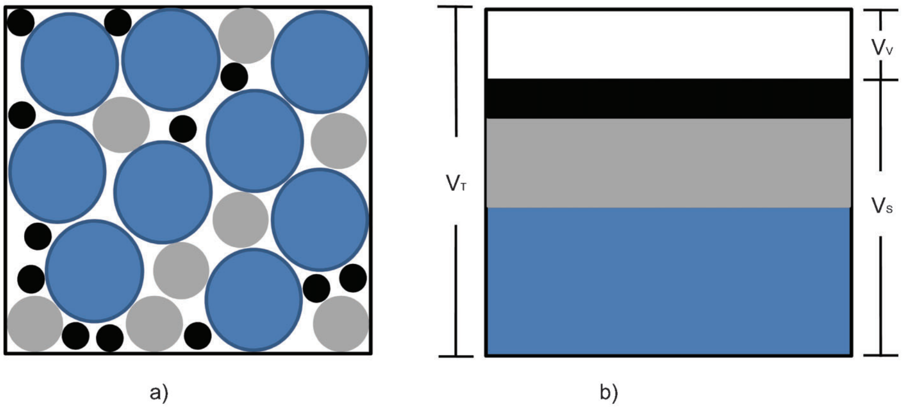


Figure 2.7 Concept of packing density of aggregate: (a) unit volume of bulk aggregate, (b) unit volume divided into fractions (*13*).

For each of the cases presented above, the packing density of the binary blend (Φ) can be predicted by one general formula, presented below.

$$\Phi = \frac{1}{\dfrac{V_1}{\varphi_1} + \dfrac{V_2}{\varphi_2} - V_2 \cdot \left[\dfrac{1}{\varphi_2} - 1\right] \cdot k_d \cdot k_s} \qquad \text{(Eqn.3)}$$

Were, V_1 is the volume fraction of small particles, V_2 is the volume fraction of large particles, d_1 is the diameter of small particles, d_2 is the diameter of large particles, φ_1 is the packing density of small particles, and φ_2 is the packing density of large particles.

The (k_d) factor is equal to $(d_2 - d_1)/(d_1 + d_2)$, whereas the (k_s) was originally developed under the assumption where one fine particle was surrounded by four large particles and is given by $1 - (1 + 4 \bullet x)/(1 + x)^4$. The parameter "*x*" is the ratio of bulk volume of fine particles to the void volume between the coarse aggregates and can be calculated using equation 4.

$$x = \frac{V_1}{V_2} \cdot \frac{\varphi_2}{\varphi_1 \cdot (1 - \varphi_2)} \qquad \text{(Eqn.4)}$$

During the validation process, it was observed that the model did not accurately predict the packing density values for systems with the higher volumes of fine particles. This drawback was corrected by introducing changes to the way of calculating the k_s value. The proposed modification is presented below (*15*).

$$\begin{aligned} k_s &= (x/x_0) \cdot k_0 \qquad for\ x < x_0 \\ k_s &= 1 - (1 + 4(/(1 + x)^4 \qquad for\ x \geq x_0 \end{aligned} \qquad \text{(Eqn.5)}$$

were, x_0 is equal to 0.4753, and k_0 is equal to 0.3881.

For estimating the packing density of a multi-component system of particles, Toufar et al.'s model assumes that any two components form a binary mixture. The binary mixture is than combined with another component, until all particle fractions are included in calculations. The biggest advantage of Toufar et al.'s model is that it can be used for estimating packing density of multi-grain components (for example sand, coarse aggregate and cement). In order to run it, the characteristic diameters of given multi-grain component (d_i) and their individual packing densities (φ_i) must be known.

2.4 Air Void Free Paste-Aggregate Void Saturation Ratio (k″)

The air void free paste-aggregate void saturation ratio (k″) represents the ratio of solid (no air voids) amount of paste to the amount of voids in the aggregate for given concrete mixture. The simplest way of calculating this parameter is shown in equation 6.

$$k'' = \frac{V_p - V_{air}}{1 - \Phi} \qquad \text{(Eqn.6)}$$

where: V_P represents a total paste volume (including volumes of cementitious materials, water and design air), V_{air} is the target (design) air content in the fresh mixtures (6.5%) and $1 - \Phi$ is the fraction of voids in the unit volume of aggregate.

The concept of air void free paste-aggregate void saturation ratio was initially introduced by Jacobsen and Arntsen (*16*). It resulted from their research during which a number of constant consistency (slump and flow) mixtures were proportioned by varying aggregate packing density (Φ) and aggregate void content ($1 - \Phi$) and using different volumes of cement paste (V_p). They observed good correlations between aggregate void content ($1 - \Phi$) and paste volume, indicating that the simple measurements of packing density of bulk aggregate can give useful information with regard to concrete proportioning. Based on their test results, Jacobsen and Arntsen suggested the value of air void free paste-aggregate void saturation ratio (k″) equal 1.15 as a good starting point for proportioning of concrete mixtures.

The influence of voids content of aggregate blends on workability was discussed in the past by Kaplan (*17*), Powers (*18*) and more recently by Neville (*19*) and Kwan et al. (*20,21*). However, there is no agreement to whether it is better to use aggregate blends with lower or higher void contents. The most recent research on this topic presented by Kwan et al. (*20,21*) suggested that maintaining the minimum void content (highest packing density) in aggregate has positive effect on concrete pumpability and strength. In the case of pumpability, aggregate with a minimum void content requires only a small excess of cement paste to make concrete mixture pumpable. In case of strength, a small void content leads to lower water requirements and, consequently, higher strength.

Both k″ and void content concepts seem to be interesting for further exploring. However, they should be also utilized in potential improvements of other (i.e., durability) concrete properties. In addition, it seems to be important to evaluate the optimum k″ values in connection with optimum paste contents developed in Phase I of the research.

2.5 Response Surface Methodology

Response surface methodology (RSM) is a collection of statistical and mathematical techniques applied for developing, improving, and optimizing processes (*22*). The typical implementation of this technique is in the industrial processes and manufacturing, particularly in situations where several input variables (factors) potentially influence some performance measure or quality characteristic. The performance measure or quality characteristic is called the *response*, whereas the input variable is known as *independent variable*. In the case of concrete mixtures, the factors influencing responses can be represented by proportions of individual constituents (i.e., cement, fly ash, GGBFS contents) or combination of some of them (i.e., w/cm ratio, paste content). On the other hand, the responses are typically associated with measured properties of fresh concrete, properties of hardened concrete or mixtures cost.

The most important advantage of using RSM method is the fact that the project specific materials can be used (and accounted for) during the experimental design, modeling and optimization stages. Moreover, the RSM gives not only the expected properties (responses) but also accounts for their uncertainty (variability). This advantage of RSM methodology has important implications for specifications and for production. The empirical model equation gives only the expected mean value of measured property (predicts the mean value for replicates). Typically, to ensure that most of the results for the considered property would comply with specifications, a producer would select target value for the mean to account for the variability and to ensure that, for example, 95% of the results would meet or exceed the specified value (*23*).

The disadvantage of RSM methodology is the fact that it requires an initial investment of time and money for planning and performing trial batches and tests. Additionally, knowledge of good experimentation procedures and some knowledge of statistical analysis are needed. Finally, sometimes when the results of optimization process are to be used for a large scale project, the mean values for predicted responses may not be accurate if materials with significantly different properties are used (i.e., fly ash from different sources, finer cement, etc.).

The Response Surface Methodology consists of three major steps: experimental design, modeling, and optimization. The detailed explanation of each of these steps is provided elsewhere (*24*).

2.6 Statistical Optimization Process

The optimization process (as required by RSM) was used in Phase I and Phase III of the research project. All steps of optimization process were essentially the same for both Phase I and Phase III. The differences between optimization processes applied in both Phases involved: use of different variables, use of different number of performance responses and use of different target values for selected responses. As an example, the steps involved in the optimization process of binary mixtures used in Phase I are briefly discussed below.

The performance characteristics chosen for the purposes of optimizing concrete proportions included the following: the 7 and 56 days flexural strength, 7, 28 and 90 days compressive strength, scaling resistance (mass loss) after 50 cycles of freezing and thawing, free shrinkage after 448 days of drying, rate of water sorption, rate of water absorption, and cost of raw materials to produce each mixture. The objective of the optimization process used in this study was to select composition of concrete mixtures which will be most economical while, at the same time, capable to satisfy requirements of minimum or maximum value for all of the performance characteristics listed above.

All of the above performance characteristics were treated in the experimental plan as the desired responses which depended on the combination of two independent variables: the total paste content in the mixture and the amount of both fly ash or GGBFS in the mixture. Excluded from the optimization process were the fresh properties of concrete as all mixtures were designed for nominally constant slump and air contents.

The optimization process utilized in this research consisted of three main steps: Step 1—development of statistical models for prediction of selected responses (performance characteristics); Step 2—selection of desirability functions and conversion of predicted responses to minimum (0) or maximum (1) desirability values; and Step 3—combining individual desirability values from Step 2 into overall desirability function and using this function to select an optimum concrete proportions. Each of these steps, in turn, contained several sub-steps which are briefly summarized below.

2.6.1 Step 1—Development of Statistical Models

The process of models development was started by performing statistical analysis of the results. The analysis was initiated by investigation of the data correctness with respect to precision and bias included in the standard specifications. Next, the statistical software was utilized to perform multiple regression analysis. This multiple regression analysis involved running ANOVA evaluation for full quadratic model, checking *t*-statistic for each model coefficient and the F-values for the regression model. The ANOVA analysis helped to evaluate initial full quadratic model. If any of the model coefficients was found to be statistically not significant, the variable associated with this coefficient was removed and ANOVA analysis was repeated using partial quadratic or linear model. Finally, the validation of a model was performed by calculating case statistics (to identify outliers) and by examining the diagnostic plots such as Quantile-Quantile (QQ) plot and residual vs. predicted value plots. The detailed description of model development process for central composite design method has been previously described by Simon (*23*) and Lu (*25*).

2.6.2 Step 2—Selection of Desirability Functions and Establishment of Desirability Values

In Step 2, the desirability (objective) functions were selected for each of the performance responses. First, three types of desirability functions minimum, maximum and linearly decreasing (*26*) were selected for optimization purposes. Next, the target performance values were assigned to each of the desirability functions. These target (critical) values were selected based on multiple literature sources, existing specifications and in-depth data analysis.

Table 2.1 presents target values for all performance responses along with type of desirability function utilized in the optimization process.

TABLE 2.1
Summary of target values for performance responses with assigned types of desirability functions

Desirability function, d_i	Basis for selection	Desirability function type
7d flex	L = 3.9 MPa (minimum value required for concrete pavements in section 500 of INDOT's specifications) (*5*)	Min.
56d flex	L = 5.6 MPa (minimum value measured for reference mixture CTRL_335)	Min.
7d comp.	L = 24.1 MPa (minimum design strength for concrete pavement mixtures in Michigan at 7 days (Specification 601 (*27*))	Min.
28d comp.	L = 34.5 MPa (typical value of compressive strength for concrete pavements in Indiana)	Min.
90d comp.	L = 37.4 9 MPa (arbitrary values, assuming 10% increase in strength from this achieved at 28 days)	Min.
Scaling	U = 0.8 kg/m^2 (the maximum amount of scaled material allowed for concrete barrier mixtures according to Ontario Provincial Standard Specification) (*28*)	Max.
Shrinkage	U = −515 με (this value represents the long-term drying shrinkage of concrete mixtures in which the expected probability of cracking is only 28.6% (*29*)	Max.
Sorptivity	U = 23.4·10 mm/s$^{0.5}$	Max.
Absorptivity	U = 26.2·10 mm/s$^{0.5}$	Max.
Cost	U= 96.53 $/m^3 L = 64.55 $/m^3	Linear

The symbols "L" and "U" used in Table 2.1 represent, respectively, lower and upper limits for desirability functions selected to optimize each response. The selection of critical values for water sorptivity and absorptivity, as well as the cost, requires further explanation and will be presented in the next paragraph.

In case of water ingress data, the critical values were selected based on observed linear correlation between these measured properties and scaling data, as illustrated in Figure 2.8.

Using the value of 0.8 kg/m^2 (this value is considered to be an acceptable limit for scaling by the Ontario Ministry of Transportation (*28*) as an input into equations shown in Figure 2.8, the target (critical) values for sorptivity and absorptivity may be established. The resulting values are reported in Table 2.1.

The cost was modeled by a linearly decreasing function, which required upper and lower limits. The upper cost limit used for ternary mixtures was the same as the one used for plain concrete with 335 kg/m^3 of cement. The lower cost limit was established based on modified standard Iowa's Class B paving mixture (*30*). This modification allows for replacement of up to 40% of cement (20% by fly ash and 20% by GGBFS).

2.6.3 Step 3—Combining of Individual Desirability Values

Once the individual predicted responses had been converted into desirability values, the composite response (representing the influence of all variables studied) was calculated using Equation 7.

$$D = (d_1 \cdot d_2 \cdot \ldots \cdot d_n)^{1/n} \qquad \text{(Eqn.7)}$$

where, d_n represents the desirability values for individual performance responses, D is the overall

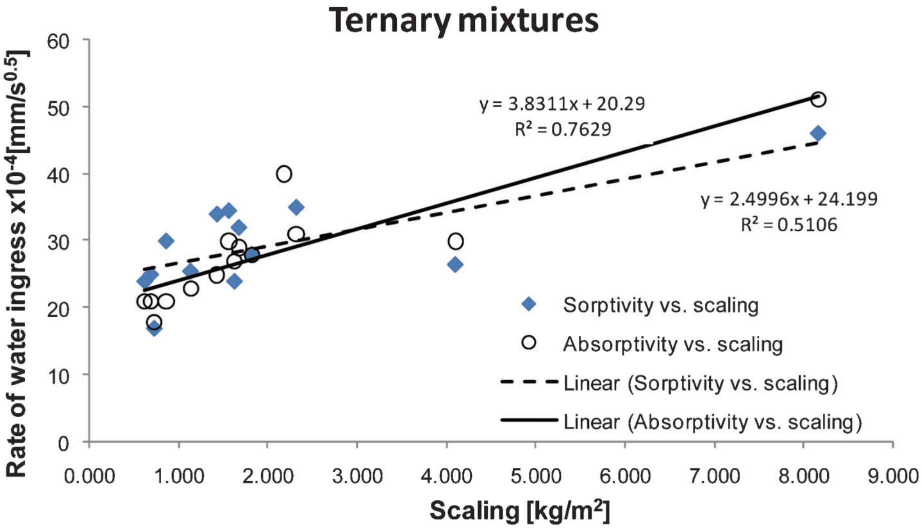


Figure 2.8 Correlation between scaling and the rate of water ingress for ternary mixtures.

desirability (geometric mean) and n is the number of performance responses utilized in optimization process. Finally, the maximum value of the overall desirability (D_{max}) was found and used to prepare a series of contour plots which can be used to graphically establish the location of the optimum point.

CHAPTER 3. EXPERIMENTAL APPROACH

3.1 Phase I—Binder Optimization

For the purposes of this project, three types of concrete mixtures were selected. These included two groups of concrete mixtures with binary binders and one group of mixtures with ternary binders. The first group of mixtures with binary binders consisted of Type I Portland cement and fly ash. The second group consisted of Type I Portland cement and GGBFS. The ternary binders consisted of Type I Portland cement and both fly ash and GGBFS.

For each mixture in these three groups of mixtures two types of experimental factors (variables) were defined: (a) the amount of supplementary cementitious material expressed as the weight percent of total cementitious materials used in mixture design, and (b) the percent of air-free paste by mixture volume. The selection of the first factor was required from the optimization perspective, since utilization of optimum amount of supplementary cementitious materials should enhance durability and reduce the cost of concrete mixtures. The paste in concrete mixtures acts as binder for aggregate skeleton, giving it required strength and stiffness. It also provides required workability, due to reduction of friction between aggregate particles. On the other hand, hardened paste is susceptible to harsh environmental conditions (mainly freezing and thawing) and action of deicing chemicals which (over time) accelerate concrete degradation. Many authors believe that paste in concrete mixtures must be optimized in order to extend the life of concrete structures since it is the least durable part of hardened concrete matrix (*1,11*). Following this approach, the air-free paste content (rather than the total amount of cementitious materials) was adopted in this study as the experimental variable. To minimize the influence of other variables, the water-to-cementitious ratio and air content of all mixtures were kept constant (at 0.44% and 6.5%, respectively).

3.1.1 Variables for Mixtures with Binary Binders

The summary of selected experimental factors used in development of binary systems is presented in Table 3.1.

The ranges of research variables presented in Table 3.1 resulted in production a total of 18 different concrete mixtures. The detailed proportions of all concrete binary concrete mixtures are listed in Table 3.2 (fly ash) and Table 3.3 (GGBFS).

In addition to binary mixtures shown in Table 3.2 and 3.3, two reference (cement only) mixtures were also produced. The first mixture contained 515 pounds of cement per cubic yard of concrete, and represented typical plain concrete mixture (with about 23.2% of paste) used by contractors from Indianapolis (USA) area. This mixture contained the amount of cement close to the limit of total cementitious materials recommended by ACPA (of 506 lb/yd^3) (*6*) to produce satisfactory concrete for pavements. The second reference mixture contained 565 pounds of cement per cubic yard of concrete and represented standard prescriptive paving mixture as per Section 502 of Indiana's standard specification for pavements (*5*).

3.1.2 Variables for Mixtures with Ternary Binders

The summary of selected experimental factors used in development of ternary systems is presented in Table 3.4.

The ranges of research variables presented in Table 3.4 resulted in production a total of 15 different concrete mixtures. The detailed proportions of all ternary concrete mixtures are listed in Table 3.5.

*3.1.3 Materials Selected for Phase **I***

All mixtures produced in Phase I were designed using the following parameters:

(a) Constant water to binder ratio (w/cm = 0.44).
(b) Constant fine to total aggregate ratio (FA/total aggregate = 0.45) by mass.
(c) Target slump: 2 in. ± 1 in. (50 mm ± 25 mm).
(d) Target air content: 6.5% ± 1.0%.

The materials selected for the purpose of concrete mixtures design represented typical concrete constituents

TABLE 3.1
Summary of ranges of experimental variables for binary binder systems

	Experimental factors (Fly ash binder system)		Experimental factors(GGBFS binder system)	
	X_1	X_2	X_1	X_2
Ranges	Fly ash content (14–30%)[1]	Paste volume(21–25%)[2]	GGBFS content (20–40%)[1]	Paste volume(21–25%)[2]
Levels (%)	14, 18, 22, 26, 30	21, 22, 23, 24, 25	20, 25, 30, 35, 40	21, 22, 23, 24, 25

[1] Weight% of total cementitious materials.

[2] Paste volume is defined as the sum of absolute volumes of water and cementitious materials only (excluding entrapped and entrained air).

TABLE 3.2
Mixture proportions for binary cementitious system (PC + FA)

Paste volume [%]	21.0	22.0	22.0	23.0	23.0	23.0	24.0	24.0	25.0	23.2	25.5
	Fly Ash Type C									**Ref.**	**Ref.**
Fly ash amount	22.0%	18.0%	26.0%	14.0%	22.0%	30.0%	18.0%	26.0%	22.0%	0.0%	0.0%
Components [lb/yd^3]											
Cement	357	395	354	433	391	349	431	386	425	515	565
Fly ash	101	87	124	71	110	149	95	135	120	0	0
Total cementitious mat.	458	482	478	504	501	498	525	521	545	515	565
Water	202	212	210	222	220	219	231	229	240	227	249
Fine agg. mass	1456	1436	1436	1416	1416	1416	1396	1396	1375	1412	1367
Coarse agg. mass	1779	1755	1755	1730	1730	1730	1706	1706	1681	1725	1671
Total aggregate mass	3235	3191	3191	3146	3146	3146	3101	3101	3057	3137	3039
Water reducer (WR) [fl. oz/cmwt]	8.50	6.50	6.00	5.00	4.70	4.00	2.80	2.40	1.00	6.25	2.00
Air entrainer (AE) [fl. oz/cmwt]	0.65	0.75	0.75	0.70	0.80	0.90	0.85	0.90	1.10	0.60	0.90
Air [%]	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
w/cm	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44

TABLE 3.3
Mixture proportions for binary cementitious system (PC + GGBFS)

Paste volume [%]	21.0	22.0	22.0	23.0	23.0	23.0	24.0	24.0	25.0	23.2	25.5
	Ground Granulated Blast Furnance Slag (GGBFS)									**Ref.**	**Ref.**
Slag amount	30.0%	25.0%	35.0%	20.0%	30.0%	40.0%	25.0%	35.0%	30.0%	0.0%	0.0%
Component [lb/yd^3]											
Cement	323	363	313	406	354	302	396	342	384	515	565
GGBFS	139	121	169	101	152	201	132	184	165	0	0
Total cementitious mat.	462	484	482	507	505	503	528	526	549	515	565
Water	203	213	212	223	222	221	232	231	242	227	249
Fine agg. mass	1456	1436	1436	1416	1416	1416	1396	1396	1375	1412	1367
Coarse agg. mass	1779	1755	1755	1730	1730	1730	1706	1706	1681	1725	1671
Total aggregate mass	3235	3191	3191	3146	3146	3146	3101	3101	3057	3137	3039
Water reducer (WR) [fl. oz/cmwt]	9.75	9.00	7.00	5.70	6.50	6.50	5.00	4.80	3.30	6.25	2.00
Air entrainer (AE) [fl. oz/cmwt]	0.60	0.55	0.60	0.65	0.75	0.80	0.75	0.80	0.80	0.60	0.90
Air [%]	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
w/cm	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44

TABLE 3.4
Summary of ranges of experimental variables for ternary binder systems

	Experimental Factors (variables)		
	X_1	**X_2**	**X_3**
Ranges	Fly ash content (10–20%)[1]	GGBFS content (18–30%)[1]	Paste volume (21–25%)[2]
Levels (%)	10, 12.5, 15, 17.5, 20	18, 21, 24, 27, 30	21, 22, 23, 24, 25

[1] Weight% of total cementitious materials.

[2] Paste volume is defined as the sum of absolute volumes of water and cementitious materials only (excluding entrapped and entrained air).

TABLE 3.5
Mixture proportions for ternary cementitious system (PC + FA + GGBFS)

Paste volume [%]	21.0	22.0	22.0	22.0	22.0	23.0	23.0	23.0	23.0	23.0	24.0	24.0	24.0	24.0	25.0	23.2	25.5
	Fly ash Class C/GGBFS cement															**Ref.**	**Ref.**
Fly ash/GGBFS amount	15/24	12.5/21	12.5/27	17.5/21	17.5/27	10/24	15/18	15/24	15/30	20/24	12.5/21	12.5/27	17.5/21	17.5/27	15/24	0/0	0/0
Components [lb/yd^3]																	
Cement	279	319	290	294	265	331	336	305	274	279	348	316	321	289	332	515	565
Fly ash	69	60	60	84	83	50	75	75	75	100	66	65	91	91	82	0	0
GGBFS	110	101	129	100	129	120	90	120	150	120	110	141	110	141	131	0	0
Total cementitious mat.	458	480	479	478	477	502	501	500	499	498	524	523	522	521	544	515	565
Water	202	211	211	210	210	221	220	220	220	219	231	230	230	229	239	227	249
Fine agg. mass	1456	1436	1436	1436	1436	1416	1416	1416	1416	1416	1396	1396	1396	1396	1375	1412	1367
Coarse agg. mass	1779	1755	1755	1755	1755	1730	1730	1730	1730	1730	1706	1706	1706	1706	1681	1725	1671
Total aggregate mass	3235	3191	3191	3191	3191	3146	3146	3146	3146	3146	3101	3101	3101	3101	3057	3137	3039
Water reducer (WR) [fl. oz/cmwt]	8.50	7.00	7.50	6.80	7.00	6.50	6.00	5.50	5.50	3.80	4.00	3.50	3.00	2.00	0.50	6.25	2.00
Air entrainer (AE) [fl. oz/cmwt]	0.70	0.75	0.80	0.80	0.85	0.80	0.80	0.85	0.90	0.93	0.95	0.95	0.90	1.00	1.25	0.60	0.90
Air%	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
w/cm	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44

used by contractors in Indiana. The cementitious materials used in this study included: ASTM C 150 Type I Portland cement (*31*), ASTM C 989 Grade 120 slag cement (ground granulated blast furnace slag (GGBFS)) (*32*) and ASTM C 618 Class C fly ash (*33*).

Locally available natural siliceous sand (SpG = 2.66 and absorption 1.27%), meeting gradation requirements of INDOT's specification for #23 material (*34*) was used as fine aggregate. The coarse aggregate used was crushed limestone (SpG = 2.64 and absorption 1.30%) with maximum size of 19 mm (¾ in.) and gradation meeting the requirements of INDOT's specification for #8 stone (*3*). In order to eliminate batch-to-batch variations all coarse aggregates where sieved and recombined prior to mixing. Figure 3.1 shows the combined aggregate gradation superimposed on 8-to-18 plot proposed by Iowa DOT (*35*), as well as on the USAF version of Shilstone's Coarseness Factor Chart (*36*).

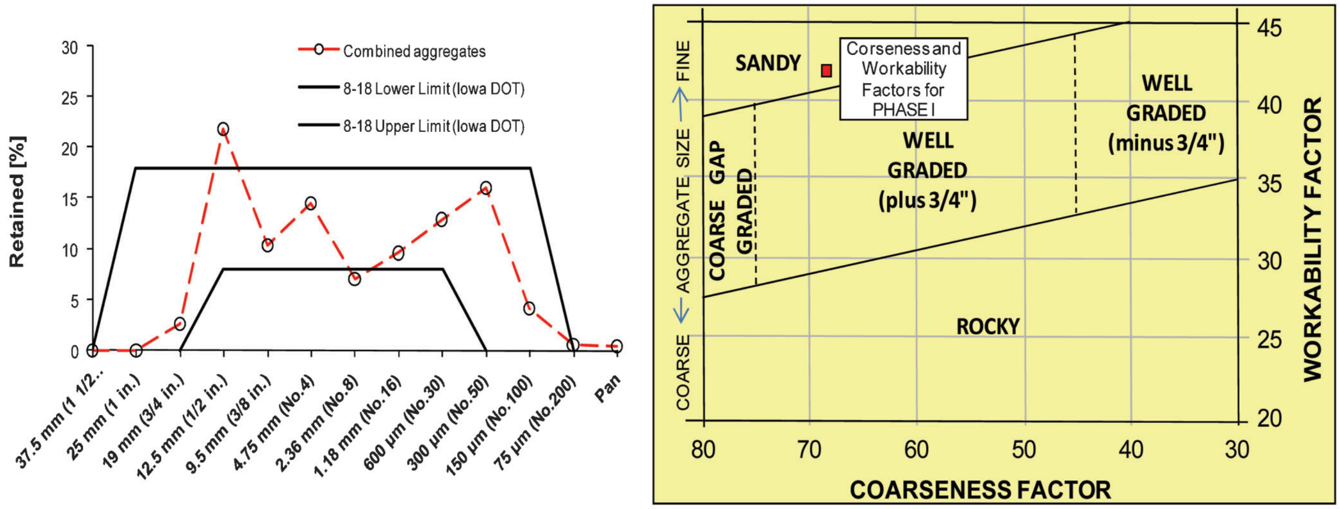
The combined aggregate gradation selected for Phase I of the study satisfied the ranges for percentages retained specified by Iowa DOT (see Figure 3.1) in a sense that none of the results for two subsequent sieve sizes were outside the "8-18" limits. However, this gradation was considered "sandy" when plotted on Shilstone's chat (mainly due to high content of sand, which was 45% of total aggregate). The selection of this gradation was recommended by project advisors and was consistent with typical practices of Indiana DOT (*12*).

Two chemical admixtures: vinsol-based air entraining agent (AEA) and modified glucose polymer-based normal range water reducing admixture (WR) (complying with ASTM C 494 Type A) (*37*) were used to achieve target air content of 6.5% ± 1.0% and slump of 50 mm ± 25 mm (2 in. ± 1 in.).

3.2 Phase II—Evaluation of the Influence of Aggregate Gradation on Concrete Properties

It has been generally established that aggregates occupy from 70 to 80% of the volume of concrete mixture and thus they strongly influence several concrete properties. Some aggregate properties are inherently connected to the concrete mixture design process (i.e., shape and texture, maximum size and gradation, moisture content, specific gravity, and unit weight). Among them, the shape and texture, as well as the maximum particle size and gradation were considered to be most relevant in this research because they are directly linked to the amount of cement paste required for a given mixture. As such, they can be used in mixture optimization process to lower the cost and to improve other properties (i.e., to reduce shrinkage) (*38*). For these reasons, it was decided to account for these parameters in the current project and thus make the process of optimization of concrete proportions more comprehensive.

Based on literature review related to research and recommendations on optimum combination of aggre-



a) b)

Figure 3.1 Combined aggregate gradation for Phase I mixtures shown on "8-to-18" plot (a) and on Shilstone's Chart (b).

gates for paving mixtures (more details can be found in (*24*)), it was decided to conduct some additional study addressing following issues:

(a) Evaluate the influence of aggregate gradation from Zone II of Shilstone's coarseness chart on the demand for water reducing admixture
(b) Evaluate the effect of aggregate gradations from Zone II of Shilstone's coarseness chart on shrinkage and durability
(c) Establish guidelines for selection the optimum aggregate gradations suitable for inclusion in the Indian's Specification for Concrete Pavements
(d) Explore the potential to increase the maximum allowable coarse aggregate size for paving mixtures in Indiana (from ¾ in. to 1 in.)
(e) Identify additional parameters influencing selection of optimum aggregate gradation for paving mixtures (i.e., aggregate packing density, paste requirements).

The research conducted as Phase II of this study was a continuation of binder optimization efforts conducted during Phase I. In order to minimize the number of variables, and to maintain the same quality of the paste, the same materials (except for one type of coarse aggregate) as those utilized in Phase I were also used in Phase II. Type I Portland cement used in Phase II of the study was from the same producer as the cement used in Phase I. Similarly, the Grade 120 GGBFS and Class C fly ash were the same as those used in Phase I. In order to achieve the desired fresh concrete properties (slump of 2.0±1.0 in. and air content of 6.5±1.0%), the set of chemical admixtures (normal range water reducer and air-entraining agent) as previously used in Phase I was utilized in Phase II.

3.2.1 Individual Aggregate Gradations

Phase II of the study was accomplished using the following aggregates:

(a) Fine aggregate, consisted of natural siliceous sand meeting the gradation requirements of INDOT #23 aggregate (*5*). This sand was from the same source as the one used in Phase I but from different shipment.
(b) Intermediate aggregate, consisted of crushed limestone meeting the gradation requirements of INDOT #11 (NMS ⅜ in.) aggregate (*5*). This limestone was obtained from the same source as #8 coarse aggregate described below.
(c) Coarse aggregate (1), consisted of crushed limestone meeting the requirements of INDOT #8 (NMS ¾ in.) aggregate (*5*). This limestone was obtained from the same limestone source used in Phase I but it was from different shipment.
(d) Coarse aggregate (2), consisted of crushed dolomite meeting the requirements of INDOT #5 (NMS 1 in.) aggregate (*5*). This dolomite aggregate was obtained from different source and producer than #8 stone).

All aggregates used during Phase II of the study were classified as highest quality (AP) aggregates, according to Section 900 of INDOT specification (*5*). The values of bulk specific gravity (in saturated surface dry conditions), absorption of these aggregates as well as their individual gradations can be found in Section 4.7.3 of another publication (*24*).

3.2.2 Selection of Combined Gradations

As a part of the aggregate optimization segment of the study, the aggregates with individual gradations described in previous section were further combined (using various percentages of each) to produce blends with varying packing densities. The procedure used for selection of the individual combined gradations was as follows:

(a) First, the Shilstone's chart was used to select desired pair of combination of coarseness and workability factors, which will give blends leading to concrete with selected type of response.
(b) Next, different proportions of selected individual aggregates were combined to meet proposed values of coarseness and workability factors.
(c) Finally, the gradation of the combined blends was plotted on the "8-to-18" and 0.45 power charts in order to better illustrate the differences between selected combined gradations.

The selection of Shilstone's coarseness chart as the primary source for defining the properties of combined aggregate gradation was based on the results of literature review previously presented in Section 4.3 of another publication (*24*). Many state and government agencies, i.e., Iowa DOT (*35*), USAF (*7*), as well as independent researchers, i.e., Cramer (*39*), Quiroga and Fowler (*40*) recommended and used this method to identify well or gap-graded aggregate blends. Figure 3.2 shows the values of coarseness and workability factors selected for combined aggregate blends utilized in Phase II of the study.

There are total of 6 different combined aggregate gradations (Grad 1–Grad 6) (marked with star symbol) shown in Figure 3.2. These gradations represent the widest spread of coarseness and workability factors in Zone II of Shilstone's chart which was possible to obtain by blending individual aggregate gradations selected for Phase II. The individual aggregate gradations were kept constant for entire Phase II of the research project. That means that final blends used throughout Phase II were produced by combining various percentages of individual gradations (namely, INDOT #23, #11, #8 or #5).

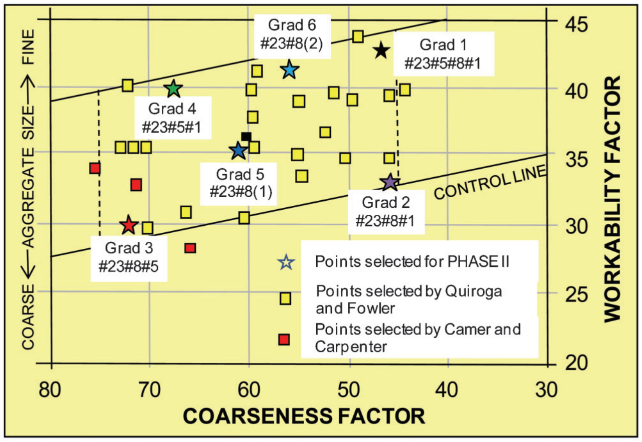


Figure 3.2 The Shilstone's coarseness factor chart with points representing combination of coarseness and workability factors selected for investigation in Phase II of the study.

Three of the blends shown in Figure 3.2. (Grad 1, 3 and 4) were produced using aggregate with the nominal maximum size (NMS) of 1 in., whereas aggregates with NMS of ¾" were used in three other blends (Grad 2, 5 and 6). The fine aggregate content (#23 sand) was 44% for Grad 1, 33% for Grad 2, 30% for Grad 3, 40% for Grad 4, 36% for Grad 5, and 43% for Grad 6 (all expressed as percent of the total blend mass). Based on this data, it can be concluded that concrete mixtures with Grad 3 may be problematic due to insufficient amount of fine material; on the other hand, mixtures with Grad 1 may appear too sticky, due to high fines content.

Finally, in order to provide more details on combined aggregate gradations used in Phase II, the "8-to-18" chart is presented in Figure 3.3. As recommended by the Iowa DOT, this method was used herein as additional tool to analyze the combined gradations and to check to what degree they satisfy the requirements of so called optimal gradations.

The first observation that can be made from Figure 3.3 is fact that all six of the combined gradation exhibit shortage of particles retained on #8 (corresponding data points at or below 8% limit). This shortage of #8 fraction is the result of using sand with constant gradation. The second characteristic of these six combined gradations is that significant differences exist in the amount of aggregate retained on ¾, ½ and No. 4 sieves. It is expected that these differences will have significant effect on concrete workability, finishability, as well as on hardened properties. The gradation No. 3 can be considered as near-gap graded since it is characterized by the most significant gap on No. 8 and No. 16 sieves (due to low sand content). On the other hand, gradation No. 5 represents (using Shilstone's criteria (*11*)) the most optimized gradation in terms of coarseness and workability factors. Finally, combined gradations No. 4 and No. 6 seem to satisfy "8-to-18" guidelines the best. For these gradations, the proportions of coarse particles were well balanced (no significant domination by single fraction), plus, in case of gradation No. 4, utilization of #11 intermediate aggregate reduced gap at ⅜ in. sieve.

Additionally, the aggregate packing densities were measured for six selected aggregate gradations utilized in Phase II. The packing densities of aggregate blends produced in Phase II were obtained according to ASTM C 29 (*41*) using standard rodding procedure. These values are presented in Table 3.6.

3.2.3 Selection of Concrete Mixture Proportions for Phase II

The selection of concrete mixture proportions for Phase II was driven by the results of binder optimization conducted in Phase I of this research project. The main goal was to select one (optimum or practical

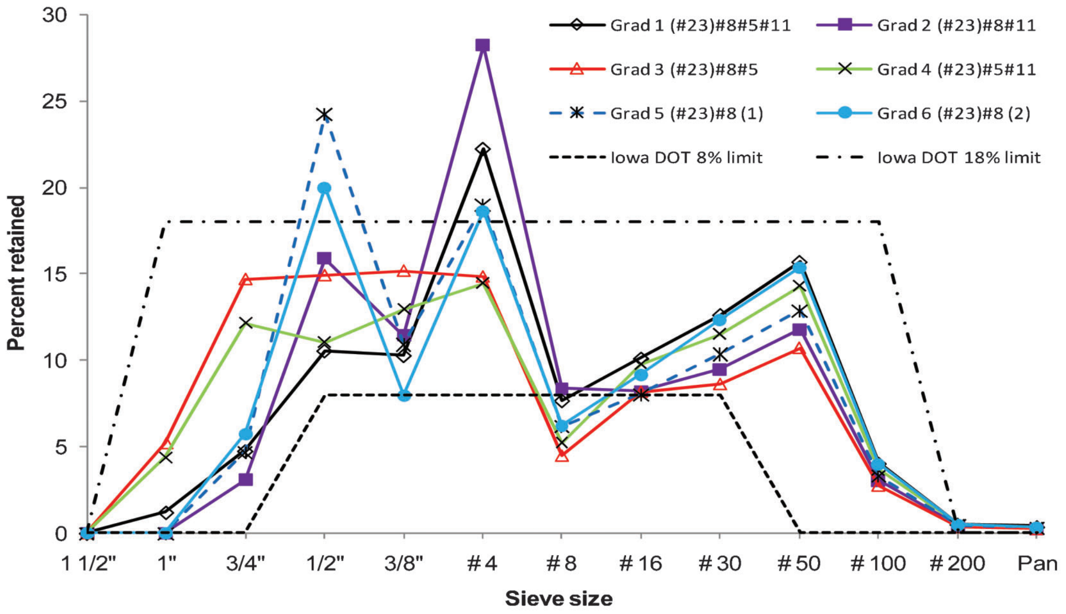


Figure 3.3 The combined gradations of Phase II aggregates blends superimposed on the "8-to-18" plot.

optimum) mixture from each three binder groups studied and use it as a basis to produce six separate concrete mixtures, each with different aggregate blend. As a result, a total of 18 new concrete mixtures were produced during Phase II of the study. The target proportions for each of the three groups of mixtures selected are given in Table 3.7.

3.3 Phase III—Influence of Packing Density on Performance of Low Slump Concretes

The observations made while analyzing the results of Phase II led to the conclusion that some optimum values of k″ must exist in order to achieve balance between required workability, shrinkage and durability of paving mixtures. This conclusion, in turn, resulted in the hypothesis that if such optimum value of k″ can be found, it could be used to further enhance the process of mixture proportioning (beyond the binder optimization approach presented in Phase I). Phase III was designed and devoted to exploring this hypothesis.

3.3.1 Variables Selected for Phase III

The variables selected for Phase III study included the combined aggregate packing density (Φ) and air void free paste-aggregate voids saturation ratio (k″). The ranges of the experimental variables were selected based on the results of simulation (details can be found in Chapter 5 of another publication (*24*)) and literature study for packing density and aggregate saturation ratio, respectively. The ranges selected for experimental factors were as follows:

- Packing density (Φ) (from 0.716 to 0.786)
- Air void free paste-aggregate void saturation ratio (k″) (from 0.900 to 1.018)

The combinations of experimental variables (presented as coded and uncoded values) are given in Figure 3.3.

As shown in Table 3.8, the experimental plan required selection of 5 aggregate blends with packing densities ranging from 0.716 to 0.786. In order to establish this range, both binary and ternary blends were utilized. Thus the 5 aggregate blends selected for Phase III concrete mixtures production must also accommodate binary and ternary blends. At this point the arbitrary decision was made to involve in the experimental plan as many ternary blends as possible. As the result ternary blends were prepared with packing density values of 0.786, 0.776 and 0.751. Whereas binary blends were prepared with packing density values of 0.726 and 0.715. The packing densities of binary and ternary blends were estimated based on

TABLE 3.6
Apparent density (ρ_{grain}), bulk density (ρ_{bulk}) and packing density values for combined aggregate gradations used in Phase II

	Grad 1	Grad 2	Grad 3	Grad 4	Grad 5	Grad 6
Apparent density (ρ_{grain}) [lb/ft^3]	163.09	162.84	165.06	164.67	162.48	162.45
Bulk density (ρ_{bulk}) [lb/ft^3]	115.47	111.38	116.04	116.75	115.52	117.13
Packing density [%]	70.8	68.4	70.3	70.9	71.1	72.1

TABLE 3.7
The target proportions of concrete mixtures selected for Phase II of the research project

Proportions [lb/yd^3]	Slag mixture	Fly ash mixture	Ternary mixture
Cement	343	375	278
Slag	162		125
Fly ash		106	77
Total cementitious	505	481	480
Water	222	211	211
Fine aggregate	1347	1366	1366
Coarse aggregate	1785	1811	1811
w/cm	0.44	0.44	0.44
Paste volume [%]	23.0	22.0	22.0

TABLE 3.8
Combination of experimental variables for Phase III

Coded		Uncoded	
Packing density, Φ	k″	Packing density, Φ	k″
0	1.414	0.751	1.081
0	0	0.751	0.975
1	1	0.776	1.050
−1	1	0.726	1.050
1	−1	0.776	0.900
1.414	0	0.786	0.975
−1	−1	0.726	0.900
0	−1.414	0.751	0.869
−1.414	0	0.715	0.975

previously presented work by Toufar et al. (*14*). A total of 5 binary blends and a total of 15 ternary blends were simulated.

3.3.2 Summary of Phase III Aggregate Blends

The best way to summarize the combined aggregate gradation selected for Phase III of the study is to present them in a form of "8-to-18", 0.45 power and Shilstone's coarseness charts as shown in Figure 3.4.

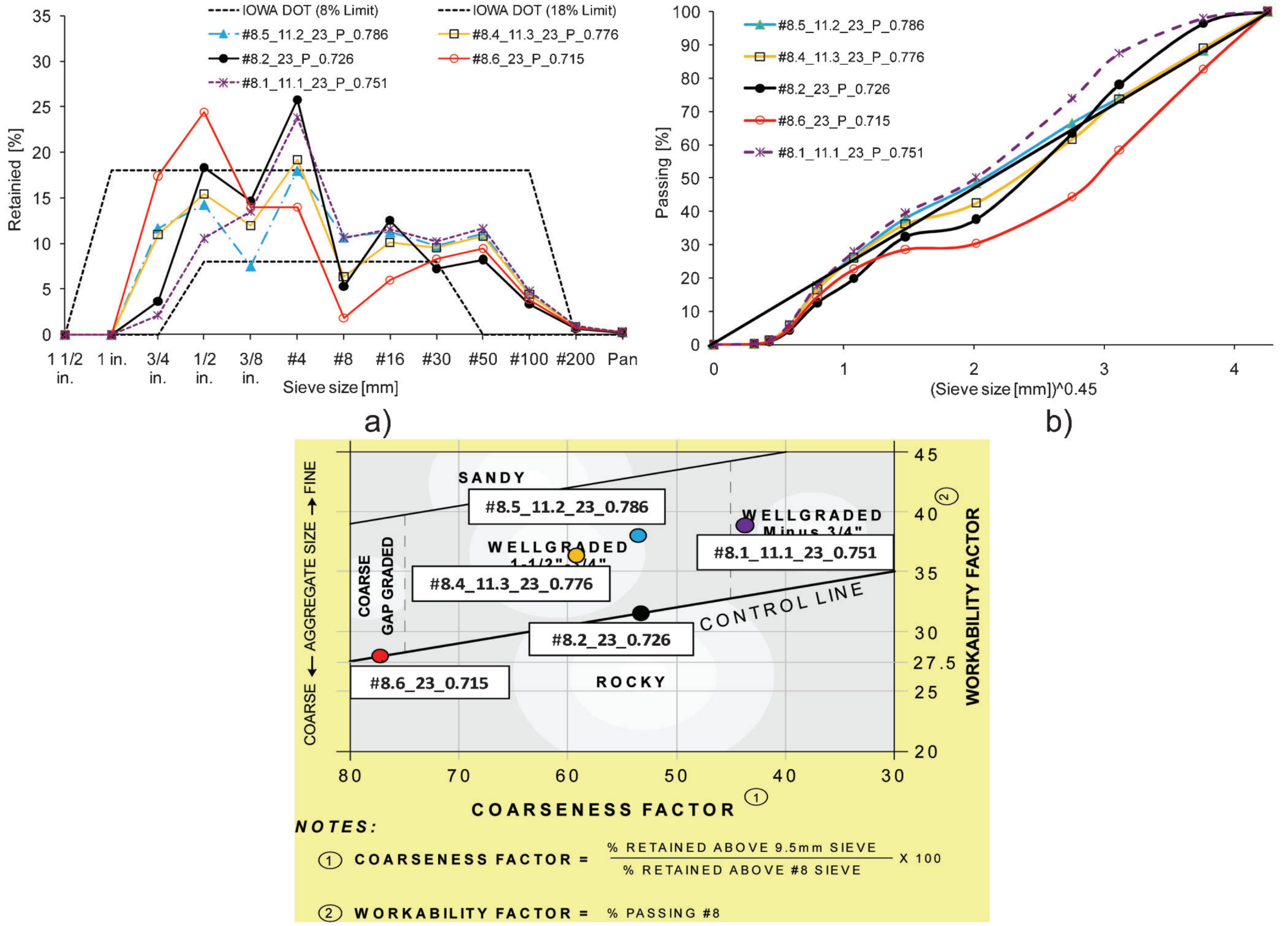
It can be seen (Figure 3.4 (a)) that gradations characterized by high packing density (0.786 and 0.776) are contained within the recommended "8-18" limits. On the other hand, gradation characterized by a lower (0.751) packing density value was designed with an excessive amount of #4 fractions. Finally, last two gradations (utilizing packing densities of 0.726 and 0.715) were designed as gap-graded gradations. The well and gap-graded gradations presented in Figure 3.4 (a) were selected for Phase III in order to produce concrete mixtures which (in author's opinion) will develop significantly different mechanical and durability properties, and thus allow for more comprehensive data analysis.

Data shown in Figure 3.4 (b) indicate that aggregate gradations with high packing density really follow the maximum density line (MDL), whereas the gap graded ones stay below or meander along the MDL. The aggregate blend with Φ=0.751 can be characterized as a sort of transitional gradation, between well and gap-graded blends, since its grading curve stays close to the MDL for small and intermediate aggregate fractions (up to 4.75 mm) and shows deficiency in the coarsest aggregate fractions (12.5 mm and 19.4 mm)".

Finally, one may see (Figure 3.4 (c)) that aggregate blends with Φ values equal to 0.786 and 0.776 selected for Phase III stay within ranges of CF from 55 to 65 and WF from 35 to 40. These ranges were proposed by Shilstone (*11*) and confirmed by Richardson (*36*) as being indicative of well-graded aggregate blends. On the other hand, aggregate blends with low packing densities (0.715 and 0.726) stay in the range of CF and WF characteristic for gap-graded gradations. Finally, the aggregate blend with Φ=0.751 can be characterized as sort of transitional between well and gap-graded gradation. The CF and WF values for this blend are located in the well-graded zone for aggregate finer than ¾ in.

3.3.3 Phase III Mixture Proportions

The selection of concrete mixture proportions for Phase III was based on the results of paste optimization conducted in Phase I of the research project, as well as on practical constrains related to the amount of cementitious materials typical used for pavement projects in Indiana (515 to 568 lb/yd^3). The main goal



a)

b)

c)

Figure 3.4 Summary of combined aggregate gradations for Phase III presented as "8-to-18" chart (a), 0.45 power chart (b), and Shilstone's coarseness factor chart (c).

of mixture selection was to obtain economical mixtures characterized by optimum desirability.

Giving the above considerations, the binary system selected for Phase II mixtures contained concrete mixture with 28.5% Class C fly ash as a replacement for cement (that level of fly ash was found to be the most desirable in Phase I of the study). A total of 9 different mixtures were produced, each with different combination of air void free paste-aggregate void saturation ratio (k″) and aggregate blend. The actual proportions of concrete mixture used in Phase III are presented in Table 3.9.

From data presented in Table 3.9. it can be seen that the total cementitious materials content of the mixtures

TABLE 3.9
The proportions of concrete mixture used for Phase III of the study

Packing density	0.715	0.726	0.726	0.751	0.751	0.751	0.776	0.776	0.786
k″	0.975	0.900	1.050	0.869	0.975	1.081	0.900	1.05	0.975
Solid paste [%]	27.8	24.7	28.8	21.7	24.3	26.8	20.2	23.6	20.9
Cement [lb/yd^3]	433	385	448	338	378	417	315	367	326
Fly ash [lb/yd^3]	169	150	174	132	147	162	122	143	127
Total cementitious	602	535	622	470	525	579	437	510	453
Water [lb/yd^3]	265	235	274	207	231	255	192	224	199
Fine agg. [lb/yd^3]	881	813	765	1196	1153	1111	1107	1087	1155
Coarse agg. [lb/yd^3]	2017	2243	2110	1993	1921	1851	2055	2019	2071
WR [fl. oz/cmwt]	0.0	1.3	0.0	6.5	2.0	0.0	6.4	2.3	6.8
AEA [fl. oz/cmwt]	3.1	2.8	2.1	1.8	1.8	2.3	1.8	2.1	2.2
w/c	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44

TABLE 3.10
Testing plan developed for research project

Test	Standard method	Phase I	Phase II	Phase III
Slump	AASHTO T 119, 2007 (*42*)	YES	YES	YES
Air content	AASHTO T 152, 2005 (*43*)	YES	YES	YES
Unit weight	AASHTO T 121, 2005 (*44*)	YES	YES	YES
VeBe time[1]	EN 12350-1 (Not US Standard)[1]	YES	NO	NO
Flexural strength at 7 and 56 days	AASHTO T 97, 2003 (*45*)	YES	YES	YES[4]
Compressive strength at 7, 28, 90 days	AASHTO T 140, 2005[2] (*46*)/ASTM C39 (*47*)	YES	YES[3]	YES[3]
Freeze-thaw resistance	ASTM C 666, 2003 (*48*)	YES	YES	YES
Scaling resistance	ASTM C 672, 2006 (*49*)	YES	YES	YES
Free drying shrinkage	ASTM C 157, 2006 (*50*)	YES	YES	YES
The rate of water absorption (by ponding) and the rate of water sorption (by capillary suction)	ASTM C 1585, 2006 (*51*)	YES	YES	YES
Restraint shrinkage	AASHTO PP 34, 2006 (*52*)	NO	NO	YES

[1] Similar to ASTM C1170 Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table (*53*).

[2] AASHTO T140 was utilized only in the Phase I as an alternative method for the purpose of saving large quantities of concrete required to produce all mixtures.

[3] Compressive strength measured on 4x8 in. cylinders according to ASTM C39.

[4] 56 day flexural strength dropped from testing list.

varied from as low as 437 lb/yd^3 to 622 lb/yd^3. At the same time, the solid (air-free) paste content (by volume) ranged from 20.2 to 28.8%. These values are well within the paste and total cementitious materials content ranges typically used in paving mixtures.

3.4 Research Testing Plan

The testing plan for research project consisted of measurements of both fresh and hardened properties. Table 3.10 summarizes the testing plan developed for this research program.

4. RESULTS OF LATORATORY TESTING

4.1 Fresh Concrete Properties—Phase I

The results of fresh concrete properties (average from three batches) are presented in Table 4.1 (for fly ash mixtures), Table 4.2 (for GGBFS mixtures) and Table 4.3 (for ternary mixtures).

The measured air contents of most binary mixtures were within ±0.3% from the target value of 6.5%, with only three mixtures (14FA_23, 40SL_23, 25SL_24) showing slightly higher variation.

The VeBe time required for compaction of binary concrete mixtures was highly dependent on the amount of paste. As can be seen from Table 4.1, Table 4.2 and Table 4.3, the VeBe values (time) dropped significantly with the increase in paste content (total cementitious materials). The reduction of the VeBe time is more pronounced for GGBFS mixtures than for fly ash mixtures. However, in case of fly ash mixtures, it can also be observed that the increase in fly ash content for mixtures with the same paste content resulted in somewhat lower VeBe values (i.e., mixtures 18FA_24 and 26FA_24). This kind of behavior was not observed for GGBFS mixtures.

Generally, in order to achieve the target slump both fly ash and slag concrete mixtures with low paste content (21% and 22% of paste) required a significantly increased (about 100% to 200%) dosage of water-reducing admixtures over that recommended by the supplier (about 2.5 fl. oz/cmwt). Fly ash mixtures with paste content below 22% and slag mixtures with paste

TABLE 4.1
Average values of fresh properties of fly ash concrete mixtures

Mixture label	Total cementitious materials [lb/yd^3]	Dosage of WR [fl. oz/cmwt]	Air [%]	Slump [in.] (mm)	VeBe time [s]	Unit weight [lb/yd^3] (kg/m^3)
22FA_21	458	8.5	6.4	[1.00] (25)	6.0	[3930] [2331]
18FA_22	482	6.5	6.5	[1.50] (40)	5.0	[3892] (2308)
26FA_22	478	6.0	6.7	[2.00] (50)	4.0	[3892] (2308)
14FA_23	504	5.0	6.9	[2.25] (55)	6.0	[3881] (2302)
22FA_23	501	4.7	6.5	[3.25] (80)	4.0	[3876] (2299)
30FA_23	498	4.0	6.8	[2.00] (50)	3.5	[3898] (2312)
18FA_24	525	2.8	6.6	[2.25] (55)	5.5	[3876] (2299)
26FA_24	521	2.4	6.5	[2.25] (55)	5.0	[3870] (2299)
22FA_25	545	1.0	6.7	[2.75] (70)	3.0	[3865] (2292)

TABLE 4.2
Average values for fresh properties of GGBFS and plain concrete mixtures

Mixture label	Total cementitious materials [lb/yd^3]	Dosage of WR [fl. oz/cmwt]	Air [%]	Slump [in.] (mm)	VeBe time [s]	Unit weight [lb/yd^3] (kg/m^3)
30SL_21	462	9.75	6.6	[1.25] (30)	8.0	[3914] (2321)
25SL_22	484	9.00	6.7	[1.75] (45)	7.0	[3908] (2318)
35SL_22	482	7.00	6.4	[1.00] (25)	7.0	[3908] (2318)
20SL_23	507	5.70	6.8	[2.00] (50)	5.0	[3876] (2299)
30SL_23	505	6.50	6.7	[1.50] (40)	6.0	[3887] (2305)
40SL_23	503	6.50	7.4	[2.50] (60)	4.0	[3854] (2286)
25SL_24	528	5.00	7.1	[2.75] (70)	3.0	[3860] (2289)
35SL_24	526	4.80	6.7	[2.00] (50)	3.0	[3876] (2299)
30SL_25	549	3.30	6.3	[2.25] (55)	3.0	[3887] (2305)

content below 23% were difficult to produce and may be impractical for field applications. However, it must be mentioned that all mixtures studied here contained relatively high amount of sand (45% of total aggregate by mass). Based on previously published study (*54*), concretes with such high amount of sand may experience reduced workability and be “harsh” to finish. As expected, the fly ash concrete mixtures were more “slumpy” and “watery” compared to slag mixtures, which were drier and more cohesive. In addition, fly ash concretes with 24% and 25% of paste experienced limited bleeding.

Similarly to mixtures with binary binders, the maximum deviation from target air content for ternary mixtures was small and equal 0.7%. The workability of ternary mixtures was comparable to workability of mixtures with fly ash. The target slump was easily obtained and VeBe time for mixtures with high paste content (24% to 25%) was even smaller than that of fly ash mixtures. This behavior of ternary mixtures can be attributed to high replacement level of cement and more uniform particle distribution of cementitious materials resulting from combining three types of binders (cement, GGBFS and fly ash).

The influence of total amount of cementitious materials on required dosage of water reducing admixture for all Phase I concrete mixtures is presented in Figure 4.1. The dosage of water reducing admixture for all systems decreased linearly with an increase in the total amount of cementitious materials (paste content). This observation may be useful in predicting the required amount of water reducing admixtures for concrete mixtures with target slump of 2 in. produced under laboratory conditions.

4.2. Fresh Concrete Properties—Phase II

The average values of fresh concrete properties determined for concrete mixtures produced for Phase II of the study are presented in Figure 4.2.

In general, (as shown graphically in Figure 4.2) the target values for fresh concrete properties were satisfied

TABLE 4.3
Average values for fresh properties of ternary and plain concrete mixtures

Mixture label	Total cementitious materials [lb/yd^3]	Dosage of WR [fl. oz/cmwt]	Air [%]	Slump [in.] (mm)	VeBe time [s]	Unit weight [lb/yd^3] (kg/m^3)
15FA24SL_21	458	8.50	6.8	[1.25] (32)	6.0	[144.3] (2312)
12.5FA21SL_22	480	7.00	6.9	[2.00] (51)	5.5	[143.5] (2299)
12.5SL27SL_22	479	7.5	7.2	[2.00] (51)	5.5	[143.1] (2292)
17.5FA21SL_22	478	6.75	6.5	[1.50] (38)	5.5	[144.3] (2312)
17.5FA27SL_22	477	7.00	7.0	[2.00] (51)	5.0	[143.9] (2305)
10FA24SL_23	502	6.50	7.1	[2.50] (64)	4.0	[143.5] (2299)
15FA18SL_23	501	6.0	6.5	[2.25] (57)	3.5	[143.9] (2305)
15FA24SL_23	500	5.5	6.9	[2.50] (64)	3.5	[143.5] (2299)
15FA30SL_23	499	5.5	6.9	[2.75] (70)	4.0	[142.7] (2286)
20FA24SL_23	498	3.75	6.0	[2.25] (57)	3.0	[144.7] (2318)
12.5FA21SL_24	524	4.0	6.8	[2.75] (70)	2.5	[142.9] (2289)
12.5SL27SL_24	523	3.5	6.9	[3.00] (76)	2.5	[142.9] (2289)
17.5FA21SL_24	522	3.0	6.2	[2.25] (57)	2.0	[143.9] (2305)
17.5FA27SL_24	521	2.0	6.1	[2.25] (57)	2.5	[143.7] (2302)
15FA24SL_25	544	0.5	6.0	[2.00] (51)	1.5	[143.7] (2302)
	Plain concrete mixtures					
CTRL_515	515	6.25	6.2	[1.50] (40)	3.0	[3887] (2305)
CTRL_565	565	2.00	6.8	[2.25] (55)	4.0	[3865] (2292)

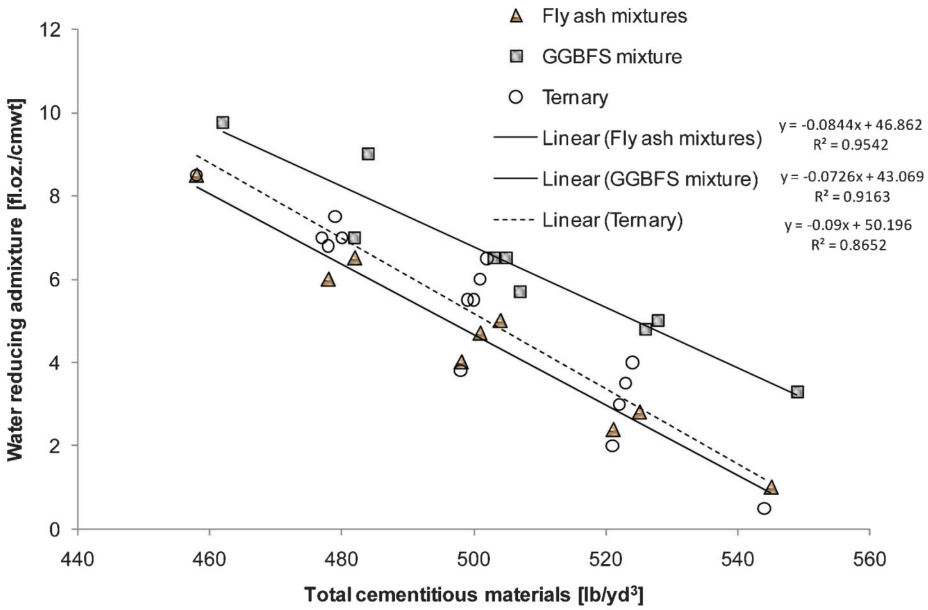


Figure 4.1 Correlation between dosage of water reducing admixture and total cementitious materials content for ternary mixtures.

for most concrete mixtures. However, two fly ash mixtures with gradation No. 3 and No. 4 (Grad 3 and Grad 4) resulted in air content a little above the 7.5% upper limit.

In order to evaluate the effect of 6 combined aggregate gradations on the workability and finishability of concrete, the summary of visual observations collected during casting concrete specimens is presented in Table 4.4.

The aggregate gradations No. 1 and 2, produced dry, sandy and hard to finish concrete mixtures. In case of Grad 1, poor workability was the effect of low amount of coarse fractions (plus ⅜ in.) and high sand content (44% of total aggregate). In addition, the amount of aggregate fractions retained on No. 4 sieve was one of the highest for all combined aggregate gradations produced in Phase II. In authors' opinion these characteristics of gradation No. 1 increased water demand and resulted in poor workability of the mixtures. It should be noted that the problems with workability and finishability of the mixtures related to gradation No. 1 could be predicted by using Shilstone's chart (the combination of CF and WF for this blend was located close to Zone V).

On the other hand, although mixtures with gradation No. 2 resulted in better satisfactory workability, their finishability was even worse than those with gradation No. 1. This was the result of high content of fraction

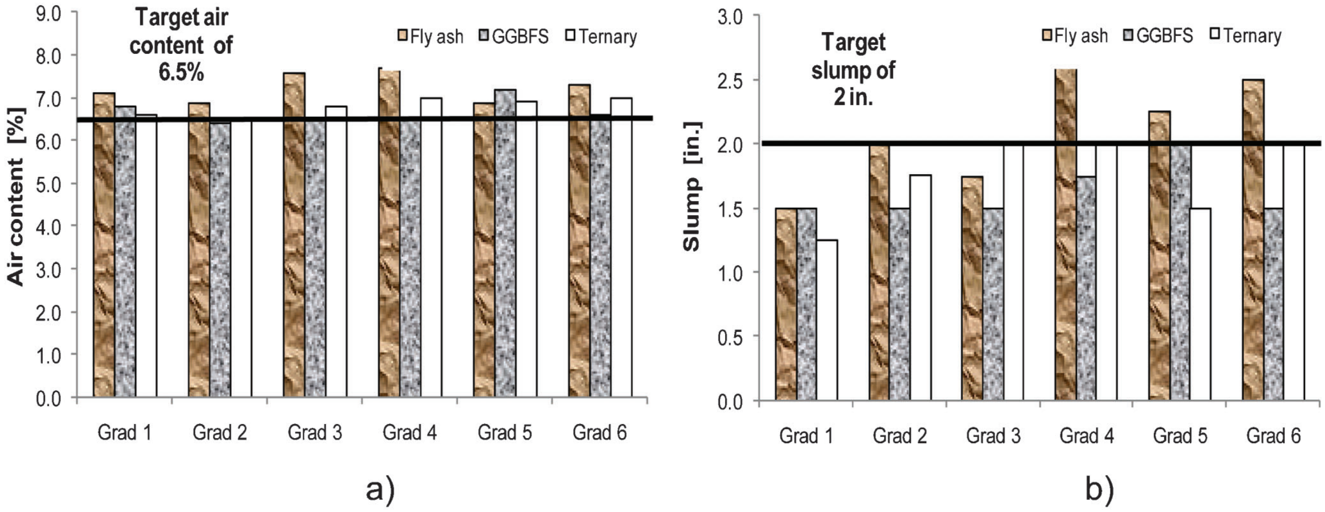


Figure 4.2 The values of fresh concrete properties for Phase II concretes: (a) air content, and (b) slump.

TABLE 4.4
Effect of combined aggregate gradations on workability and finishability of concrete mixtures in Phase II

		Visual rating of workability (W), texture (T) and finishability (F)					
		Grad 1	**Grad 2**	**Grad 3**	**Grad 4**	**Grad 5**	**Grad 6**
Mixture		**(#23) #5#8#11**	**(#23) #8#11**	**(#23) #5#8**	**(#23) #5#11**	**(#23) #8**	**(#23) #8**
32SL_23	W	Poor	**Satisfactory**	**Bad**	Good	Good	**Poor**
	T	Dry/Sandy	**Dry**	**Rocky**	Cohesive	Cohesive	**Dry/Sandy**
	F	Poor	**Bad**	**Bad**	Good	Good	**Satisfactory**
22FA_22	W	Poor	**Satisfactory**	**Bad**	Good	Good	Good
	T	Dry/Sandy	**Dry**	**Rocky**	Cohesive	Cohesive	Sandy
	F	Satisfactory	**Bad**	**Bad**	Good	Good	Good
16FA26SL_22	W	Poor	**Satisfactory**	**Bad**	Good	Good	Good
	T	Dry/Sandy	**Dry**	**Rocky**	Cohesive	Cohesive	Cohesive
	F	Satisfactory	**Bad**	**Bad**	Good	Good	Good

NOTE: **Boldface** indicates data for mixtures that were either hard to finish or showed excessive bleeding.

retained on #4 sieve. This excess of #4 fraction resulted in aggregate particles sticking out from the surface after each pass the finishing tools.

The most problematic mixtures were those produced with gradation No. 3. In this case, all three mixtures showed extensive segregation and bleeding. In addition, they were difficult to compact by rodding (and also difficult to finish), due to high content of plus ⅜ in. fractions. In addition, due to low fine aggregate content they were also difficult with respect to air entrainment.

The aggregate gradations No. 4 and 5, were the most desired regardless of the type of binder used. All mixtures with these gradations were very workable and did not show signs of bleeding. This was due to the fact that both of these gradations had balanced content of fine aggregates (36% or 40% of total aggregates for gradation 4 and 5, respectively). The main difference between these two gradations was in the amounts of #4 and ½ in. aggregates, as well as in the NMS of aggregate used to produce combined gradation. Gradation No. 4 contained 1 in. maximum particle size, whereas for gradation No. 5 that size was ¾ in. In the case of gradation No. 4, the utilization of #5 INDOT's coarse aggregate (NMS equal 1 in.) caused the percent retained curve to be smoother for the range of aggregate particles from ¾ in. to #4. In addition, using INDOT's #11 intermediate aggregate (NMS equal to ⅜ in.) helped to fill in the gaps between large #5 particles. This resulted in improvement of overall workability and finishability. On the other hand, for combined gradation No. 5, good workability was the effect of high amount of ½ in. and #4 aggregate, followed by increased amount of sand. The Shilstone's coarseness chart showed that gradation No. 5 can be considered as being optimized in terms of combination of CF and WF, whereas good performance of gradation No. 4 can be attributed to introduction of INDOT's #11 aggregate (intermediate aggregates helped to maintain high workability factor).

The combined gradation No. 6 was designed to contain only sand and INDOT's #8 coarse aggregate (NMS equal ¾ in.). It showed inconsistent workability and finishability, which depended on the type of binder used. The most difficult to work with was concrete mixture with GGBFS, whereas the easiest to work with was mixture with ternary binder. This improvement in performance was attributed to the decrease in the amount of cement resulting from the use of higher amount of supplementary cementitious materials. The combined gradation No. 6 contained more fine fractions and less big particles (particularly ½ in.) than gradation No. 5. These changes shifted the WF for gradation No. 6 upward from the center of Zone II while (at the same time) they decreased the CF toward Zone III (characteristic for gradations with smaller aggregates). These shifts offer additional explanation to observed inconsistencies in workability of concrete mixtures with gradation No. 6.

4.3 Fresh Concrete Properties—Phase III

The average values of slump, air content and measured unit weight of fresh Phase III concrete mixtures are given in Table 4.5.

The data in Table 4.5 indicate that all concrete mixtures were produced with satisfactory air content (in the range from 6.2% to 7.0%). However, the slump of three mixtures (labeled 0.715_0.975, 0.726_1.050 and 0.751_1.081) was too high for a typical pavement mixture (usually about max 3 in.). These high slump value measured for these mixtures was the result of high paste content and was achieved without any addition of water-reducing admixtures. Due to utilization of different aggregate gradations and k″ values in the experimental plan, it was expected that concrete workability and finishability will differ (depending on the combinations of these two variables). Table 4.6 presents the results of visual evaluation of concrete mixtures produced in Phase III.

TABLE 4.5
Fresh concrete properties obtained for concrete mixtures produced in Phase III

Mix label	Packing density (Φ)	Agg-void saturation ratio (k″)	Paste content [%]	Slump [in.] (mm)	Air content [%]	Unit weight [lb/ft^3] (kg/m^3)
0.715_0.975	0.715	0.975	27.8	5.00 (13)	6.2	140.0 (2244)
0.726_0.900	0.726	0.900	24.7	2.00 (5)	7.4	140.4 (2250)
0.726_1.050	0.726	1.050	28.8	4.25 (11)	6.3	140.9 (2258)
0.751_0.869	0.751	0.869	21.7	2.00 (5)	6.3	143.2 (2295)
0.751_0.975	0.751	0.975	24.3	2.75 (7)	6.5	141.0 (2260)
0.751_1.081	0.751	1.081	26.8	3.75 (10)	6.8	140.0 (2244)
0.776_0.900	0.776	0.900	20.2	2.00 (5)	6.4	143.6 (2301)
0.776_1.050	0.776	1.050	23.6	2.50 (6)	6.7	142.0 (2276)
0.786_0.975	0.786	0.975	20.9	2.75 (7)	7.0	142.6 (2285)

In general, the concrete mixtures characterized by either very low (0.869) or very high (1.050 and 1.081) paste-aggregate void saturation ratio k″ exhibited, respectively, either quick loss of workability or bleeding and extensive segregation. In case of concrete mixtures with low aggregate packing density (0.715 and 0.726) the workability problems were also related to low sand content and gap-graded character of aggregate blend.

The concrete mixtures with aggregate packing density higher than 0.751 and k″ value higher than 0.900 can be considered to be very workable and should not create problem with placement and finishing. In case of these mixtures, the use of well-graded aggregate gradation was essential for achieving good performance. Contrary to common opinion, concrete mixture with the highest packing density (0.786) showed satisfactory workability, however noticeable slump loss was observed with in relatively short time after mixing (about 15 min).

Based on the presented data, it seems that in order to achieve satisfactory fresh performance characteristics the mixture requires (in addition to well graded aggregates) a paste content in the range from about 21% to 24% and k″ value of about 0.975 to 1.050.

4.4 Hardened Concrete Properties—Phase I

The hardened concrete properties measured for Phase I mixtures included the following: flexural and compressive strength, scaling and freeze-thaw resistance, rate of water sorptivity and absorptivity and free shrinkage. The goal of this section is to briefly present the hardened concrete properties values obtained from binary and ternary concretes, as well as to describe the selection process for performance criteria used in the optimization process. Due to space limitation the detailed discussion of the test results will not be presented.

4.4.1 Binary Mixtures (Phase I)

The summary of the test results for all binary and plain concrete mixtures are given in Table 4.7. Table 4.7 does not include the results of freeze-thaw resistance as the measured values of the durability factor for both fly ash and GGBFS mixtures was highly variable and thus they were omitted from the statistical optimization. In addition, Table 4.7 gives the estimated cost of the raw materials used in each mixture.

The flexural strength results at 7 days indicated that, on average, the slag mixtures were stronger than other mixtures and that their strength was closer to the flexural strength of reference mixtures. Also, for all mixtures, the 7 days flexural strength significantly exceeded the minimum strength of 3.93 MPa (570 psi) required by the current Indiana Department of Transportation (INDOT) specifications (INDOT 2005). After 56 days of curing, all slag mixtures and 8 out of 9 fly ash mixtures achieved flexural strength higher than both reference mixtures.

The amount of cement used to produce slag mixtures varied from 179 to 241 kg/m^3 (302 to 406 lb/yd^3). By combining this information with the results of flexural strength tests it can be concluded that the current

TABLE 4.6
The results of visual evaluation of concrete mixtures produced in Phase III

Packing density	0.715	0.726	0.726	0.751	0.751	0.751	0.776	0.776	0.786
k″	0.975	0.900	1.050	0.869	0.975	1.081	0.900	1.050	0.975
Paste content [%]	27.8	24.7	28.8	21.7	24.3	27.0	20.2	23.6	20.9
Workability	Good	Good	Good	Poor	Good	Good	Good	Good	Good
Finishability	Good	Good	Good	Poor	Good	Good	Good	Good	Good
Bleeding	Yes	Yes	Yes	No	No	Yes	No	No	No
Segregation	Yes	No	Yes	No	No	Yes	No	No	No
Overall	**Soupy**	Good	**Soupy**	**Slump loss**	Good	**Soupy**	**Slump loss**	Good	Good

NOTE: Mixtures with workability problems (either soupy or exhibited quick slump loss) are identified with **boldface**.

TABLE 4.7

Test results of hardened concrete properties for binary mixtures

Mix label	Fly ash [%]	Slag [%]	Paste [%]	Flexural str. [psi] (MPa)		Compressive str. [psi] (MPa)			Scaling [lb/ft^2] (kg/m^2)	Shrinkage [%]	Sorption rate [10^{-4} in./s$^{0.5}$] (mm/s$^{0.5}$)	Absorption rate [10^{-4} in./s$^{0.5}$]	Material cost, [\$/yd^3] (\$/m^3)
				7 days	56 days	7 days	28 days	90 days					
22FA_21	22.0		21.0	687 (4.7)	826 (5.7)	5648 (39.0)	7242 (49.9)	8613 (59.4)	0.06 (0.27)	−0.0401	1.3 (34.0)	1.6 (40.0)	44.39 (58.03)
18FA_22	18.0		22.0	710 (4.9)	842 (5.8)	6075 (41.9)	7294 (50.3)	8559 (59.0)	0.07 (0.36)	−0.0460	1.2 (31.5)	1.7 (43.0)	45.24 (59.14)
26FA_22	26.0		22.0	631 (4.4)	853 (5.9)	4945 (34.1)	6575 (45.3)	8102 (55.9)	0.09 (0.42)	−0.0465	1.5 (38.5)	1.7 (42.0)	44.15 (57.72)
14FA_23	14.0		23.0	720 (5.0)	843 (5.8)	5745 (39.6)	7333 (50.6)	7769 (53.6)	0.07 (0.35)	−0.0501	1.8 (45.0)	1.6 (40.5)	46.07 (60.23)
22FA_23	22.0		23.0	725 (5.0)	850 (5.9)	5490 (37.7)	7282 (50.2)	54.2 (7864)	0.11 (0.52)	−0.0450	1.6 (41.5)	1.6 (40.5)	45.02 (58.85)
30FA_23	30.0		23.0	645 (4.4)	920 (6.3)	4952 (34.2)	6352 (43.8)	7914 (54.6)	0.23 (1.11)	−0.0465	1.9 (49.0)	2.5 (63.5)	43.91 (57.40)
18FA_24	18.0		24.0	723 (5.0)	822 (5.7)	5263 (36.3)	6816 (47.0)	7232 (49.9)	0.20 (0.97)	−0.0470	2.1 (54.0)	2.4 (61.5)	45.90 (60.00)
26FA_24	26.0		24.0	707 (4.9)	839 (5.8)	4720 (32.6)	5383 (37.1)	7421 (51.2)	0.18 (0.86)	−0.0456	2.4 (61.5)	3.4 (86.0)	44.71 (58.45)
22FA_25	22.0		25.0	726 (5.0)	768 (5.3)	5135 (35.4)	6629 (4537)	7304 (50.4)	0.21 (1.04)	−0.0500	3.2 (80.0)	3.6 (92.5)	45.58 (59.59)
30SL_21		30.0	21.0	727 (5.0)	927 (6.4)	5637 (38.9)	7880 (54.3)	7722 (53.3)	0.10 (0.49)	−0.0484	0.7 (19.0)	0.0 (23.0)	44.93 (58.35)
25SL_22		25.0	22.0	723 (5.0)	890 (6.1)	5006 (34.5)	7708 (53.2)	7433 (51.3)	0.04 (0.20)	−0.0444	0.9 (22.0)	0.7 (19.0)	45.81 (59.52)
35SL_22		35.0	22.0	781 (5.4)	925 (6.4)	5852 (40.4)	6971 (48.1)	50.1 (7271)	0.10 (0.49)	−0.0435	1.2 (31.0)	1.1 (29.0)	44.73 (58.19)
20SL_23		20.0	23.0	781 (5.4)	846 (5.8)	4011 (27.7)	6746 (46.5)	7502 (51.7)	0.04 (0.20)	−0.0490	0.1 (25.0)	1.2 (30.0)	46.39 (60.41)
30SL_23		30.0	23.0	767 (5.3)	931 (6.4)	5848 (40.3)	7871 (54.3)	7592 (52.4)	0.06 (0.27)	−0.0440	1.3 (32.0)	1.1 (27.5)	45.69 (59.46)
40SL_23		40.0	23.0	794 (5.5)	937 (6.5)	5038 (34.7)	5383 (37.1)	6573 (45.3)	0.14 (0.70)	−0.0420	1.4 (34.5)	1.7 (43.0)	44.82 (58.31)
25SL_24		25.0	24.0	756 (5.2)	898 (6.2)	5400 (37.2)	7187 (49.6)	7295 (50.3)	0.11 (0.53)	−0.0540	1.0 (25.0)	1.3 (32.0)	46.46 (60.52)
35SL_24		35.0	24.0	775 (5.3)	943 (6.5)	5760 (39.7)	7095 (48.9)	7041 (48.9)	0.17 (0.84)	−0.0470	1.5 (38.5)	1.9 (47.5)	45.56 (59.35)
30SL_25		30.0	25.0	777 (5.4)	921 (6.4)	5544 (38.2)	6667 (46.0)	7262 (50.1)	0.18 (0.88)	−0.0435	1.6 (40.5)	1.8 (46.0)	46.33 (60.42)
CTRL_515	0.0	0.0	23.2	790 (5.4)	838 (5.8)	5858 (40.4)	7207 (49.7)	7671 (52.9)	0.08 (0.39)	−0.0540	1.2 (30.0)	1.8 (46.0)	48.29 (62.85)
CTRL_565	0.0	0.0	25.4	790 (5.4)	813 (5.6)	5525 (38.1)	6482 (44.7)	7236 (49.9)	0.25 (1.23)	−0.0557	1.4 (35.0)	2.2 (56.0)	49.20 (64.22)

minimum amount of cement (261 kg/m^3 (440 lb/ft^3)) required by INDOT specification (*34*) to produce pavement mixture can be reduced even further.

The compressive strength results showed relatively high variability and thus the analysis of these data is complicated. That variability was, at least in part, the result of using the sawed-off parts of beams as test specimens. However, the data seem to indicate that at 90 days the strength of both slag and fly ash systems decreased with an increase in paste content.

The scaling data indicated that the increase in both paste content and the amount of pozzolanic material for both fly ash and slag systems resulted in higher scaling. This conclusion was most evident for fly ash mixtures, where mix with 30% of fly ash scaled the most. From this stand point, it seems that the increase in Class C fly ash content above 30% will significantly accelerate the scaling. Similar observation was made by other authors (*55*).

The sorptivity and absorptivity data for both slag and fly ash systems showed the same trends as scaling data. The sorptivity (and absorptivity) increased with the increase in the paste content and in the amount of supplementary cementitious materials. This observation resulted in establishing correlation between scaling and sorptivity (absorptivity) data which was later used to define sorptivity (absorptivity) optimization performance criteria. The values of measured sorptivity (and absorptivity) of slag mixtures were smaller than those of fly ash mixtures and, in majority of cases, even smaller than those of reference mixtures.

Finally, for slag system, it was observed that (when compared at constant paste content) the increase in slag replacement caused the decrease in drying shrinkage. In case of fly ash mixtures, the same analysis did not indicate the clear effect of fly ash content on measured drying shrinkage. However, for fly ash mixtures the increase in paste content (when keeping fly ash content constant) resulted in higher shrinkage.

The data presented in Table 4.7 and summarized above were used directly in the optimization process. The optimization process itself consisted of statistical analysis of data, development of prediction models and numerical optimization. All three of these steps are at the core of the Response Surface Methodology (RSM) approach, which was utilized to find the optimum combination of variables used. The initial evaluation of data was performed using ANOVA analysis, the statistical method designed to find potential correlations between multiple variables and measured responses. These correlations resulted in the prediction models, which were then used to define desirability functions. Finally, the desirability functions for all measured responses were combined to find an optimum combination of variables.

4.4.2 Ternary Mixtures (Phase I)

Due to space limitation the detailed data analysis of hardened concrete properties obtained for ternary mixtures cannot be included in this section. However, for reader's convenience the average values of hardened properties are summarized in Table 4.8. The same table also includes the estimated cost of all materials used to prepare the mixtures.

All ternary mixtures prepared during this study exceeded the minimum 7 day flexural strength of 570 psi as required by INDOT's specifications for QC/QA pavements (*5*). The percentage by which INDOT's requirement was exceeded varied from 16% to 36%. The basic statistical analysis of both the 7 day and 56 day flexural strength data indicated that the mean of 7 day results for all mixtures was 740 psi (5.1 MPa) with standard deviation 36 psi (0.3 MPa). For 56 day those values were respectively, 919 psi (6.3 MPa) and 23 psi (0.2 MPa).

Although the compressive strength of pavement concretes is typically not as critical as their flexural strength, it is sometimes used as one of the requirements for the purposes of determining the time of opening the road to traffic. The results of compressive strength were found to be more difficult to interpret than the flexural strength data and no clear influence of paste, fly ash and slag content on this property could be identified. As expected, the 7 day compressive strength of ternary mixtures was lower than that of the control, plain concrete mixture. Predictably, with the increase in the length of curing time the strength of ternary mixtures kept increasing and at 28 days 9 out of 15 mixtures developed the strength higher than that of the control mixture. In addition, the relative increase in compressive strength between 7 and 28 day was much higher for ternary concretes than for control mixture. At 180 day the compressive strength for all ternary mixtures was higher than that of the control mixture. This fact clearly shows that incorporation of both fly ash and slag (ternary binder) in the mixtures has positive effect on long-term compressive strength development.

It has been previously reported that the type of supplementary cementitious materials and their amount in the concrete mixture can significantly affect the scaling resistance (*55*). Scaling results for control and all ternary concrete mixtures used in this study (presented in Table 4.8) indicate strong relationship between paste content and the amount of scaled material. In general, the scaling was found to increase (non-linearly) with the increase in the volume of paste (as well as the total amount of cementitious materials). The other interesting observation from Table 4.8 is that scaling of majority of ternary concretes with 21% and 22% of paste (4 out of 5 mixtures) was equal or smaller than that of the control mixture with 515 lb of cement. It should be noted that scaling test specimens prepared from these mixtures were difficult to finish and did not show signs of bleeding. On the other hand, noticeable bleeding was observed during finishing of surfaces of specimens from mixtures with 24% and 25% of paste, as well the reference mixture. The presence of bleed water on the surface of scaling specimens from these

TABLE 4.8
Test results of hardened concrete properties for Phase I ternary mixtures

Mix label	Fly ash [%]	Slag [%]	Paste [%]	Flexural str. [psi] (MPa)		Compressive str. [psi] (MPa)			Scaling [lb/ft^2] (kg/m^2)	Shrinkage [%]	Sorption rate [10^{-4} in./s$^{0.5}$] (mm/s$^{0.5}$)	Absor ption rate [10^{-4} in./s$^{0.5}$] (mm/s$^{0.5}$)	Material cost, [\$/yd^3] (\$/m^3)
				7 days	56 days	7 days	28 days	90 days					
15FA21SL_21	15.0	21.0	21.0	667 (4.6)	899 (6.2)	5003 (34.5)	7076 (48.8)	7482 (51.6)	0.15 (0.73)	−0.0390	0.71 (18)	0.70 (17)	43.63 (56.93)
12.5FA21SL_22	12.5	21.0	22.0	754 (5.2)	899 (6.2)	4814 (33.2)	5844 (40.3)	6438 (44.4)	0.18 (0.86)	−0.0435	0.95 (24)	1.18 (30)	44.49 (58.04)
12.5FA27SL_22	12.5	27.0	22.0	711 (4.9)	899 (6.2)	5177 (35.7)	7134 (49.2)	7511 (51.8)	0.13 (0.62)	−0.0451	0.83 (21)	0.95 (24)	44.09 (57.52)
17.5FA21SL_22	17.5	21.0	22.0	682 (4.7)	972 (6.7)	5293 (36.5)	7453 (51.4)	8251 (56.9)	0.29 (1.43)	−0.0430	0.99 (25)	1.34 (34)	43.85 (57.21)
17.5FA27SL_22	17.5	27.0	22.0	667 (4.6)	928 (6.4)	4220 (29.1)	6250 (43.1)	6467 (44.6)	0.23 (1.14)	−0.0488	0.91 (23)	1.05 (26)	43.40 (56.64)
10FA24SL_23	10.0	24.0	23.0	769 (5.3)	914 (6.3)	5496 (37.9)	7279 (50.2)	7497 (51.7)	0.14 (0.69)	−0.0479	0.83 (21)	0.99 (25)	45.02 (58.72)
15FA18SL_23	16.5	18.0	23.0	696 (4.8)	870 (6.0)	4611 (31.8)	6148 (42.4)	7395 (51.0)	0.32 (1.57)	−0.0444	1.18 (30)	1.38 (35)	44.83 (58.48)
15FA24SL_23	16.5	24.0	23.0	754 (5.2)	928 (6.4)	5133 (35.4)	6888 (47.5)	7932 (54.7)	0.37 (1.82)	−0.0510	1.10 (28)	1.10 (28)	44.26 (57.75)
15FA30SL_23	16.5	30.0	23.0	754 (5.2)	914 (6.3)	4640 (32.0)	6583 (45.4)	7004 (48.3)	0.33 (1.63)	−0.0520	1.06 (27)	0.95 (24)	43.76 (57.10)
20FA24SL_23	20.0	24.0	23.0	711 (4.9)	914 (6.3)	5293 (36.5)	6627 (45.7)	8236 (56.8)	0.4.8 (2.32)	−0.0410	1.22 (31)	1.38 (35)	43.41 (56.65)
12.5FA21SL_24	12.5	21.0	24.0	725 (5.0)	928 (6.4)	4771 (32.9)	6322 (43.6)	6989 (48.2)	0.34 (1.68)	−0.0485	1.46 (37)	1.26 (32)	45.20 (58.96)
12.5FA27SL_24	12.5	27.0	24.0	754 (5.2)	870 (6.0)	5003 (34.5)	6757 (46.6)	6728 (46.4)	0.84 (4.10)	−0.0460	1.18 (30)	1.04 (27)	44.61 (58.20)
17.5FA21SL_24	17.5	21.0	24.0	740 (5.1)	928 (6.4)	4582 (31.6)	6134 (42.3)	6786 (46.8)	0.45 (2.19)	−0.0477	1.81 (46)	1.73 (44)	44.39 (57.91)
17.5FA27SL_24	17.5	27.0	24.0	740 (5.1)	899 (6.2)	4669 (32.2)	6685 (46.1)	7888 (54.4)	1.83 (8.94)	−0.0495	1.58 (40)	1.46 (37)	43.88 (57.25)
15FA24SL_25	16.5	24.0	25.0	769 (5.3)	943 (6.5)	4336 (29.9)	6076 (41.9)	6076 (41.9)	1.67 (8.17)	−0.0515	2.01 (51)	2.09 (53)	44.64 (58.24)
CTRL_515	0.0	0.0	23.2	790 (5.4)	838 (5.8)	5858 (40.4)	7207 (49.7)	7671 (52.9)	0.08 (0.39)	−0.0540	1.2 (30.0)	1.8 (46.0)	48.29 (62.85)
CTRL_565	0.0	0.0	25.4	790 (5.4)	813 (5.6)	5525 (38.1)	6482 (44.7)	7236 (49.9)	0.25 (1.23)	−0.0557	1.4 (35.0)	2.2 (56.0)	49.20 (64.22)

mixtures is believed to be strongly related to the observed increase in the amount of scaled material.

Another important property of hardened concrete measured for ternary mixtures was rate of water sorption and absorption. Similarly to scaling results, the sorptivity and absorptivity data indicated relatively strong relationship between paste content and this property. Relatively strong relationship between total cementitious materials (and increasing paste content) and absorption can be observed by analyzing data from Table 4.8. Moreover, it seemed that the increase in GGBFS content decreased the rate of both water absorption and water sorption, whereas the increase in the fly ash content made both of these values higher.

In case of free shrinkage, the clear relationship between the measured values and paste content was not observed. However, it was concluded that the average value of shrinkage for mixtures with 21% and 22% of paste was slightly lower than that observed for mixtures with 24% and 25% of paste (-0.0419 and -0.0467%, respectively). The absolute value of this difference is within one standard deviation of the precision test of itself. The final shrinkage of control mixture was the highest in comparison with ternary mixtures with the same (23%) paste content, thus indicating beneficial effects of ternary binder on the overall drying shrinkage values. Among all mixtures produced, mixtures 15FA24SL_21 and 20FA24SL_23 were found to have the lowest shrinkage values, than the rest of the mixtures tested (the average shrinkage values about −0.039% and −0.0410%).

4.5 Hardened Concrete Properties—Phase II

Similarly to the approach used in the analysis of data from Phase I, only the most critical findings from Phase II testing are presented in order to keep the size of this report at a manageable level. Table 4.9 summarizes Phase II hardened concrete results.

All but one mixture (fly ash mixture with gradation No. 3 aggregate) concretes produced in Phase II satisfied the minimum 7 days flexural strength of 570 psi (3.93 MPa) required by the current INDOT specifications (*5*). The low strength of that mixture can be attributed to its extensive segregation. It can be also observed that mixtures with GGBFS resulted in the highest values of flexural strength at both 7 and 56 days. In addition, the measured differences in flexural strength did not seem to correlate with type of gradation used to produce individual mixtures. This may be due to the fact that flexural strength results are inherently variable and the effects of this variability may be more significant than the differences caused by changes in gradations.

Similarly to flexural strength, the compressive strength results showed relatively high variability and thus the analysis of these data is not very straightforward. However, it can be seen that, in general, the

TABLE 4.9
Test results of hardened concrete properties for Phase II ternary mixtures

Mix label	Flexural str. [psi] (MPa)		Compressive str. [psi] (MPa)			Scaling [lb/ft^2] (kg/m^2)	Shrinkage [%]	Sorption rate [10^{-4} in./s$^{0.5}$] (mm/s$^{0.5}$)	Absorption rate [10^{-4} in./s$^{0.5}$] (mm/s$^{0.5}$)	Durability factor [%]
	7 days	56 days	7 days	28 days	90 days					
Fly ash										
Grad 1	578 (4.0)	709 (4.9)	4592 (31.7)	5800 (40.0)	6992 (48.2)	0.470 (2.29)	−435	36.5 (1.49)	40.0 (1.63)	96.8
Grad 2	597 (4.1)	708 (4.9)	4096 (28.2)	5487 (37.8)	7213 (49.7)	0.934 (4.56)	−400	37.0 (1.51)	51.0 (2.08)	94.4
Grad 3	545 (3.8)	701 (4.8)	3344 (23.1)	4813 (33.2)	5895 (40.7)	0.234 (1.14)	−348	39.0 (1.59)	51.0 (2.08)	99.3
Grad 4	614 (4.2)	741 (5.1)	4227 (29.2)	5417 (37.4)	6130 (42.3)	0.013 (0.06)	−426	36.0 (1.47)	37.0 (1.51)	99.1
Grad 5	654 (4.5)	676 (4.7)	3973 (27.4)	5394 (37.2)	6341 (43.7)	0.147 (0.72)	−485	30.1 (1.23)	37.4 (1.53)	93.0
Grad 6	626 (4.3)	742 (5.1)	3938 (27.2)	5571 (38.4)	7094 (48.9)	0.081 (0.40)	−523	26.0 (1.06)	30.6 (1.25)	95.8
GGBFS										
Grad 1	713 (4.9)	814 (5.6)	5447 (37.6)	7189 (49.6)	8122 (56.0)	0.068 (0.33)	−333	31.0 (1.27)	31.5 (1.29)	95.5
Grad 2	706 (4.9)	864 (6.0)	5530 (38.1)	7595 (52.4)	8464 (58.4)	0.107 (0.52)	−317	24.5 (1.00)	26.5 (1.08)	85.7
Grad 3	705 (4.9)	930 (6.4)	5386 (37.1)	6897 (47.6)	7267 (50.1)	0.063 (0.31)	−280	33.0 (1.35)	27.5 (1.12)	99.0
Grad 4	761 (5.2)	854 (5.9)	4955 (34.2)	6805 (46.9)	7738 (53.4)	0.028 (0.14)	−323	20.0 (0.82)	22.5 (0.92)	98.7
Grad 5	636 (4.4)	871 (6.0)	4680 (32.3)	6343 (43.7)	7601 (52.4)	0.072 (0.35)	−417	21.5 (0.88)	25.0 (1.02)	80.6
Grad 6	723 (5.0)	784 (5.4)	4493 (31.0)	7255 (50.0)	7919 (54.6)	0.064 (0.31)	−477	20.5 (0.84)	21.0 (0.86)	93.7
Ternary										
Grad 1	642 (4.4)	866 (6.0)	4450 (30.7)	6878 (47.4)	8052 (55.5)	0.078 (0.38)	−410	31.8 (1.30)	32.1 (1.31)	94.9
Grad 2	652 (4.5)	738 (5.1)	4671 (32.2)	6786 (46.8)	7700 (53.1)	0.224 (1.09)	−350	33.6 (1.37)	36.4 (1.49)	85.1
Grad 3	585 (4.0)	831 (5.7)	3939 (27.2)	5732 (39.5)	6742 (46.5)	0.195 (0.95)	−240	31.0 (1.27)	31.4 (1.28)	97.2
Grad 4	654 (4.5)	768 (5.3)	4365 (30.1)	6546 (45.1)	7942 (54.8)	0.066 (0.32)	−335	25.1 (1.02)	27.6 (1.13)	99.5
Grad 5	669 (4.6)	756 (5.2)	4888 (33.7)	6704 (46.2)	8001 (55.2)	0.156 (0.76)	−400	30.6 (1.25)	34.8 (1.42)	74.5
Grad 6	651 (4.5)	793 (5.5)	4751 (32.8)	7001 (4.8.3)	8110 (55.9)	0.091 (0.44)	−437	24.6 (1.00)	26.4 (1.08)	84.1

compressive strength of mixtures with gradation No. 3 had a tendency to be the lowest among all mixtures tested. That reduced strength can be most probably attributed to segregation tendency of this mixture due to low sand content. Mixtures with gradations No. 1 and No. 2 resulted in high strength, irrespectively to binder used and the length of curing period. These high strength values of mixtures with gradations No. 1 and No. 2 can be related to the high amount of aggregate fractions retained on #4 sieve for each these two blends. Such influence of #4 fractions on concrete strength was previously reported by Shilstone (*11*).

The scaling results indicate that the influence of aggregate gradation on the amount of scaled material is highly dependent on the type of binder used. The most severe scaling was obtained for mixtures with fly ash. In this case, concrete mixtures with gradations No. 1 and No. 2 developed high scaling, mostly as the result of their poor workability and "overworking" of the surface during finishing. On the other hand, mixtures with gradation No. 3, although very easy to finish, showed segregation and bleeding, which also accelerated scaling. All other fly ash mixtures proportioned with remaining gradations showed acceptable scaling (below 0.164 lb/ft^2 limit recommended by Ontario Ministry of Transportation (MOT) (*28*)). Among these mixtures the best scaling resistance was observed for concrete made with gradation No. 4. Finally, only a little more severe scaling was measured for fly ash mixtures with gradations No. 5 and No. 6.

Aggregate gradations influenced the scaling properties of ternary mixtures in the same way as for fly ash mixtures. There were only two exceptions. Firstly, the measured amounts of scaled material were smaller than those collected for fly ash mixtures, and secondly, mixtures with gradation No. 1 showed better scaling resistance in comparison to fly ash mixtures with the same gradation. It is believed that good performance of ternary mixtures with gradations No. 1, No. 4, No. 5 and No. 6 can be attributed to improvement of paste quality by addition of GGBFS.

Finally, the highest overall scaling resistance was obtained for binary mixtures with GGBFS. Among these mixtures, concrete with gradation No. 4 was the most durable, whereas remaining concretes resulted in comparable scaling resistance. For readers convenience the results of scaling for Phase II concretes are presented in Figure 4.3.

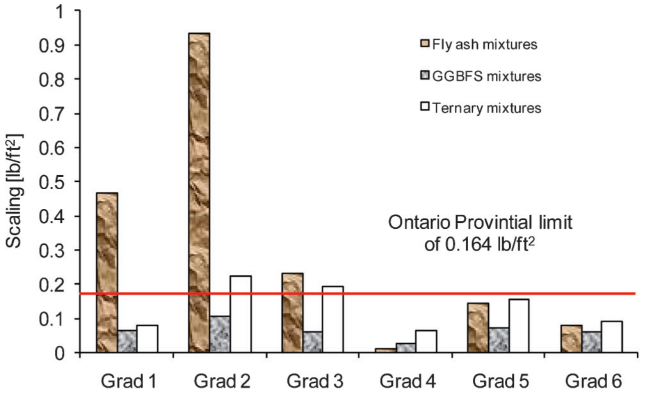


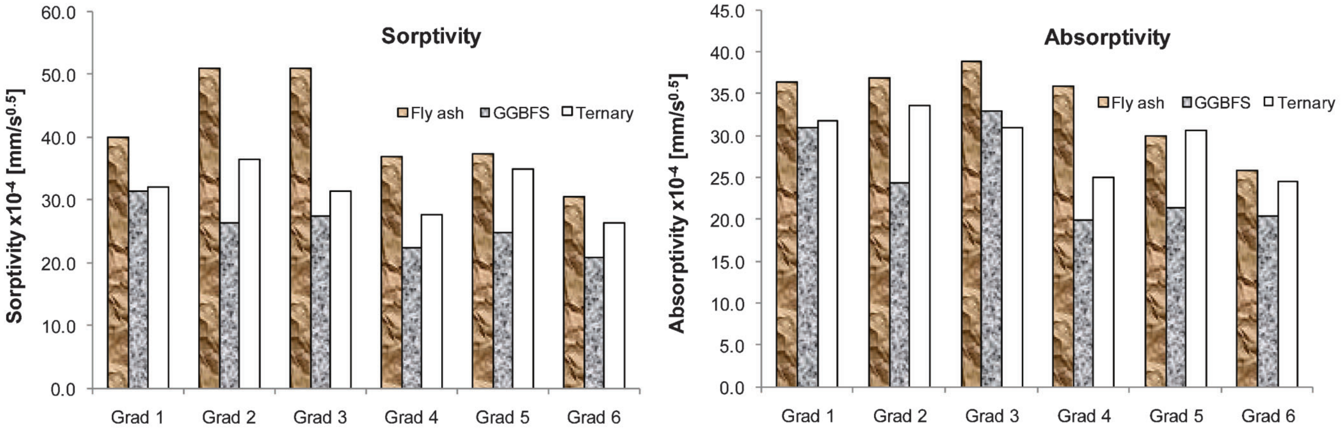
Figure 4.3 The results of scaling resistance for Phase II mixtures.

Figure 4.4 presents the rate of sorptivity and absorptivity measured for PHSE II mixtures. On average, for each type of concrete studied, the values of sorptivity were higher than the values of absorptivity. The overall lowest values of sorptivity and absorptivity were recorded for GGBFS mixtures, followed by slightly higher results for ternary mixtures. The highest sorptivity and absorptivity was observed for fly ash mixtures. In addition, it seems that concrete mixtures with gradations No. 1, No. 2 and No. 3 showed higher sorption and absorption values, than concretes with the remaining gradations. The reason for that may be fact that they were difficult to finish and consolidate (especially mixtures with gradations No. 1 and No. 2), or (as in the case of mixtures with gradation No. 3) showed segregation. On the other hand, mixtures with gradations No. 4, No. 5 and No. 6 usually showed lower sorption and absorption. More detailed analysis of this data did not result in any significant correlation between measured rate of absorption/sorption values and the amount of scaled material.

The analysis of free shrinkage data reveals that, regardless of binder type, the free shrinkage is highly dependent on the aggregate gradation. Figure 4.5 presents the results of shrinkage measured for Phase II mixtures.

The lowest overall shrinkage values were recorded for mixtures with gradation No. 3 despite the fact that these mixtures developed severe segregation and bleeding. It is believed that such good performance of these mixtures was the result of very low fine aggregate (sand) content (30% of total aggregate mass) and utilization of the coarse aggregate with NMS of 1.0 in. The use of 1.0 in. aggregate also helped to reduce shrinkage in mixtures with gradation No. 4. However, particularly for this gradation, it seems that well graded smooth gradation curve was also beneficial from shrinkage perspective. On the other hand, mixtures with gradation No. 1, developed high shrinkage, despite utilizing aggregate with NMS of 1.0 in. For this gradation, the high content of sand (44%) and #4 intermediate stone were most likely responsible for high shrinkage values. Quite surprisingly, mixtures with gradation No. 5 and No. 6 developed the highest shrinkage, despite the fact that concrete mixture with gradation No. 5 was classified as optimized having the most desirable values of CF (61.3) and WF (35.2).

In general, Phase II mixtures showed excellent F-T resistance (durability factor (DF) above 80% for all but one mixture). The only one mixture with DF lower than 80% was ternary binder mixture with gradation No. 5. Most likely, this reduced durability was a result of high total cement replacement (42%) and visible signs of aggregate failure (pop-outs). It can be also observed



a) b)

Figure 4.4 The results of water sorptivity (a) and absorptivity (b) for Phase II mixtures.

that concrete mixtures containing aggregates with NMS aggregate of 1.0 in. (gradations No. 1, 3, 4) displayed better frost durability than mixtures containing other gradations. Finally, for those three gradations, the DF measured was practically independent of the type of binder used. The reduced F-T resistance of mixtures with gradations No. 2, No. 5 and No. 6 can, most likely, be attributed to the fact that these gradations contained INDOT's #8 limestone. This limestone contained frost-susceptible chert inclusions that resulted in numerous pop-outs. Moreover, the most severe pop-outs were cause by larger (1.2 or ¾ in.) particles. Whenever particle of this size was present near the surface, the concrete spalling and cracking resulting from aggregate failure caused drop in the value of relative dynamic modulus. These observations can be used to explain the differences between FT results for mixtures with gradations No. 5 and No. 6. The gradation No. 5 was designed with higher amount of ¾, ½ and ⅜ in. coarse aggregate particles than gradation No. 6. In case of concrete mixtures with gradations No. 1, No. 3, and No. 4, the pop-outs, if present, were not that frequent because these gradations contained very little amount of ½ and ¾ in. particles with chert inclusions.

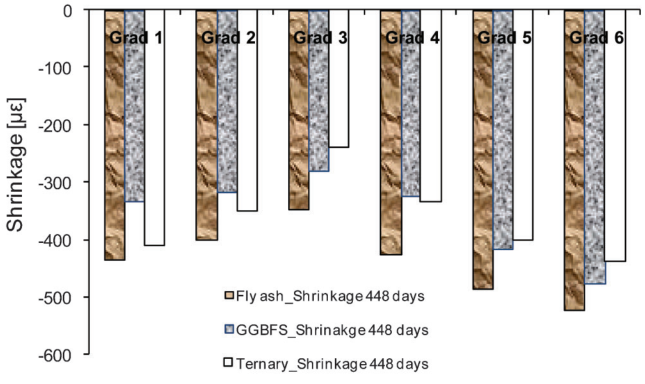


Figure 4.5 The results of free shrinkage for Phase II mixtures.

Utilization of "8-to-18" guidelines and Shilstone's Coarseness and Workability Chart did not result is satisfactory explanations for some observed trends in the data collected during Phase II. Some observations related to strength and durability gave only intuitive answers for observed trends, and thus additional analysis of the data with respect to air-free aggregate void saturation ratio (k″) and packing density will be presented in the Discussion Section of this report.

4.6 Hardened Concrete Properties—Phase III

The summary of the hardened concrete properties obtained for Phase III mixtures is presented in Table 4.10. The detailed optimization results and influence of each variable studied on concrete hardened properties will be discussed in the next section of this report.

The 7 days flexural strength data obtained from testing Phase III concrete mixtures revealed that all but one concrete mixture achieved the minimum target flexural strength of 570 psi specified by INDOT (*5*). The low (502 psi) flexural strength of this particular mixture (0.726-0.900) is most likely related to the fact that it contained highest (7.4%) air content among all concretes produced. The highest flexural strength was obtained for mixtures with packing density (Φ about 0.75) and paste-void saturation ratio (k″ about 1.0). This result seems to be reasonable because concrete mixture characterized by that combination of (Φ and k″) typically have good workability, what is crucial in case of casting and finishing concrete specimens used for flexural strength testing.

The compressive strength results analysis revealed that, regardless of the testing age, the majority of concrete mixtures with the highest compressive strength can be produced with (k″) values ranging from 0.869 to 1.0 and packing density from 0.74 to 0.77. It seems that

TABLE 4.10
Test results of hardened concrete properties for Phase III mixtures

Packing	K″	Flexural str. [psi] (MPa)	Compressive str. [psi] (MPa)			Scaling, $[\mathrm{lb/ft}^2]$ $(\mathrm{kg/m}^2)$	Shrinkage [%]	Sorption rate $[10^{-4}$ in./s0.5] (mm/s0.5)	Absorption rate $[10^{-4}$ in./s0.5] (mm/s0.5)	Durability factor [%]
		7 days	7 days	28 days	90 days					
0.715	0.975	617 (4.3)	3829 (26.4)	5414 (37.3)	6035 (41.6)	0.301 (1.47)	−0.0550	64.1 (2.62)	71.0 (2.90)	72.1
0.726	0.9	502 (3.5)	3297 (22.7)	6786 (46.8)	5647 (38.9)	0.244 (1.19)	−0.0555	55.8 (2.28)	57.1 (2.33)	84.6
0.726	1.05	608 (4.2)	3321 (22.9)	5977 (41.2)	6622 (45.7)	0.322 (1.57)	−0.0580	74.5 (3.04)	80.1 (3.27)	83.0
0.751	0.869	594 (4.1)	4750 (32.8)	6596 (45.5)	7395 (51.0)	0.290 (1.41)	−0.0430	56.2 (2.29)	61.4 (2.51)	93.7
0.751	0.975	640 (4.4)	4549 (31.4)	6142 (42.4)	7194 (49.6)	0.147 (0.72)	−0.0433	41.6 (1.70)	45.1 (1.84)	94.1
0.751	1.081	645 (4.5)	3378 (23.3)	5117 (35.3)	5766 (39.8)	0.397 (1.94)	−0.0530	57.2 (2.33)	58.7 (2.40)	94.5
0.776	0.9	594 (4.1)	4124 (28.4)	5512 (38.0)	7004 (48.3)	0.160 (0.78)	−0.0390	35.6 (1.45)	37.6 (1.53)	94.6
0.776	1.05	585 (4.0)	3640 (25.1)	5395 (37.2)	6937 (47.8)	0.241 (1.17)	−0.0440	50.4 (2.06)	49.4 (2.02)	92.1
0.786	0.975	579 (4.0)	4274 (29.5)	5492 (37.9)	6148 (42.4)	0.092 (0.45)	−0.0387	32.1 (1.31)	33.6 (1.37)	96.7

the highest compressive strength (of about 4500 psi) and 90 days compressive strength values were obtained for Φ values similar to those associated with highest values of flexural strength. However, the k″ range was slightly wider in the use of the compressive strength data (from about 0.869 to 0.975). This shift of highest compressive strength toward lower k″ values can be related to the increase in concrete density, what definitely helps in achieving higher strength. On the other hand, when k″ values reached value of 1.050 or higher, the concrete mixtures exhibited segregation which resulted in low compressive strengths (see mix 0.726_1.050 and 0.751_1.081). For these mixtures, the minimum 28 days compressive strength of 3500 psi specified by Michigan DOT (*27*) was not achieved.

With respect to scaling, it can be observed in Table 4.10 that the performance limit for scaling of $0.164\ \mathrm{lb/yd}^3$ was satisfied only by 3 out of 9 produced mixtures. All these well performing mixtures were characterized by k″ values between 0.900 and 0.975. These results seem to support conclusions from Phase II of the study, that good scaling resistance requires production of well workable mixtures and specific k″ values. This specific value of k″ exists around 0.975, and is associated with packing densities above about 0.750.

The rate of water absorption and water sorption depended on both packing density and the amount of paste used (expressed as k″ value). The lowest values of absorptivity and sorptivity can be observed when the aggregate is characterized by high packing density, but at the same time the (k″) value will not reach 1.0 value. Those results seem to be pretty reasonable, since the amount of water absorbed by concrete is related to density of the matrix, its workability and its ability to consolidate (to prevent formation of large voids). Based on the data obtained during this phase of the study, a correlation between scaling and the rate of water sorptivity (absorptivity) was developed.

The free shrinkage results indicate that this property is particularly dependent on the packing density of aggregates. A significant decrease in measured shrinkage was achieved by increasing packing density of aggregate skeleton. In addition, the positive effect of decreasing of k″ value on shrinkage was also observed. Generally, the results of free shrinkage recorded for mixtures in Phase III are very comparable to those described in Phase II. It seems that in order to maintain low concrete shrinkage, both k″ and aggregates packing should be kept as low as possible.

With respect to the freezing and thawing resistance, only one of 9 concrete mixtures tested failed 80% DF performance criterion established for this research project. In addition, the data presented in Table 4.10 indicate that keeping packing density at high value improves F-T resistance. On the other hand, it is difficult to say what was the effect of (k″) ratio on measured freeze and thaw durability, since both mixtures with low and high (k″) values performed well.

5. DISCUSSION

5.1 Optimization of Binary Mixtures

The optimization results (desirability plots) for fly ash and GGBFS mixtures are shown in Figure 5.1, respectively.

It can be seen that in both cases these results appear as a more-or-less flat surfaces elevated above the plane representing various paste vs. fly ash (or slag) combinations. For fly ash mixtures, see Figure 5.1, the maximum desirability surface declines diagonally toward the region defined by mid-range (~22.5%) paste content and low (~15%) fly ash content. For the paste content in the range from 21.5 to 23%, this surface spans most of the fly ash replacement levels studied. The point with highest desirability (0.973) is located near one of the corners of this surface and is defined by the combination of about 21.75% of paste and about 29.5% of fly ash. Similarly, in the case of the slag system, see Figure 5.2, the maximum desirability surface also declines diagonally toward the region defined by mid-range (~23.5%) paste content and low (~23%) slag content. For the slag replacement level in the range from 24 to 37% the maximum desirability surface covers wide range of paste contents (from 21 to 23.75%). The point with highest desirability (0.988) is located near one of the corners of this surface and is

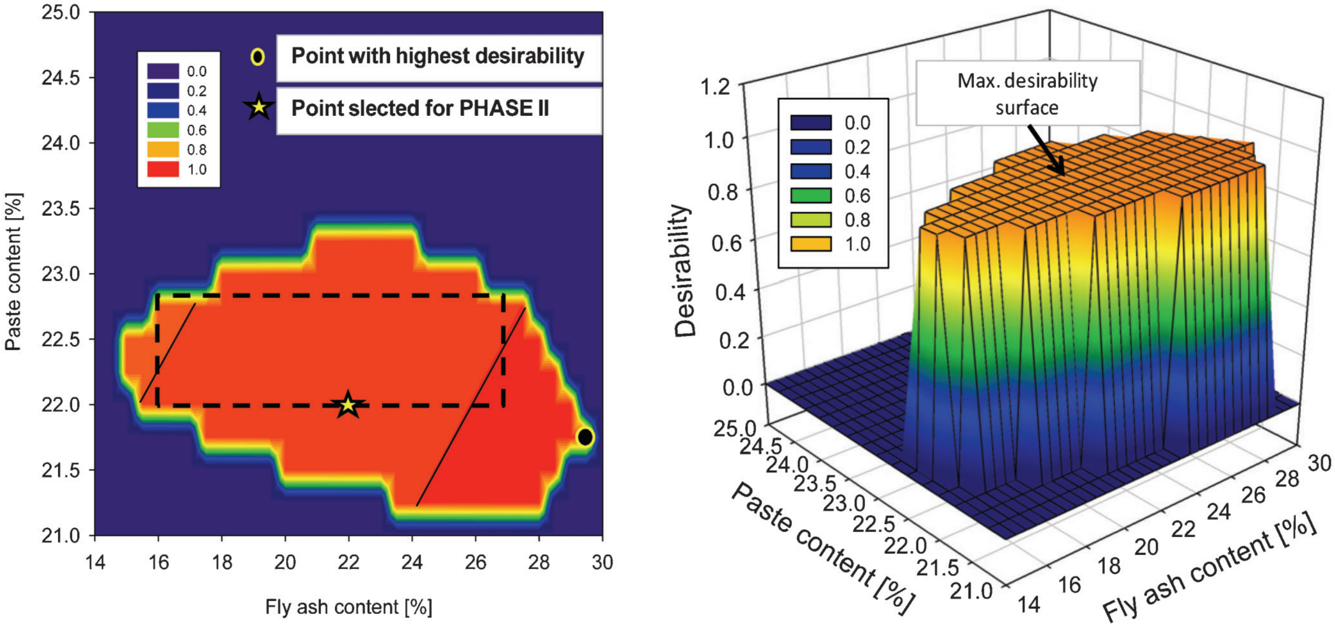


Figure 5.1 Combined desirability plots for fly ash mixtures.

defined by the combination of about 21% of paste and about 37% of slag.

Although the surfaces described above represent the combination of variables that should yield mixtures with optimum properties, it should be realized that (as mentioned earlier) fresh concrete properties were not included in the optimization process. The fresh properties were excluded from the optimization process for two reasons. First, as already mentioned, all mixtures were designed to have the same nominal slump and air contents. Second, the workability of mixtures is difficult to quantify and some mixtures, especially these with low paste content, were relatively harsh, despite having met the target slump requirements. As a result, it was arbitrarily decided than in order to insure workability of mixes with different aggregate gradations is would be more practical to artificially raise the paste content above the values obtained from the optimization

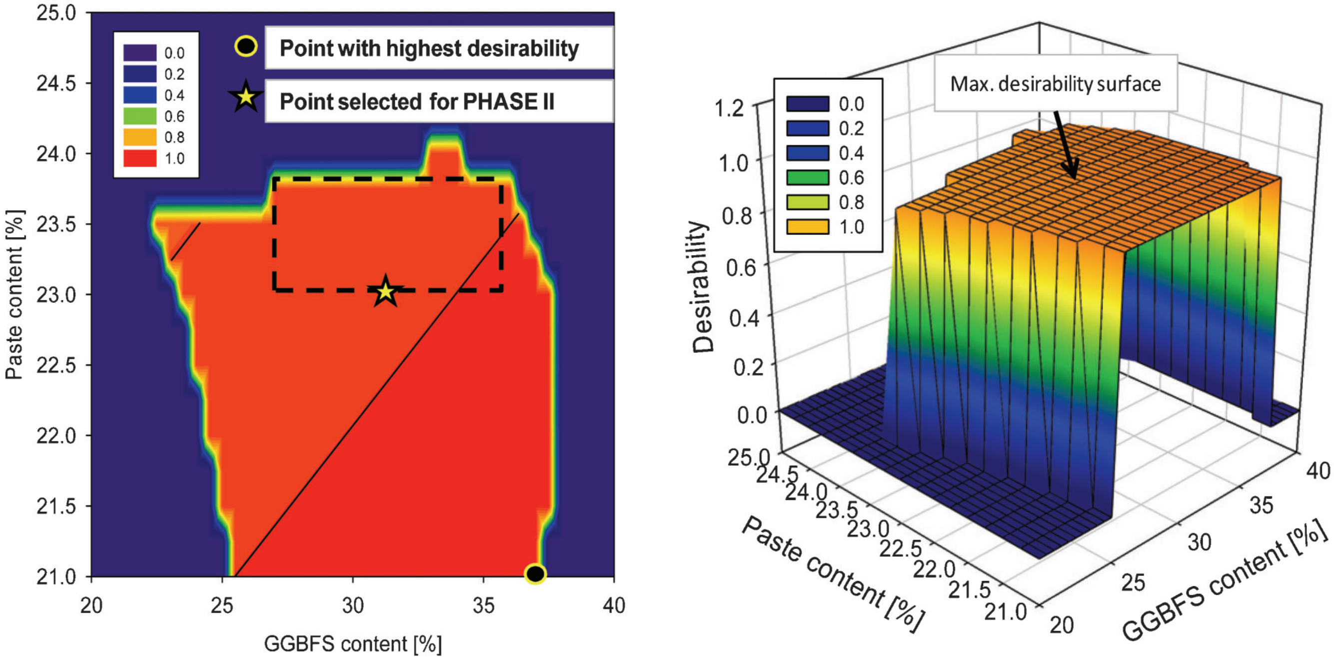


Figure 5.2 Combined desirability plots for GGBFS mixtures.

process. The proposed increase is 0.25% for fly ash mixes (for a total of 22% of paste) and 2% for slag mixtures (for a total of 23%).

Based on the limited laboratory trials, the proposed percentage increase in paste content was observed to consistently result in mixtures with adequate workability, despite variations in aggregate gradations. In case of concrete mixtures with fly ash, the adjustment in paste content forced the adjustment in the percentage of fly ash content (to ~29%) in order to retain the point representing these two variables on the maximum desirability surface. In case of GGBFS mixtures the adjusted paste content of 23%, did not force the change in the slag content from what was obtained during optimization process. Based on the above adjustments, the final recommendations for "optimized" mixtures are as follows:

- mixture with 22% of paste and 29% of fly ash (desirability level 0.970)—Fly ash system
- mixture with 23% of paste and 37% of slag (desirability level 0.968)—Slag system

Both of the selected mixtures are located close to the highest desirability point and on the maximum desirability surface. As a result, they can (in the authors' opinion) provide significant benefits in the form of reduced cement content and cost.

Finally, from a practical point of view, the single combination of variables studied will not give enough flexibility in mixture design. That is why the author further decided to propose a concept of "desirability window", which will allow for more flexible selection of paste and slag (or fly ash) combinations. In order to satisfy the assumptions used for optimization purposes (target performance criteria at minimum cost) and also taking into account the need for satisfactory workability and practical relevance of proposed mixtures, the following "desirability windows" were established:

- for fly ash mixtures: paste content from 22% to 22.75% and fly ash content from 16 to 27%
- for slag mixtures: paste content from 23% to 23.75% and slag content from 27% to 36%

The desirability windows defined above are presented as the rectangular boxes in Figure 5.1 and 5.2. In the opinion of the authors concrete mixtures characterized by combination of research variables within the desirability windows will show good performance. However, for some marginal combinations they may vary with respect to cost and some properties (i.e., scaling, sorptivity) mainly due to amount of supplementary cementitious materials, as previously discussed in sections related to analysis of the raw data.

5.1.1 Influence of Fly Ash and Paste on Concrete Properties

Although they provide adequate illustration of the optimum levels of paste and SCMs, the 3D and contour plots given in Figure 5.1 and 5.2 are not very convenient in practical application. For example, if one is interested in selecting performance-related optimum mixture proportions, presented optimization results do not state whether selected combination of research variables would give expected performance. For this reason additional analysis was performed to show the reader how different combinations of studied research variables affect the most important (in the authors' opinion) concrete properties (7 day flexural strength, 7 and 28 day compressive strength, scaling, free shrinkage, absorptivity) and cost. The results (discussed in this section) represent predicted concrete properties for combinations of research variables with non-zero overall desirability. As an example, Figure 5.3 presents predicted 7 day flexural strength for fly ash concrete mixtures.

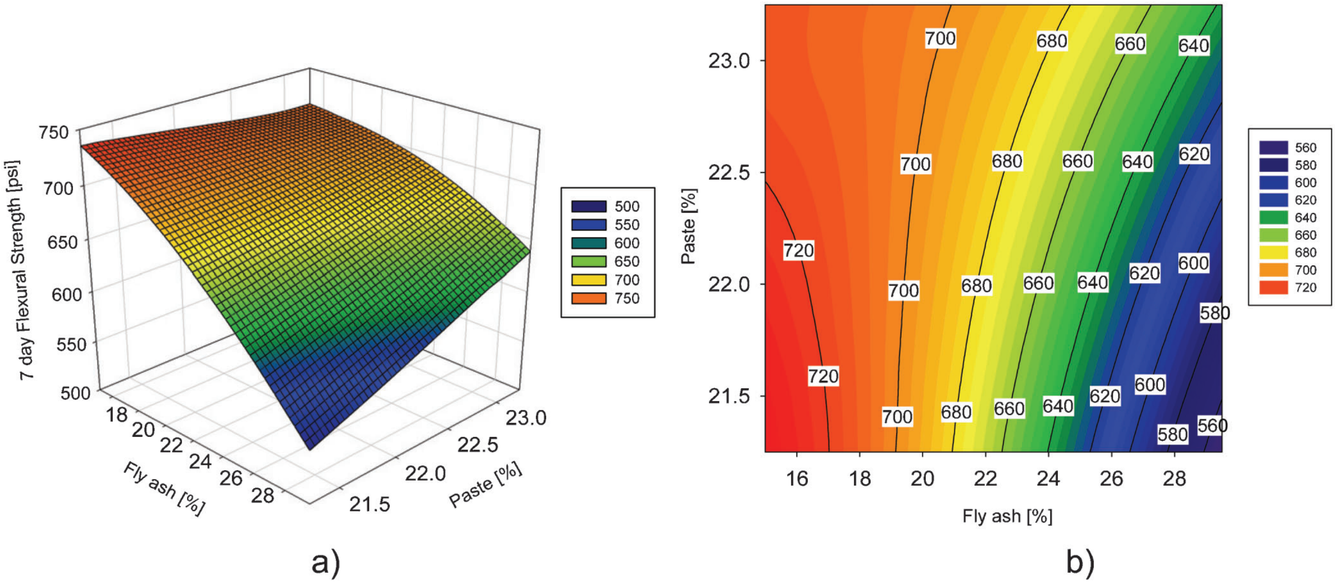


Figure 5.3 Predicted 7 day flexural strength for fly ash mixtures: (a) 3D plot and (b) contour plot.

As indicated in the figure, the flexural strength of 680 psi (100 psi higher than that required by INDOT) can be obtained for mixtures with paste content from 21.25% to 23.25% and fly ash content from 16.5% to about 23%.

The 7 and 28 day compressive strength results for the same combinations of fly ash and paste are presented in Figure 5.4 (a) and (b), respectively.

As shown in Figure 5.4 (a) and (b), predicted compressive strength increases diagonally toward combinations of low amount of fly ash and paste contents. There are two probable explanations of observed trends. First, fly ash reacts slower than cement and the increased amount of this supplementary cementitious material in concrete mixtures results in lower early age strength. In addition, decrease in paste volume helps to attain higher density of concrete mixtures, thus the compressive strength of such mixtures should be higher. The results presented in both graphs indicate that, after 7 days, the compressive strength of 3500 psi (required by some state DOTs) and compressive strength of 5000 psi (typical for pavement mixtures after 28 days) is possible for almost all paste content-fly ash content combinations.

As mentioned in Statistical Optimization Process section of this report, the results of scaling and absorptivity correlated well. From this reason, the influence of research variables on predicted scaling resistance and water absorption will be discussed together. Figure 5.5 shows the contour plots for, respectively, predicted scaling resistance (a) and water absorption (b).

As can be seen in Figure 5.5 the smalest values of scaling and water absorptivity can be obtained for mixtures with low paste and fly ash contents. For both of these properties, the test procedure requires testing concrete samples after about 28 days of curing. However, it is believed that such short curing period may not be adequate for testing concretes with Class C fly ash. In addition, it was observed during the laboratory experiments that concrete mixtures with high paste content (above 23%) and high fly ash content (above 25%) developed some bleeding and were more prone to overfinishing. Surface overfinish and bleeding may explain trends presented in Figure 5.5.

Predicted free shrinkage of fly ash concretes is shown in Figure 5.6. The results indicate that the most favorable (lowest) values of free shrinkage would be obtained for mixtures with 20% to 26% of fly ash, regardless of the paste content. The reasonable explanation of such results is difficult. However, during the experimental phase, it was noted that mixtures with 22% of fly ash were very workable, cohesive and did not show bleeding. It was very easy to place and vibrate them without segregation. As discussed in optimization results section, the authors believe that 22% of fly ash is the most desirable amount of Class C fly ash for paving mixtures. The predicated free shrinkage results support this selection.

Finally, Figure 5.7 shows predicted cost of fly ash mixtures. As indicated in this figure, the cost drops about 2$ per cubic yard toward mixtures with high amount of fly ash and low paste content. Such mixtures contain lower amounts of Portland cement, which is the most expensive ingredient of any mixture.

In summary, the analysis of predicted properties of fly ash mixtures indicate that the amount of fly ash and paste influence concrete performance in two directions. The mechanical properties and durability reach the highest values when fly ash and paste are at the low end

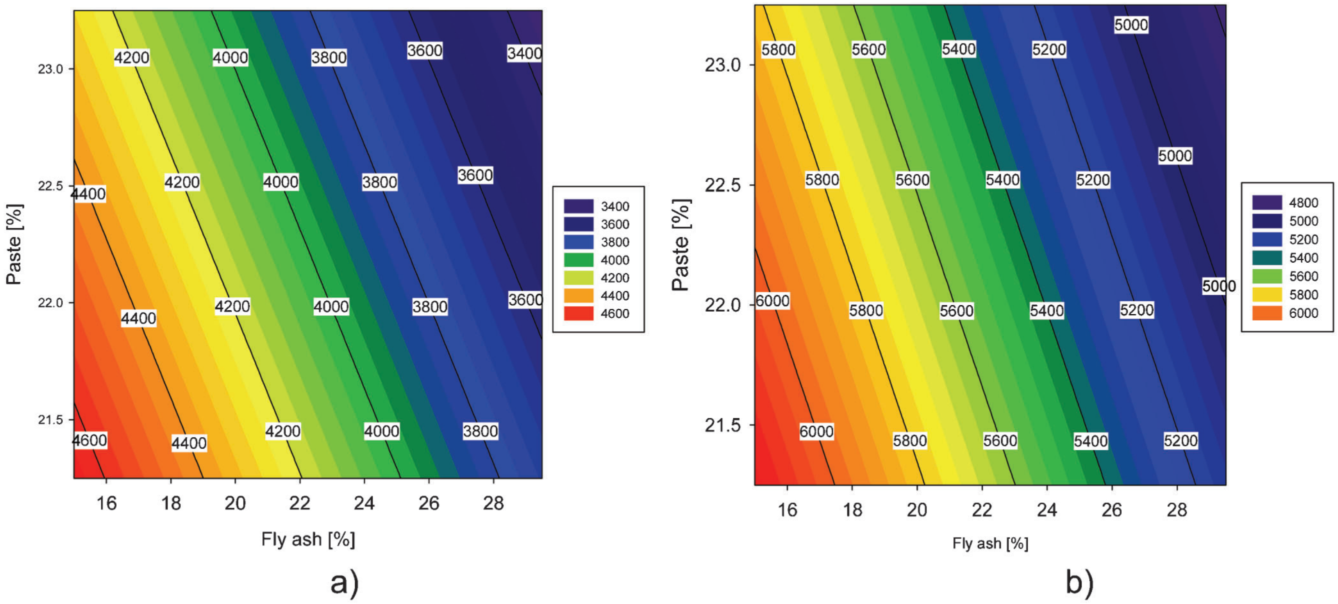


Figure 5.4 Predicted 7 day (a) and 28 day (b) compressive strength for fly ash mixtures.

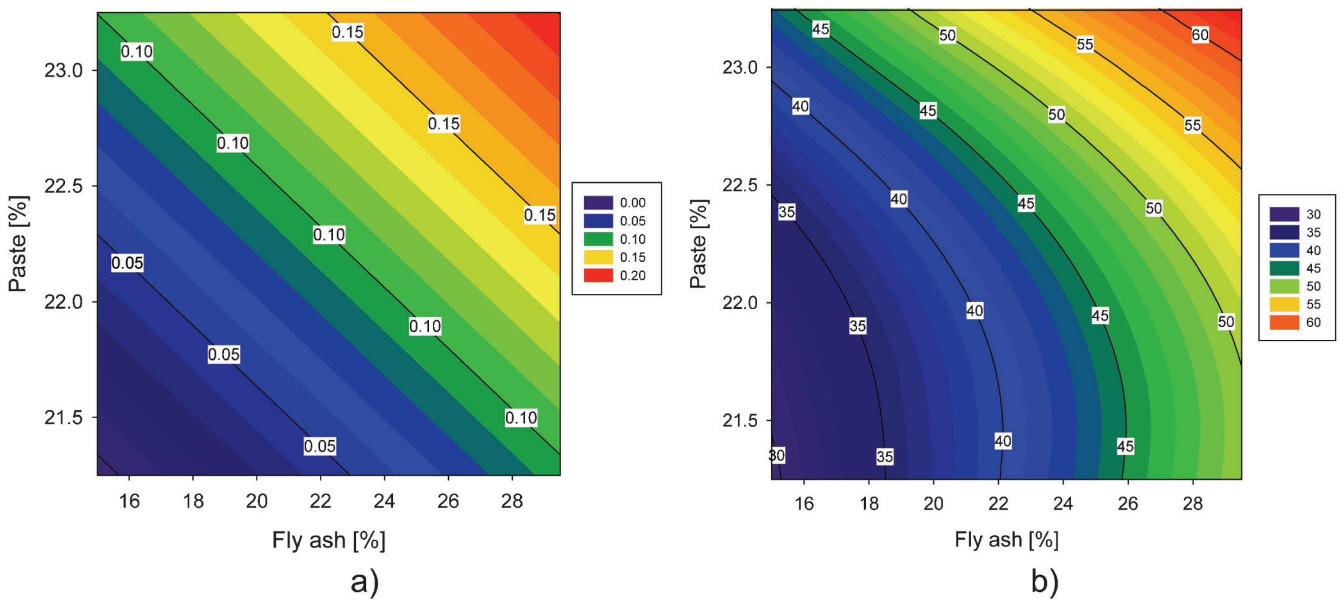


Figure 5.5 Predicted results of scaling (a) and absorptivity (b) for fly ash mixtures.

of studied ranges. For cost the trend is reversed (the most desirable cost is obtained by reducing paste and increasing fly ash content). Predicted results of free shrinkage are the most difficult to explain, but they can be related to performance of fresh concrete mixtures tested in the laboratory. Since, the most desirable results for majority of selected performance criteria exist at the extreme range of research variables, it is reasonable to base performance-related optimum mixture composition on predicted free shrinkage results. Thus, one can select optimum fly ash content in the range from 20 to 26% and adjust paste content based on the test result for remaining properties.

5.1.2 Influence of GGBFS and Paste Content on Concrete Properties

Similarly to fly ash mixtures, the influence of GGBFS and paste content on selected performance criteria for GGBFS system can be analyzed with help of 3D or contour plots. The analysis presented in this section was prepared for combinations of GGBFS and

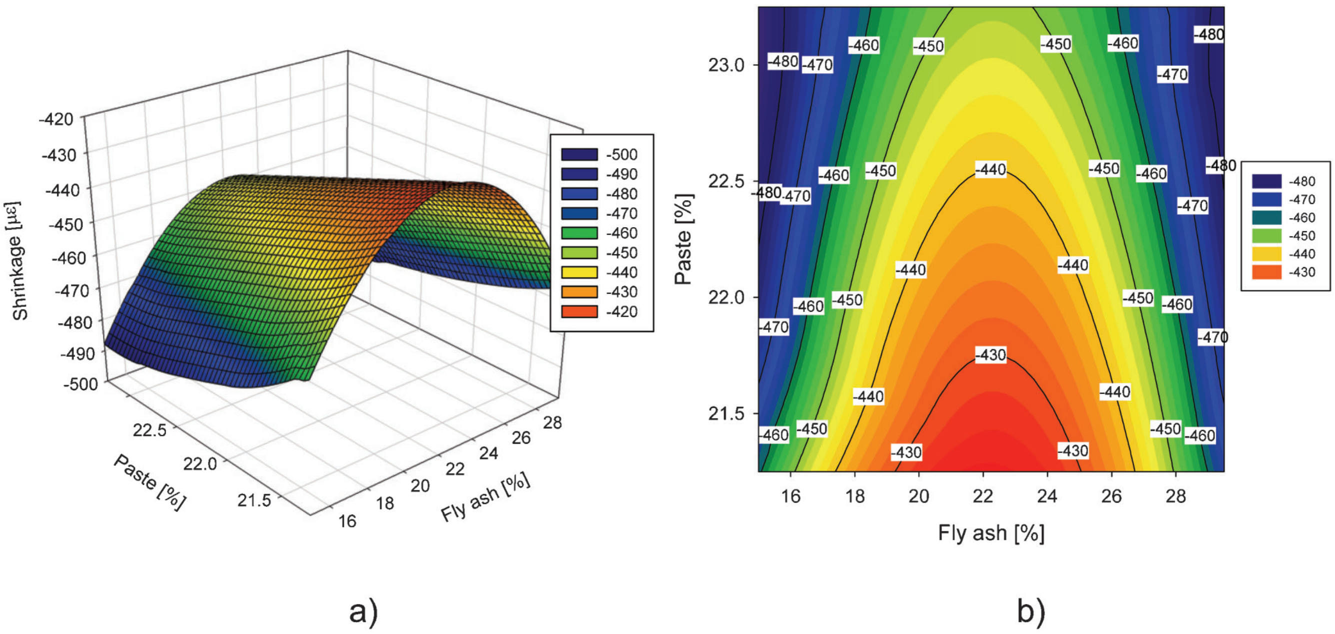


Figure 5.6 Predicted results of free shrinkage for fly ash concretes.

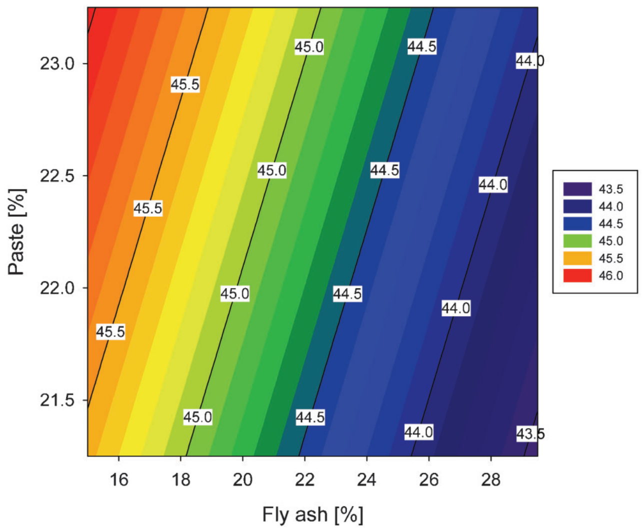


Figure 5.7 Predicted cost of fly ash mixtures.

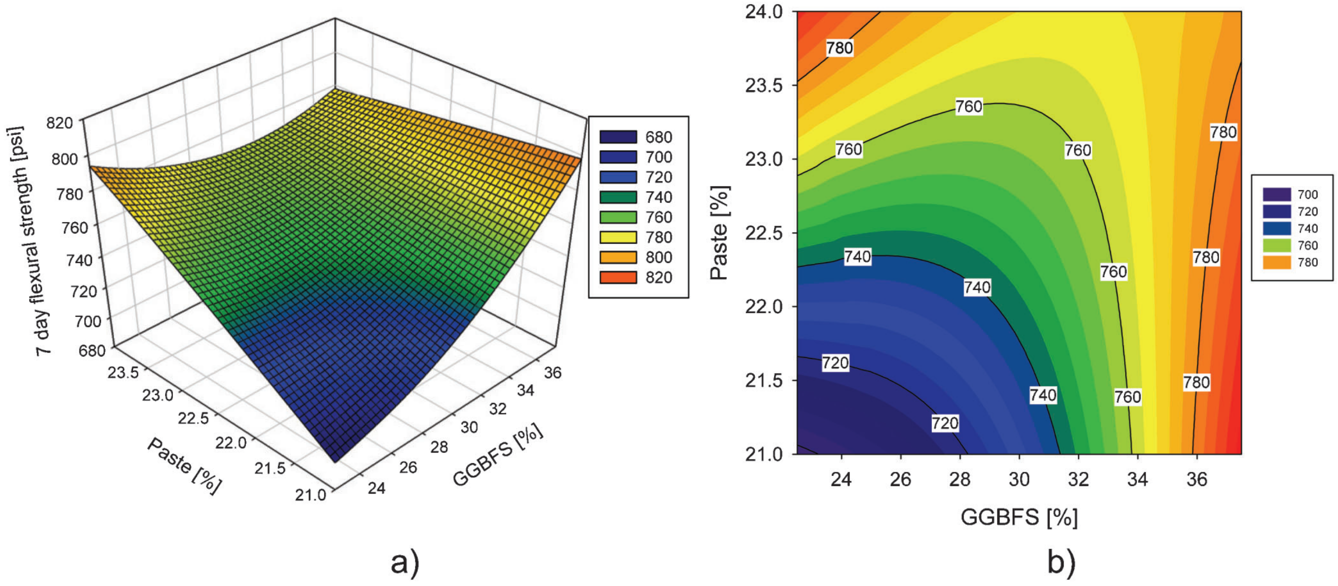
paste content with non-zero overall desirability. The range of GGBFS analyzed was from 22.5% to 37.5% and the range of paste content was from 21% to 24%. Figure 5.8 shows predicted results of 7 day flexural strength for slag mixtures.

In general, the predicted flexural strength values for slag system are higher than those observed for most of fly ash mixtures and it exceeds by far the value of 570 psi required by INDOT's specifications. Such good performance of slag mixtures can be related to high reactivity of Grade 120 GGBFS. From flexural strength perspective, any combination of GGBFS and paste from Figure 5.8 would yield satisfactory mixtures. However, flexural strength is not the only performance characteristic considered for selection of optimum mixture proportions. As shown in Figure 5.9 high compressive strength after 7 and 28 days varies by about 1500 psi, depending on selected combination of GGBFS and paste.

After 7 days of curing, the highest compressive strength can be obtained for concrete mixtures with about 21% to 22.75% of paste and slag content above 30%. These results indicate that, at early age, high amount of GGBFS helps to reach high compressive strength. Such beneficial influence of GGBFS on early strength can be explained by its high reactivity, as well as by an increase of concrete density due to use of less paste and higher packing density of binder particles (this theory was not verified during the presented research). On the other hand, after 28 days, the highest compressive strength was obtained for an "optimum" GGBFS and paste combination. It seems that this optimum combination falls within the range of 21.5% to 23% for paste and 26% to 31% for GGBFS contents. Such results indicate that compressive strength of slag mixtures beyond 28 days is obtained for combinations of variables that help to attain uniform and workable mixtures with enough paste to allow good aggregate distribution and interlocking.

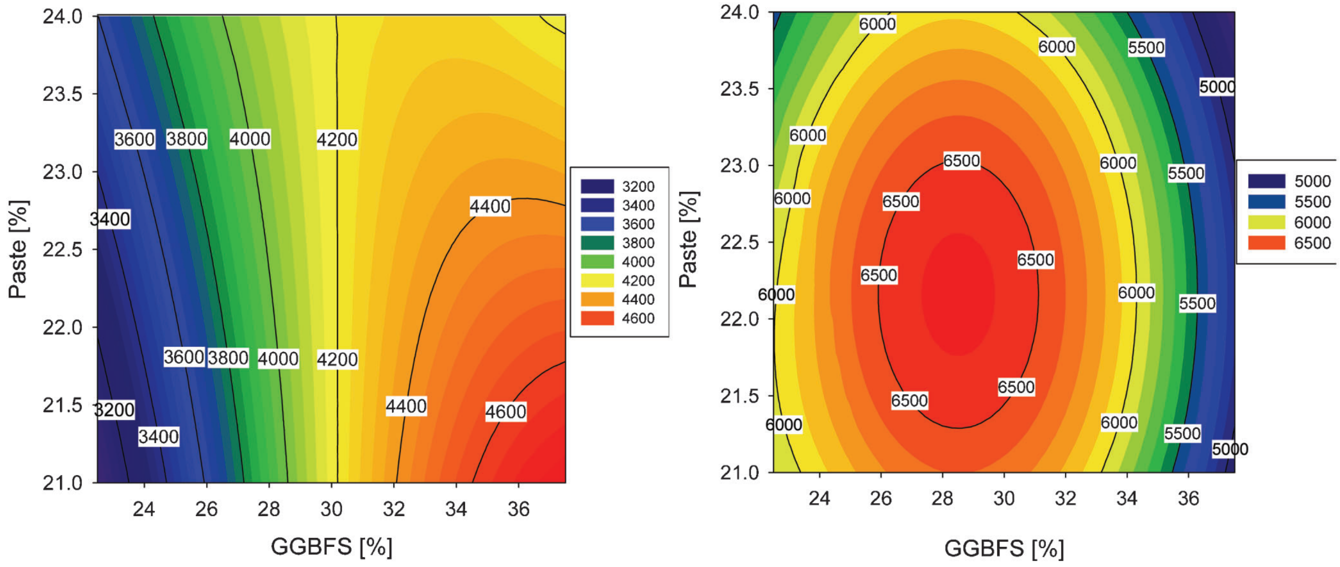
The results of scaling and water absorption presented in Figure 5.10 did not result in as clear of a trend as that observed for fly ash mixtures. However, it can be seen that both scaling and water absorption for slag mixtures can be substantially reduced when paste content and amount of slag is kept low. Next, the results for predicted shrinkage values are presented in Figure 5.11.

The results of predicted shrinkage indicate that for slag mixtures there is a preferable amount of paste required to obtain low shrinkage. That preferable paste content ranges from about 21.75% to 23%. At the same time, the content of slag has to be kept high (more than 30%). High reactivity of slag and its high fineness could



a) b)

Figure 5.8 Predicted 7 day flexural strength for slag mixtures: (a) 3D plot and (b) contour plot.



a)

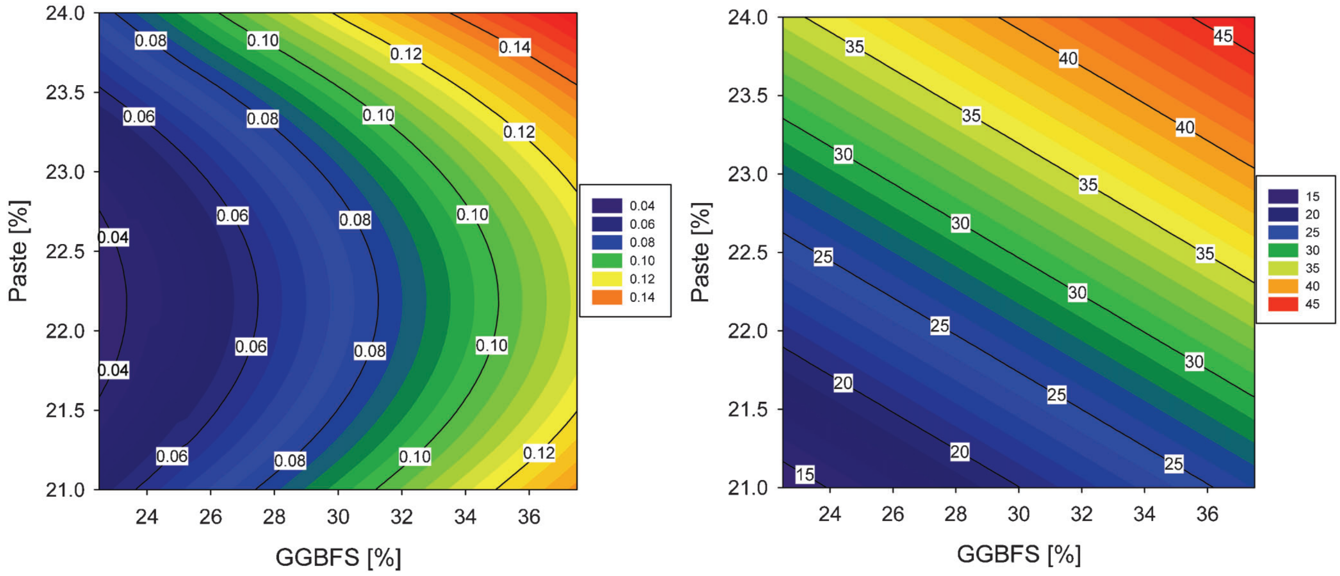
b)

Figure 5.9 Predicted 7 day (a) and 28 day (b) compressive strength for slag mixtures.

contribute to shrinkage reduction by trapping more mixing water. Finally, predicted cost of slag mixtures is presented in Figure 5.12.

As indicated in Figure 5.12, the cost drops about 2$ per cubic yard toward mixtures with high amount of slag and low paste content. Such mixtures include less Portland cement which is the most expensive ingredient of any mixture.

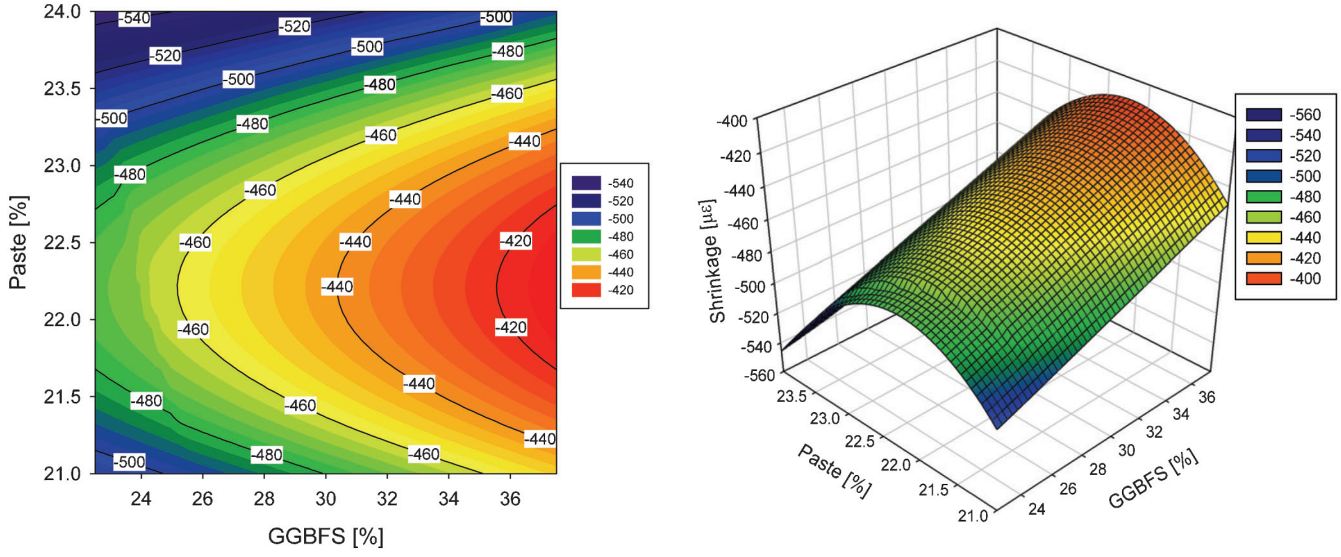
In summary, the analysis of predicted properties of slag mixtures is more complicated than of fly ash mixtures. It is difficult to point the best amount of slag for which all described concrete properties reach the most desired values. However, the predicted results for all presented properties were far from their minimal required values. On the other hand, the most preferable paste content seems to range from about 21.75% to 23%. Based on this statement, it seems that the best strategy would involve selection of mixture composition based on the price, as (based on this research data) the desired target properties could be easily satisfied target properties.



a)

b)

Figure 5.10 Predicted results of scaling (a) and absorptivity (b) for slag mixtures.



a)

b)

Figure 5.11 Predicted results of free shrinkage for slag concretes.

5.2 Optimization of Ternary Mixtures

During numerical optimization of ternary systems, a total of 8924 different combinations of test variables (fly ash, GGBFS and paste content) were investigated by means of numerical simulations. Based on these simulations, the composition containing 15% of fly ash, 26% of GGBFS and 21.5% of paste resulted in the highest (maximum) desirability value of 0.975.

From the practical perspective (i.e., needs for adjustments to account for variability in the properties of materials) utilizing the single combination of variables just because it resulted in highest desirability may be too restrictive. As such, it may be more advantageous to explore how the desirability changes around the highest value. This issue has been examined by creating the desirability surface for the pair of two independent variables, while keeping the third variable at its maximum (optimum) value (*56*). This approach is shown in Figure 5.13 (a–f), where each pair of plots (a–b, c–d, e–f) represents, respectively, the surface-contour plots for paste-GGBFS content prepared at maximum value of fly ash (15%), surface-contour plot for paste-fly ash content prepared at maximum value of GGBFS (26%), and surface-contour plot for GGBFS-fly ash prepared at maximum value of paste (21.5%).

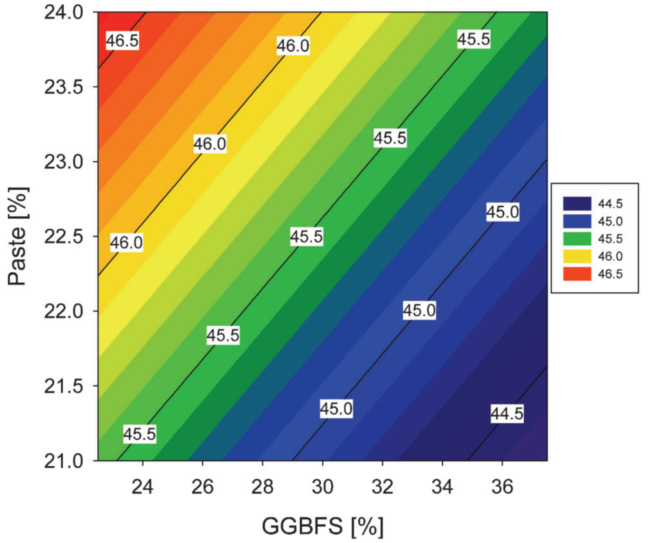


Figure 5.12 Predicted cost of slag mixtures.

As shown in these plots, the desirability surfaces (shown as the bright areas) appear to be flat. This indicates that any combination of variables contained within these areas does not significantly decrease the overall level of desirability. However, the allowable ranges within which the two variables can change without significantly decreasing desirability are not the same for different set of variables. For example, the data shown in Figure 5.13 (a) indicate that at optimum (15%) fly ash content, the area of acceptable desirability is very narrow. That practically eliminates possibility of adjusting mixture composition by changing slag or paste content while keeping the fly ash content at optimum. On the other hand, as shown in Figure 5.13 (c), when analyzed at optimum (26%) GGBFS content the mixture composition can be adjusted within much broader range without reducing overall desirability.

While the desirability area presented in Figure 5.13 (c) is broader than that presented in Figure 5.13 (a), it will still be difficult to implement this approach in practice, as one would have to change the volume of paste, which may have negative impact on workability. This is illustrated in Figure 5.14 (a), where the paste-based desirability area is small. However, this area increases with an increase in paste content (Figure 5.14 (b–d)). As mentioned earlier, mixtures with paste

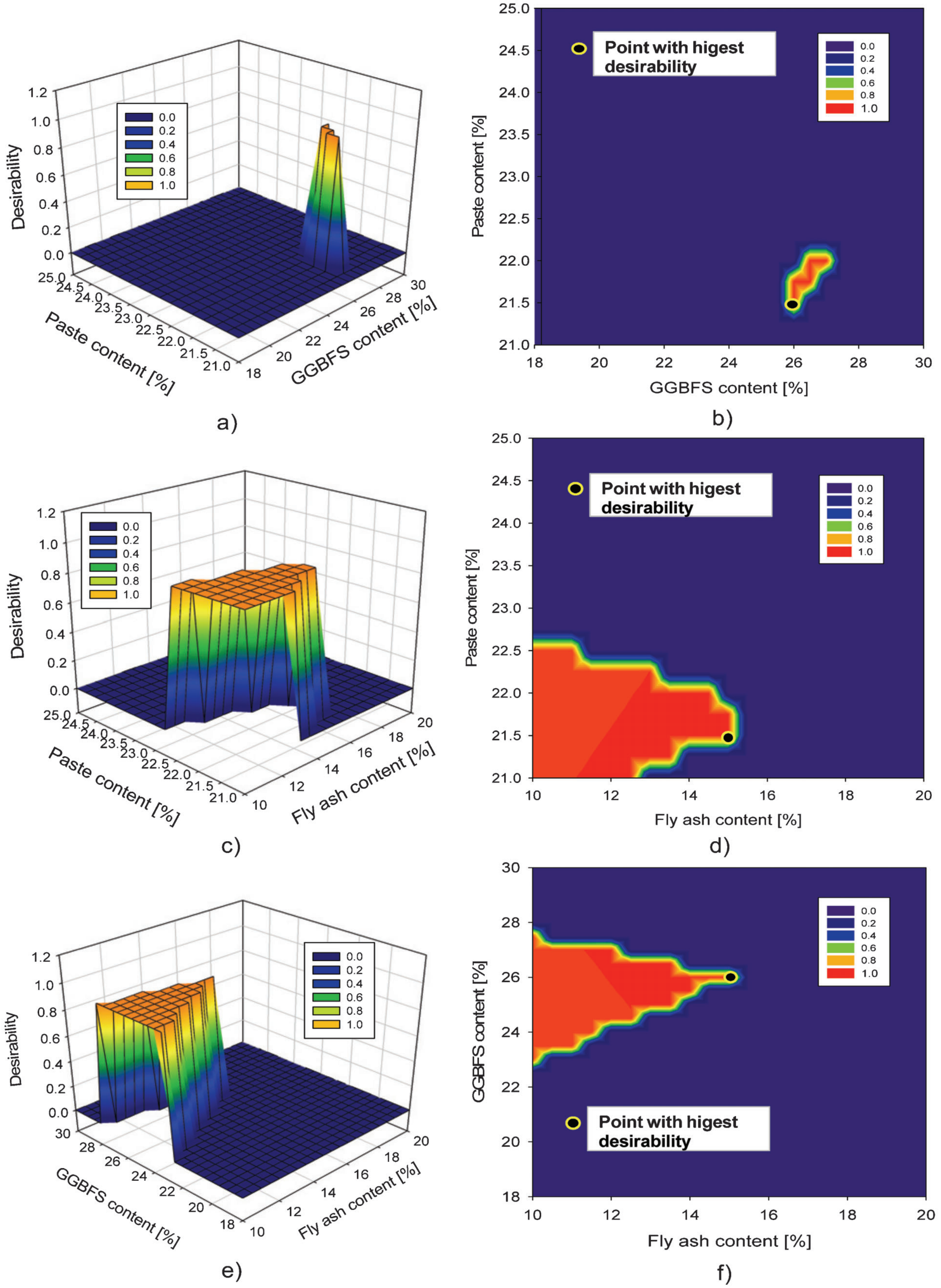


Figure 5.13 Plots of desirability surfaces for ternary mixtures at optimum (15%) fly ash content (a–b), optimum (26%) GGBFS content (c–d), optimum (21.5%) paste content (e–f).

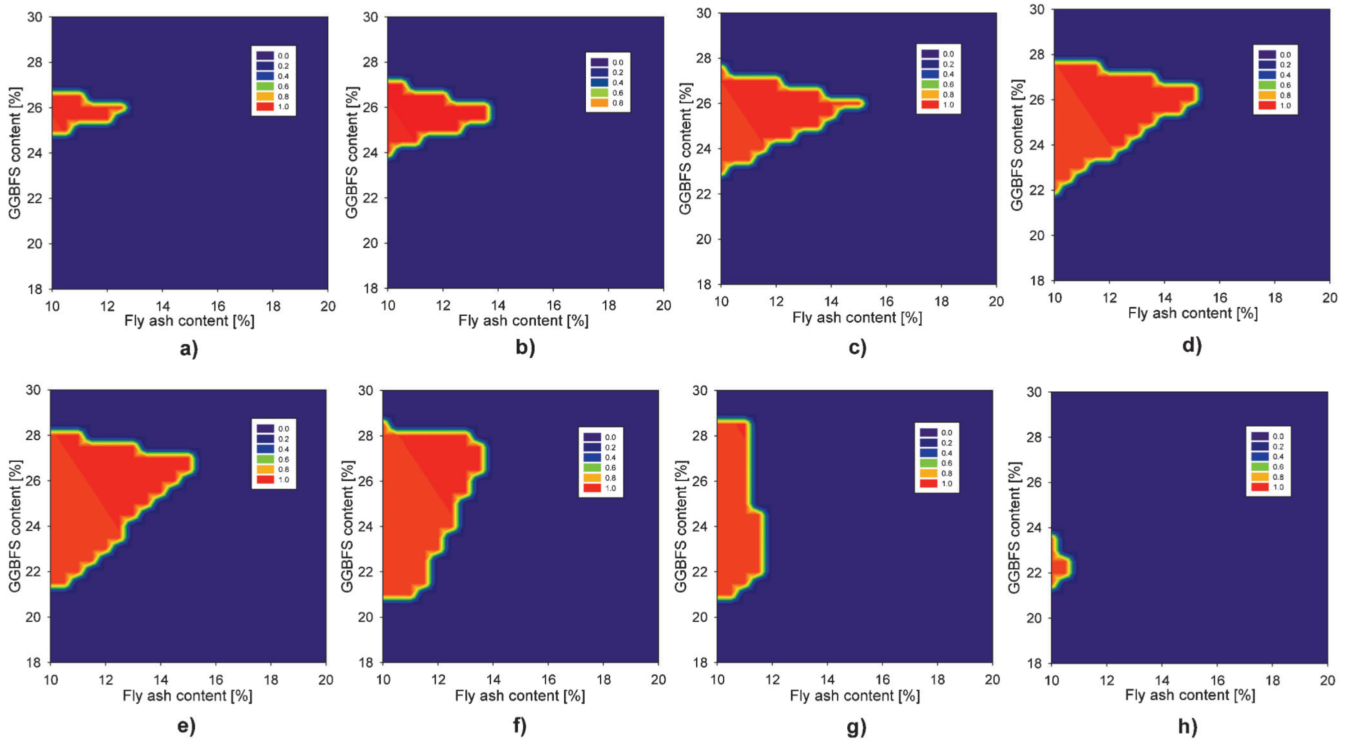


Figure 5.14 Changes of desirability surface for ternary mixtures at paste contents of: (a) 21.0%, (b) 21.25%, (c) 21.5%, (d) 21.75%, (e) 22.0%, (f) 22.25%, (g) 22.5%, and (h) 22.75%.

content below 22% were difficult to work with and to compact. It is therefore more practical to set paste content in the range that gives relatively good workability (as indicated by broad desirability surface in Figure 5.14 (e) and (f)) and adjust the fly ash and slag contents.

For mixtures with 22% of paste, the amount of GGBFS allowable for making ternary systems with fly ash was broader than for mixtures with 21.5% of paste (which was determined as being optimum). More in-depth data analysis revealed that in case of ternary mixtures with 22% of paste, the improvement in concrete workability helped to attain required scaling resistance and 7 days compressive strength for larger number of ternary mixtures. Based on these observations, it was concluded that the increase in GGBFS helped to increase scaling resistance and to gain sufficient compressive strength, but only for mixtures with 22% of paste.

The observations listed above led the authors to modify the desired optimum composition of ternary systems from that obtained by numerical optimization. The modified composition includes 15% of fly ash, 27% of GGBFS and 22% of paste. Although this modification reduced the desirability value from original (0.975) to 0.974 it is not expected that this adjustment will have negative influence on concrete properties and the price. At the same time, the proposed adjustment should also help to reduce potential workability problems.

5.2.1 Influence of Fly Ash and GGBFS on Properties of Ternary Mixtures

In order to show in details how research variables influenced properties of ternary mixtures, the approach similar to that presented for binary mixtures was developed. This approach involved the analysis of influence of paste, fly ash and GGBFS content on selected values of predicted concrete properties (flexural and compressive strength, scaling resistance, absorption, shrinkage and cost). The scope of this analysis included only predicted properties for combinations of research variables with non-zero overall desirability. However, in case of ternary mixtures, additional complication existed due to presence of the third variable. Thus, an arbitrary decision was made to group the data with respect to paste content and express the results only for different combinations of fly ash and GGBFS. Among all possible combinations studied, the amount of non-zero overall desirability for paste content ranged from 21% to 22.75%.

Figure 5.15 through 5.21 show changes of predicted concrete properties for ternary mixtures divided into four groups: for 21%, 21.5%, 22% and 22.5% of paste. Mixtures with 22.75% of paste were excluded from graphical analysis since for this amount of paste only 7 inputs was found with overall desirability higher than 0. Figure 5.15 (a–d) show the predicted results of 7 days flexural strength for ternary mixtures.

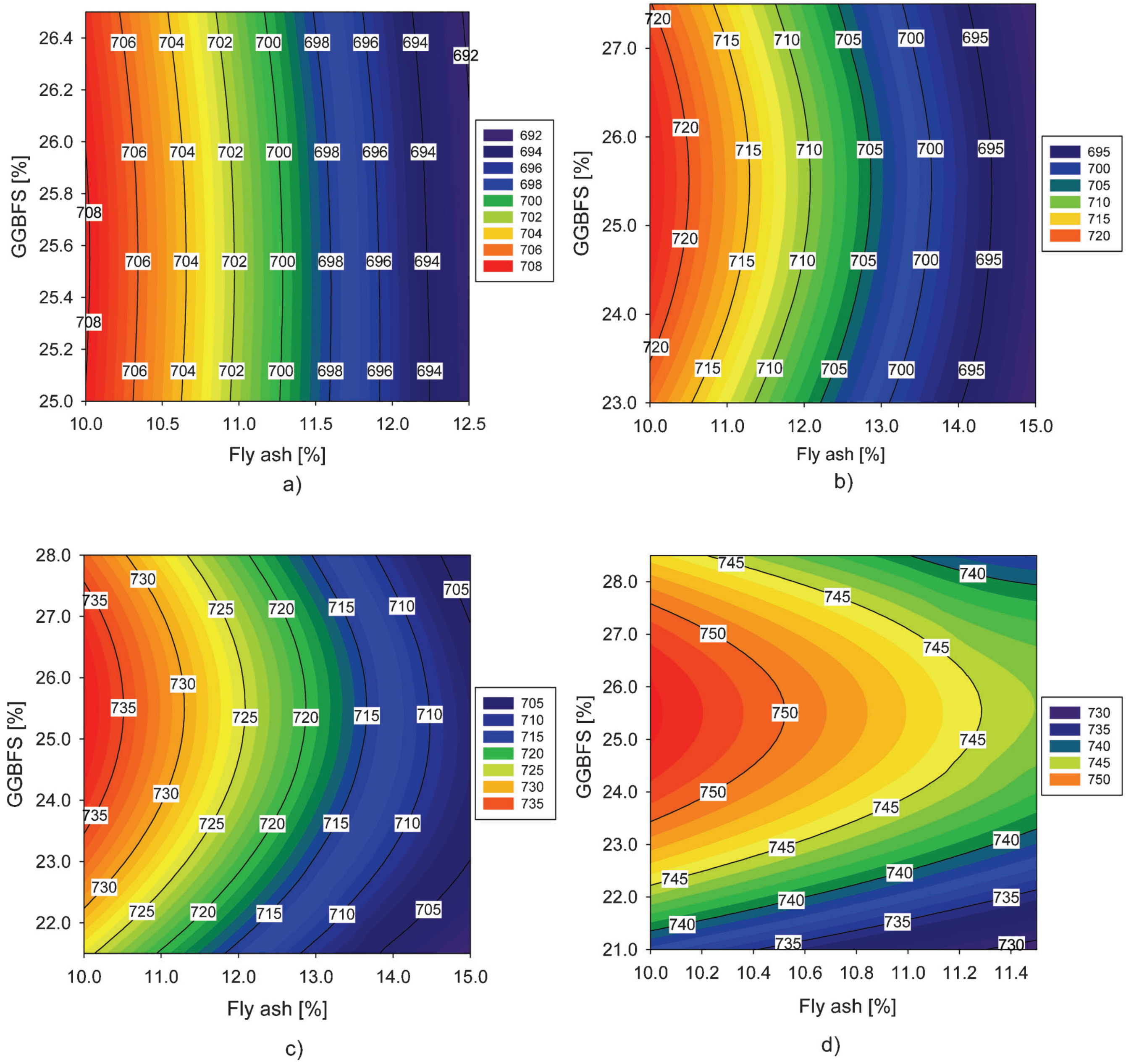


Figure 5.15 Predicted 7 days flexural strength for ternary mixtures with 21% (a), 21.5% (b), 22% (c) and 22.5% (d) of paste.

As shown in Figure 5.15, for mixtures with 21% and 22% of paste the 7 days flexural strength reaches the highest values for 10% to 11% of fly ash and for the entire range of GGBFS. For mixtures with higher paste content (22.5% and 22.75%), the flexural strength reaches higher values for similar amount of fly ash and spans for broader (22% to 28%) range of GGBFS. In general, Figure 5.15 indicates that for ternary mixtures the highest flexural strength can be obtained for mixtures with 22.5% to 22.75% of paste, broad (22% to 28.5%) range of GGBFS and small (10% to 11%) amount of fly ash. Such results indicate that for ternary mixtures the most favorable additive (strength wise) is GGBFS. In addition, high strength is also promoted for mixtures with paste content from 22% to 22.75% and 10% to 11% of fly ash since it results in mixtures with very good workability. Finally, the influence of fly ash and GGBFS on properties of ternary mixtures supports trends discussed previously for binary systems. Figure 5.16 shows the results of 7 days predicted compressive strength for ternary mixtures.

The 7 days compressive strength data indicate the same trends as described for flexural strength. The highest value of early strength were observed in mixtures with 21 to 22% of paste, up to 12% of fly

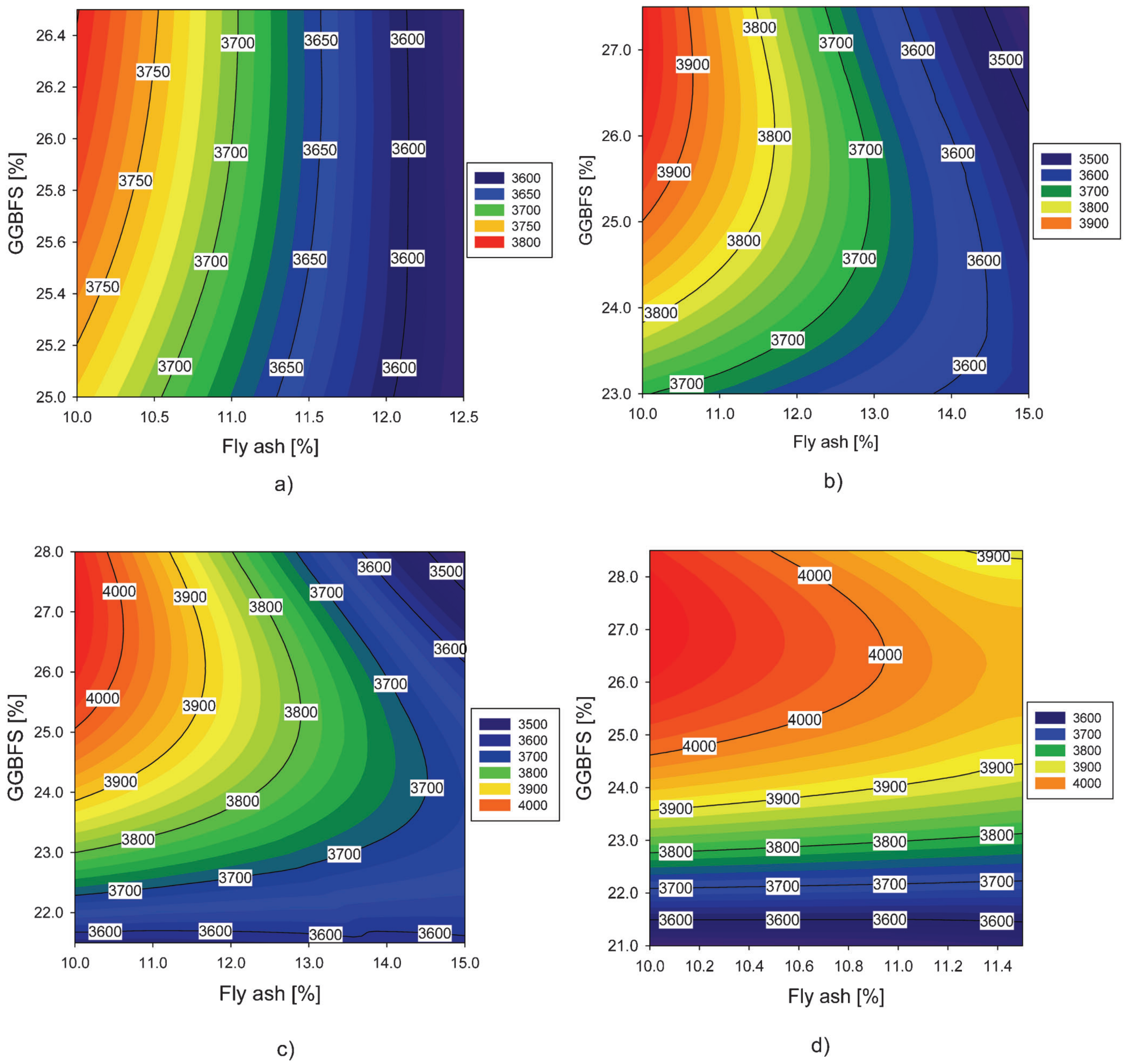


Figure 5.16 Predicted 7 days compressive strength for ternary mixtures with 21% (a), 21.5% (b), 22% (c) and 22.5% (d) of paste.

ash, and broader (23% to 28%) range of GGBFS. For mixtures with paste content higher than 22.5% the highest compressive strength was obtained for mixtures with 10% to 11.5% of fly ash and 23.5% to 28.5% of slag. The analysis of influence of fly ash and GGBFS on 7 days strength presented for binary systems support trend discussed for ternary mixtures. The highest compressive strength was developed for mixtures with low paste content and, respectively, low amount of fly ash and high amount of GGBFS. The opposite trends in strength, as those for early age strength can be found for 28 day compressive strength results, as shown in Figure 5.17.

As indicated in Figure 5.17, after 28 days of curing the highest compressive strength (regardless the amount of paste) can be developed in mixtures with 21% to 25% of GGBFS and 10% to 12.5% of fly ash (entire range of fly ash with non-zero overall desirability.) The change in observed trend (as compared to early age strength) is not clear, but it is probable that at ages longer than 28 days, fly ash contributes more to strength. On the other hand, higher reactivity of GGBFS helps to obtain higher strengths at earlier ages. It was also observed that for slag mixtures, the 28 days compressive strength reaches the highest values for specific amount of slag; this amount stays in the middle of the rage studied.

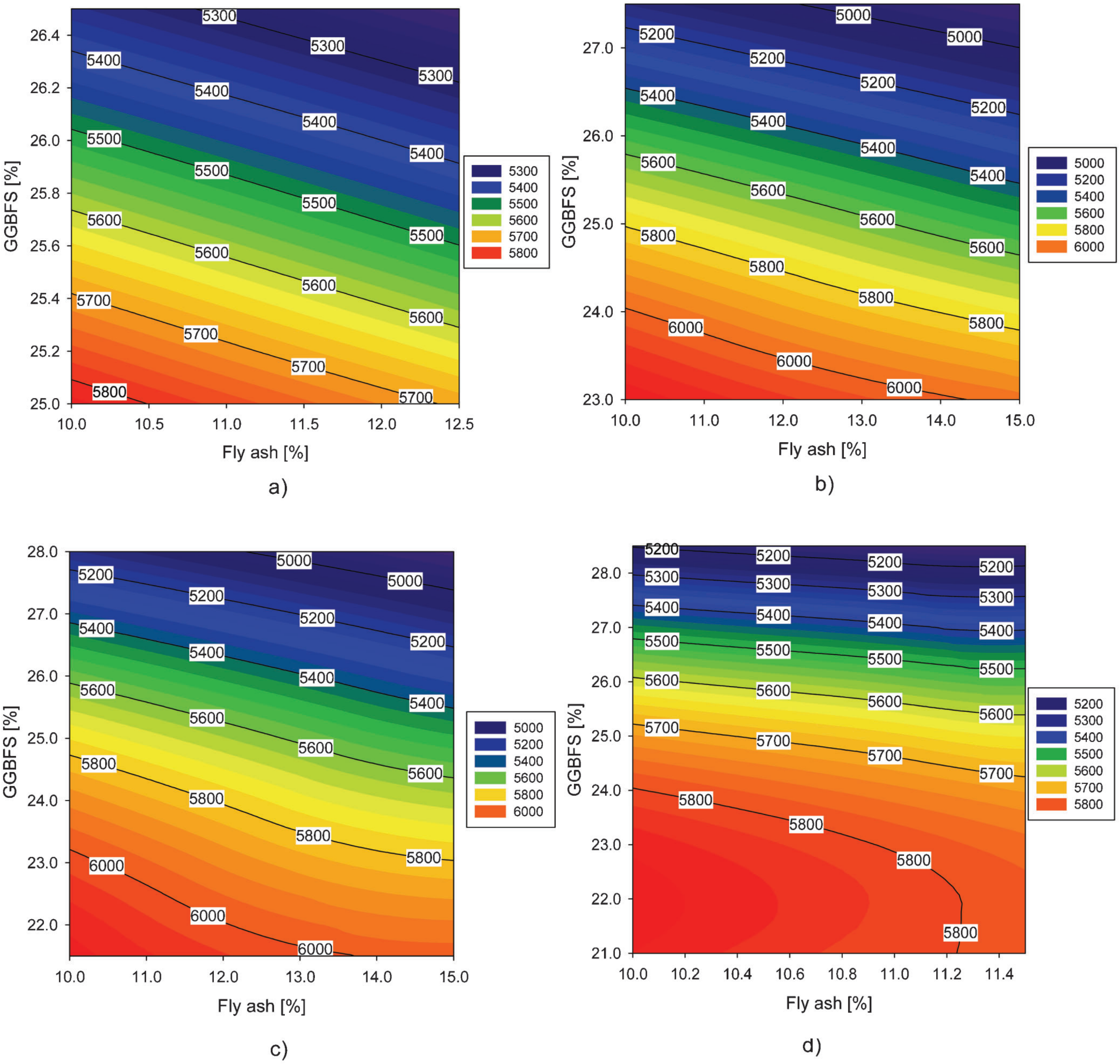


Figure 5.17 Predicted 28 days compressive strength for ternary mixtures with 21% (a), 21.5% (b), 22% (c) and 22.5% (d) of paste.

Finally, it can be seen that the highest 28 days compressive strength for ternary mixtures with non-zero overall desirability is independent of the paste content. The predicted results for scaling are presented in Figure 5.18.

Figure 5.18 indicates that for paste content up to 22% the highest scaling resistance can be obtained for mixtures containing low (10% to 12%) amount of fly ash and high (25% to 28%) amount of GGBFS. In addition, scaling resistance is significantly reduced for mixtures containing low amount of GGBFS and more than 12% of fly ash. The interesting fact is that concrete mixtures with satisfactory scaling resistance exist for proportions of GGBFS and fly ash changing diagonally from their lowest to highest allowed amounts. When paste content reaches 22.75% it can be seen that scaling resistance is independent of the amount of GGBFS. For these paste contents the satisfactory scaling resistance (less than 0.164 lb/ft^2) can be obtained for very narrow range of fly ash. As discussed in section pertaining to raw results of ternary mixtures, in case of ternary mixtures, the increase in paste content above 22.75% had very negative effect of scaling resistance. These mixtures showed similar workability and tendency for bleeding as binary fly ash

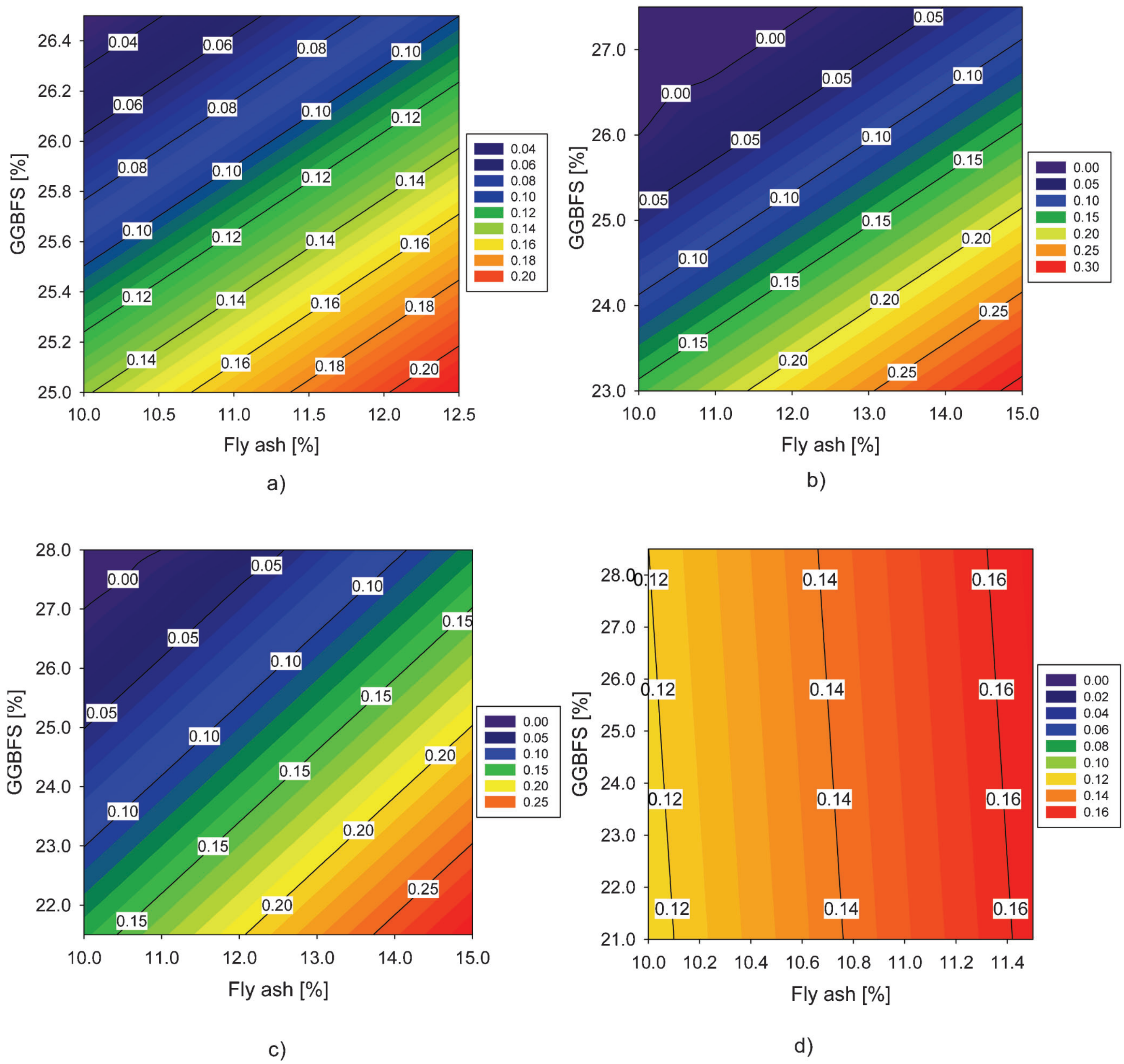


Figure 5.18 Predicted scaling for ternary mixtures with 21% (a), 21.5% (b), 22% (c) and 22.5% (d) of paste.

mixtures. The trend similar to that described for ternary mixtures with 22.75% was also found for water absorption. Figure 5.19 shows water absorption of ternary mixtures with non-zero overall desirability.

Figure 5.19 indicates that water absorption of ternary mixtures is independent of the amount of GGBFS and changes only slightly by incorporation of different amount of fly ash. In addition, except for mixtures with 21% of paste the water absorption increases with the increase in the amount of fly ash. In general, for ternary mixtures with paste content from 21% to 22.75% the results of predicted water absorption values are very comparable. Predicted results of free shrinkage for ternary mixtures are shown in Figure 5.20.

First, the results presented in Figure 5.20 indicate that the lowest values of shrinkage can be obtained for mixtures with 21% of paste (regardless the amount of GGBFS and fly ash). Next, the shrinkage can be reduced by using smaller amount of fly ash. This is especially true for 21%, 21.5% and partially for 22% of paste. For mixtures with 21% to 22% of paste, the shrinkage is almost independent of GGBFS content. When paste content is higher than 22%, most GGBFS and fly ash combinations that result in low shrinkage fall within the range from 27% to 28.5% of GGBFS

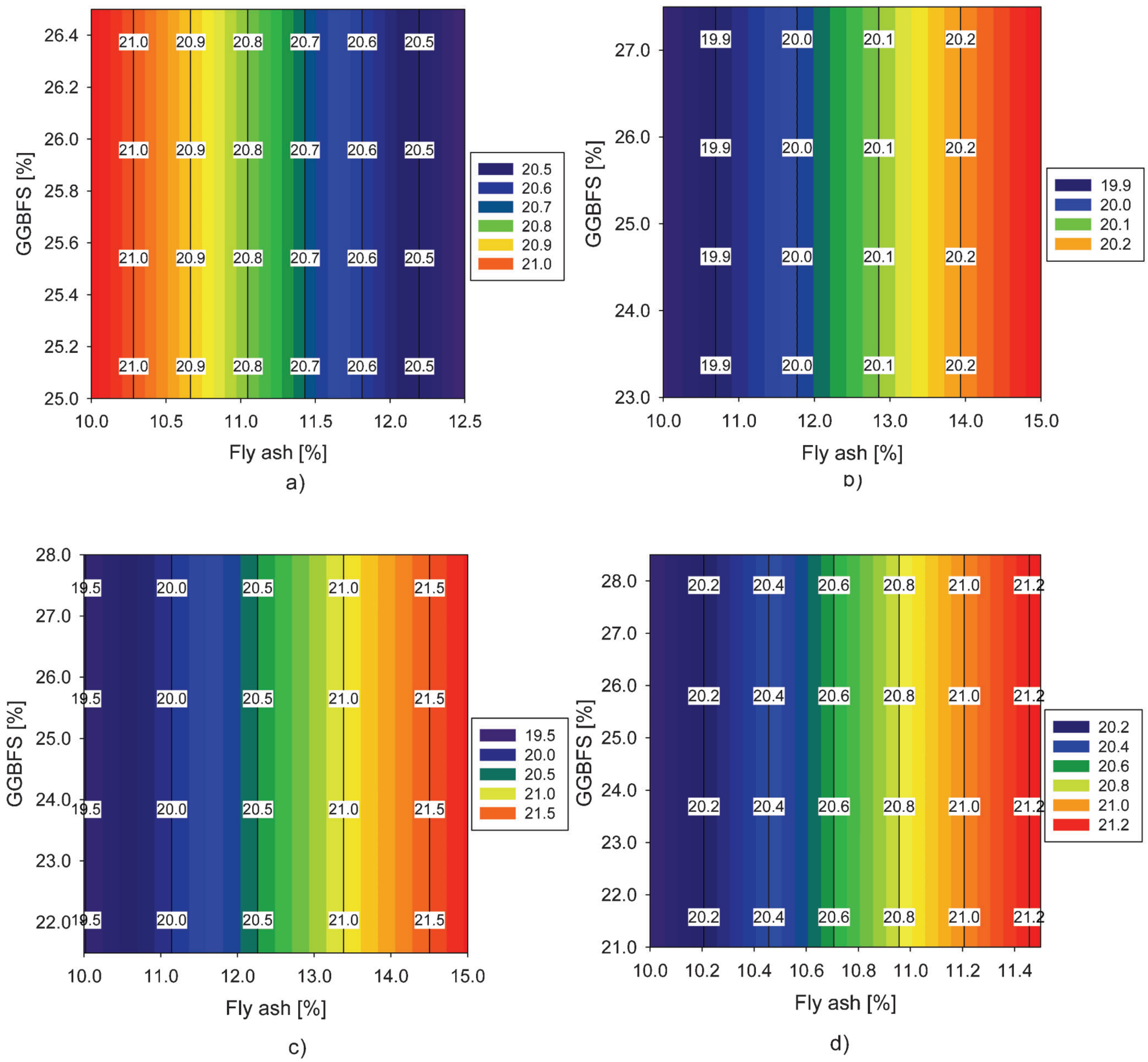


Figure 5.19 Predicted absorption for ternary mixtures with 21% (a), 21.5% (b), 22% (c) and 22.5% (d) of paste.

and from 10% to 11.5% of fly ash. The influence of GGBFS on free shrinkage observed for ternary mixtures matches that previously described for binary systems with slag. Figure 5.21 presents the predicted cost of ternary mixtures.

As seen in Figure 5.21, the cost drops about 1$ per cubic yard for each paste content toward mixtures with high amount of slag and fly ash, and low percent of paste content. Such mixtures include less Portland cement, which is the most expensive ingredient of concrete mixtures.

The predicted results for ternary binder combinations with 22.75% of paste are presented in Table 5.1.

Generally, the results of ternary binder combinations shown in Table 5.1 follow the trends discussed in details for mixtures with 22.5% of paste. However, the number of possible combinations is small and the amount of substituted cement is limited to maximum 33% of total binder. For this reason, the combinations presented in Table 5.1 are not the most desirable ones. In particular, the scaling and price values will reduce the possibilities of utilization of presented combinations in real application.

In summary, the analysis of predicted properties of ternary mixtures is more complicated than for any binary mixtures. It is difficult to point the best combination

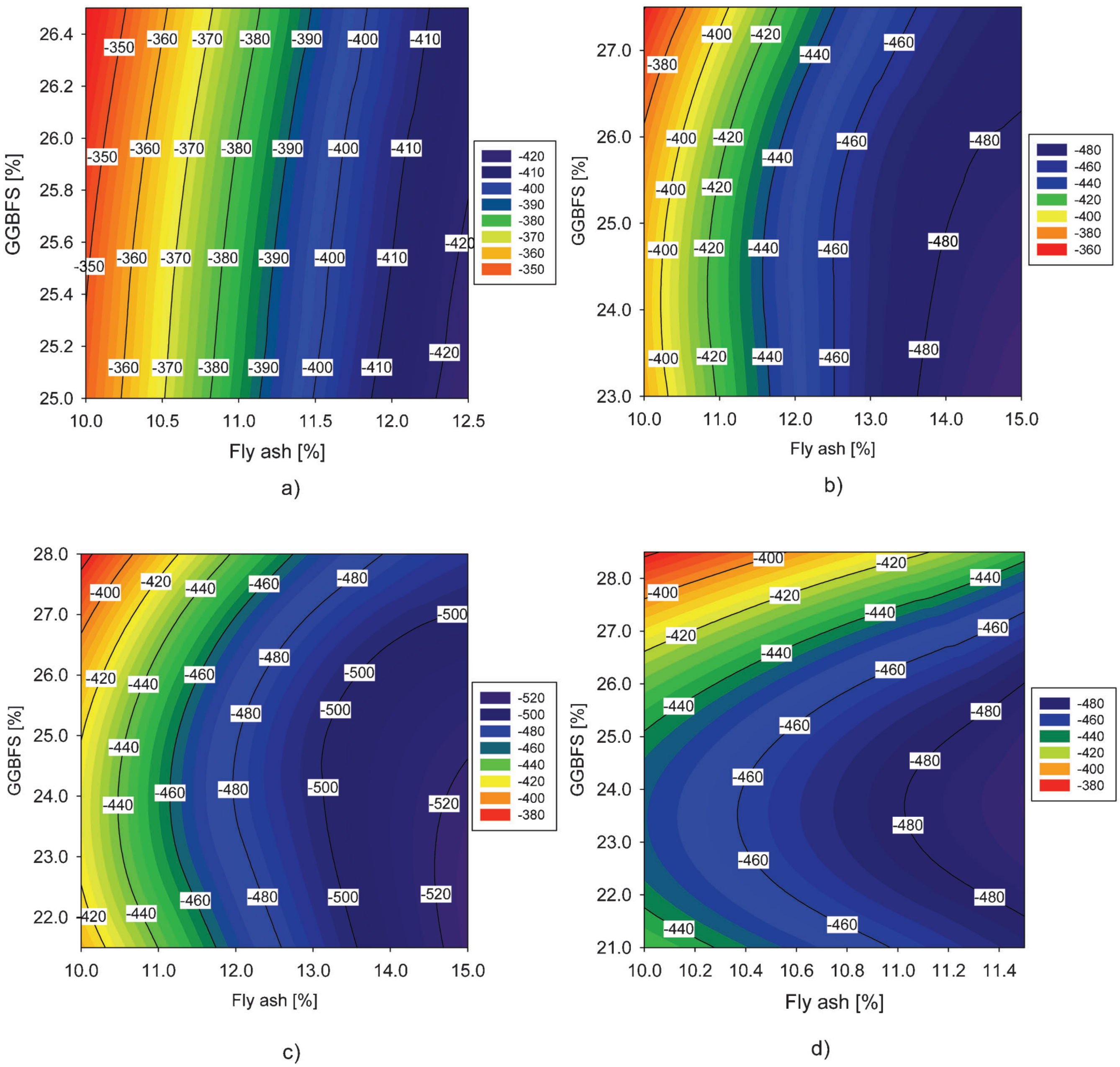


Figure 5.20 Predicted shrinkage for ternary mixtures with 21% (a), 21.5% (b), 22% (c) and 22.5% (d) of paste.

between all three variables which will produce the most desirable outcomes. However, based on presented results, it seems that in order to get the best performance, the selection of concrete mixture proportions for ternary binders should be based on predicted results for scaling and shrinkage for 22% of paste. In this way the amount of slag and fly can be balanced, and the critical values desired for concrete properties will be obtained.

5.3 Influence of k″ on Selected Properties of Phase II Mixtures

Utilization of "8-to-18" guidelines and Shlistone's Coarseness and Workability Chart did not always provide satisfactory trends in the data collected during Phase II of the study. From this reason, the authors of this publication decided to perform some additional analysis implementing the concept of air void free aggregate void saturation ratio (k″) and packing density. Based on previously provided definition, k″ can be directly linked to the amount of paste overfilling the voids in combined blend of aggregate. As commonly believed, the total amount of paste (as well as the excessive amount of paste) significantly affects both fresh and hardened concrete properties. Using equation 6, the values of air void free paste-aggregate void saturation ratio (k″) for Phase II concrete mixtures can be calculated. These values are shown in Table 5.2.

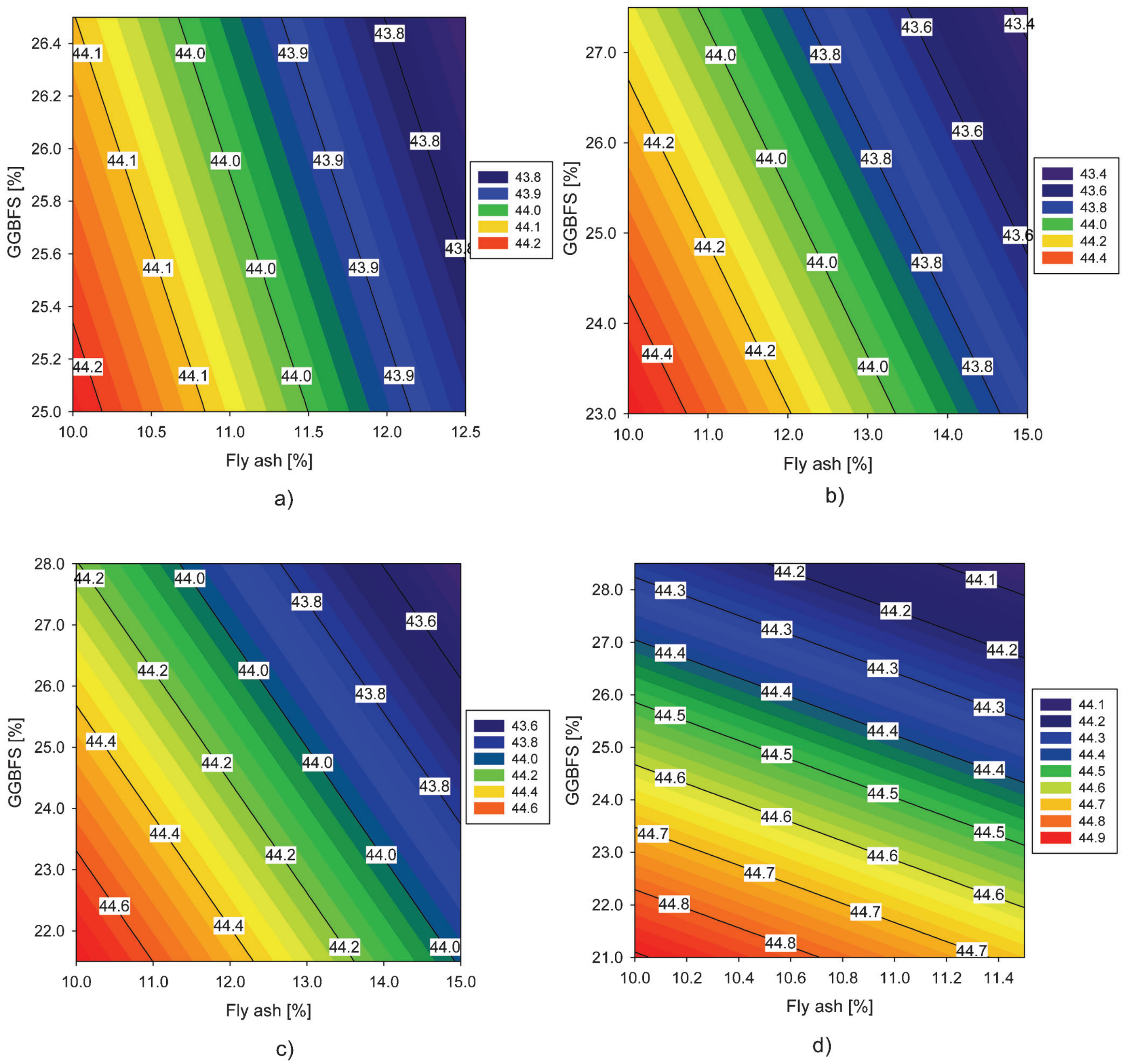


Figure 5.21 Predicted cost for ternary mixtures with 21% (a), 21.5% (b), 22% (c) and 22.5% (d) of paste.

Table 5.2 indicates that the k″ values adopted for Phase II are much lower than the reference value of 1.15 proposed by Jacobsen and Arntsen (*16*). However, their research was originally developed for very rich cement mixtures (containing from 811 to 1168 lb/yd^3 of cement), whereas mixtures presented in this study were much leaner and contained, respectively, 480, 481 and 505 lb of cementitious materials per cubic yard. Since the most significant differences in mixtures performance were observed for scaling resistance, water absorption and shrinkage, the influence of k″ on these properties will be discussed below.

Figure 5.22 presents the correlation between measured scaling resistance and k″ values calculated for all Phase II mixtures.

Figure 5.22 is divided into two plots: plot (a) showing the results for concrete mixtures containing only limestone as coarse aggregates (gradations No. 2, No. 5 and No. 6), and plot (b) showing the results for mixtures containing both limestone and dolomite as a coarse aggregate (gradations No. 1, No. 3 and No. 4). The reason for distinguishing between these two groups of mixtures was fact that limestone aggregate significantly contributed to the amount of scaled material due to failure of ½ and ¾ in. particles, and thus affected

TABLE 5.1
The results of ternary binder combinations with non-zero overall desirability for mixtures with 22.75% of paste

			Flexural strength [psi]	Compressive strength [psi]						
Fly ash	**GGBFS**	**Paste**	**7 day**	**7 day**	**28 day**	**Scaling [lb/ft^2]**	**Shrinkage [%]**	**Absorption 10^{-4} [mm/s$^{0.5}$]**	**Cost $[\$/\text{yd}^3]$**	**D (overall)**
10.0	21.5	22.75	748	3593	5734	0.136	−448	20.6	44.92	0.941
10.0	22.0	22.75	751	3678	5723	0.142	−452	20.6	44.88	0.942
10.0	22.5	22.75	754	3755	5764	0.149	−455	20.6	44.84	0.943
10.0	23.0	22.75	756	3823	5768	0.155	−456	20.6	44.80	0.944
10.0	23.5	22.75	758	3884	5763	0.162	−457	20.6	44.76	0.946
10.5	22.0	22.75	748	3673	5724	0.157	−468	21.1	44.81	0.944
10.5	22.5	22.75	751	3745	5736	0.164	−471	21.1	44.76	0.945

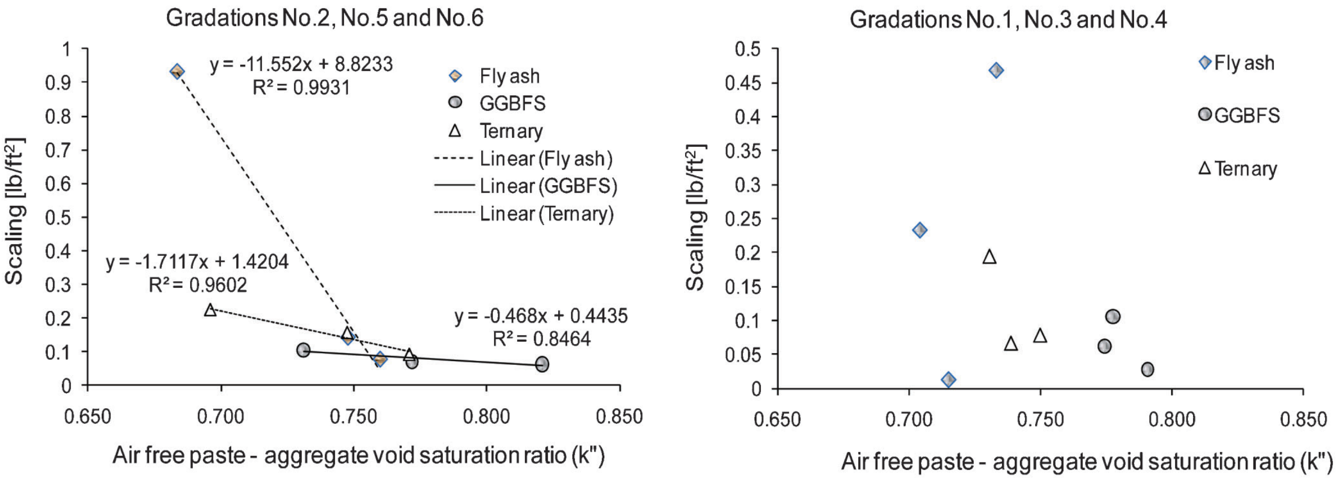
TABLE 5.2
Values of k′ calculated for Phase II concrete mixtures

	k″					
Type of binder	**Grad 1**	**Grad 2**	**Grad 3**	**Grad 4**	**Grad 5**	**Grad 6**
Fly ash	0.733	0.684	0.704	0.715	0.747	0.760
GGBFS	0.777	0.731	0.774	0.790	0.772	0.821
Ternary	0.750	0.696	0.731	0.739	0.747	0.771

the overall resistance to scaling. At the same time, the amount of scaled material for mixtures containing mainly dolomite as the coarse aggregate was only attributed to failure of hardened paste. The poor performance of limestone coarse aggregate (formation of pop-outs) was already discussed in Chapter 3 of this report. In this case, it can be seen in Figure 5.22 (a) that there is potentially a linear correlation between k″ and scaling. On the other hand, such correlation was not found for data shown in Figure 5.22 (b), mainly due to very narrow range of k″ values used (see Table 5.1). The observations shown in Figure 5.22 lead to general conclusion that the influence of k″ values on scaling needs to be further addressed using durable aggregate with broader ranges of k″.

Next, the relationship between the rate of water absorption (expressed as either sorptivity or absorptivity) and k″ values can be analyzed. Figure 5.23 shows the correlation between sorptivity and absorptivity and k″ values for gradations No. 2, No. 5 and No. 6.

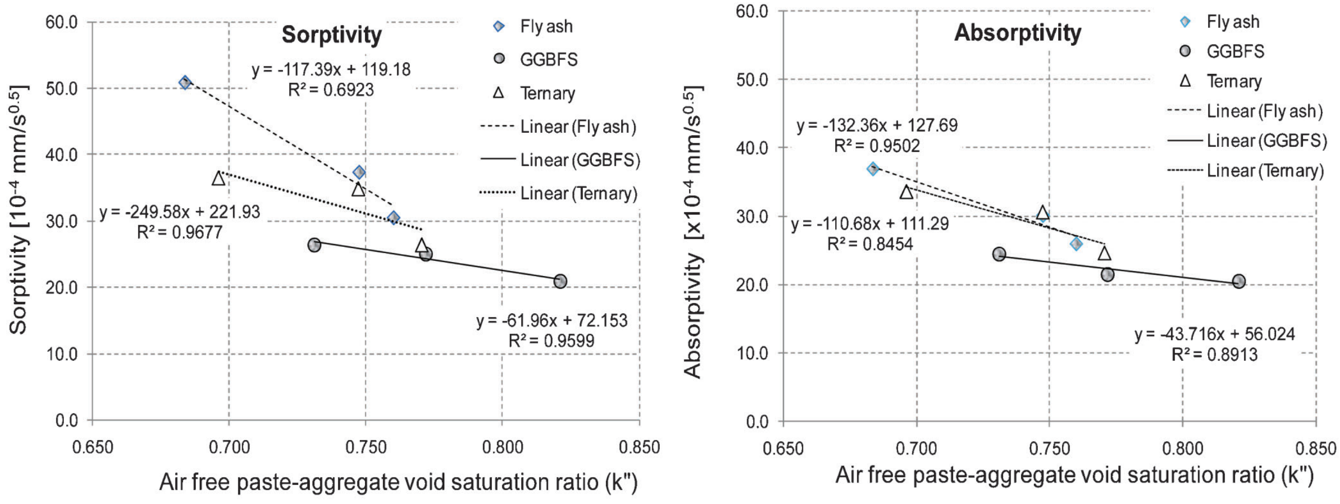
In general, both the sorptivity and absorptivity decreased with an increase of the k″ values. The potential reason for that behavior may be the fact that (due to poor consolidation) samples with low k″



a)

b)

Figure 5.22 Correlation between air-free paste-aggregate void saturation ratio (k″) and scaling for: (a) gradations No. 2, No. 5 and No. 6, and (b) gradations No. 1, No. 3 and No. 4.



a)

b)

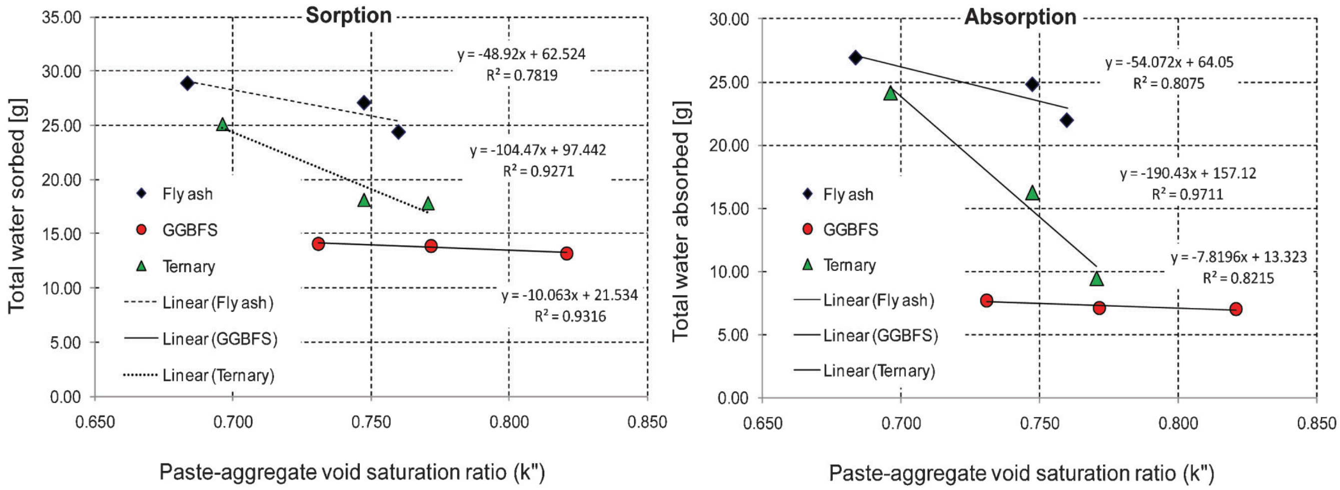
Figure 5.23 Correlation between (a) sorption and (b) absorption and k″ values for concrete mixtures with limestone coarse aggregate only.

contained higher amount of bigger pores which can be filled with water faster than the smaller pores. That assumption was further confirmed by establishing correlation between k″ values and total amount of water sorbed (absorbed) by the specimens. These correlations are shown Figure 5.24.

Analysis of Figure 5.24 reveals that mixtures with lower values of k″ indeed absorbed more water than mixtures with higher values of k″. This behavior may additionally explain why concrete mixtures with low k″ resulted in high scaling rate. However, these trends were true only for some gradations and more general validation of this theory should be performed.

Finally, the relationship between air-free paste-aggregate void saturation ratio k″ and free shrinkage measured for Phase II concrete mixtures is presented in Figure 5.25.

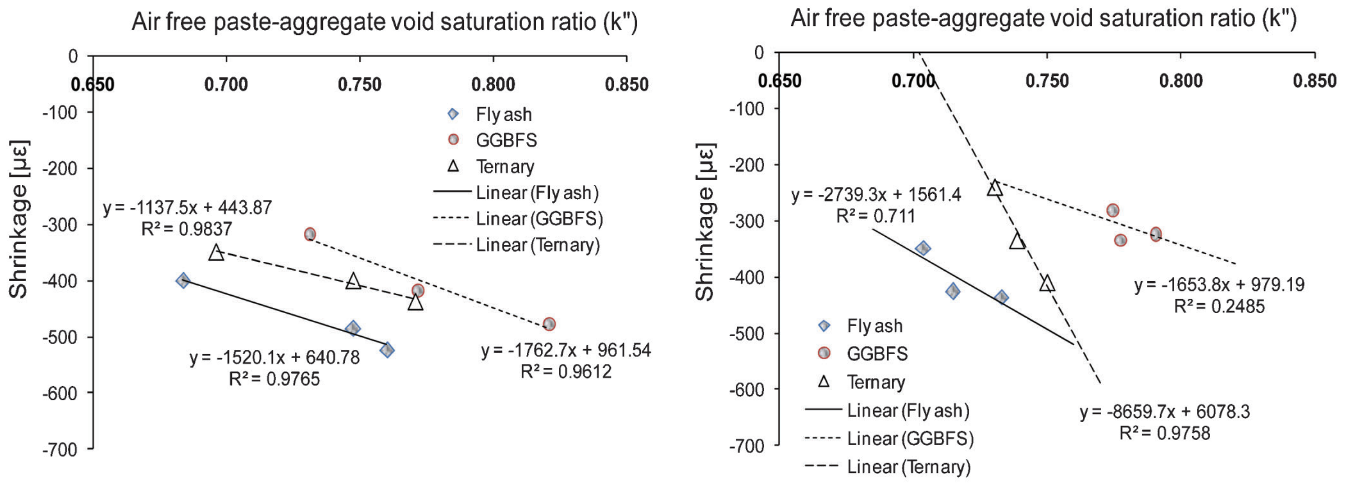
The correlation between k″ values and 448 day drying shrinkage for limestone only concrete mixtures was very good, irrespective of the binder system used (see Figure 5.25 (a)). Similar clear relationship can be observed in Figure 5.25 (b) for mixtures with gradations No. 3, No. 4 and No. 5, but only for fly ash and ternary binder systems. Based on these results, it may be concluded that reduction of k″ values helps in decreasing of free shrinkage, and is independent of the



a)

b)

Figure 5.24 Correlation between total mass of water (a) absorbed or (b) water sorbed water and k′ values for concrete mixtures with limestone coarse aggregate only.



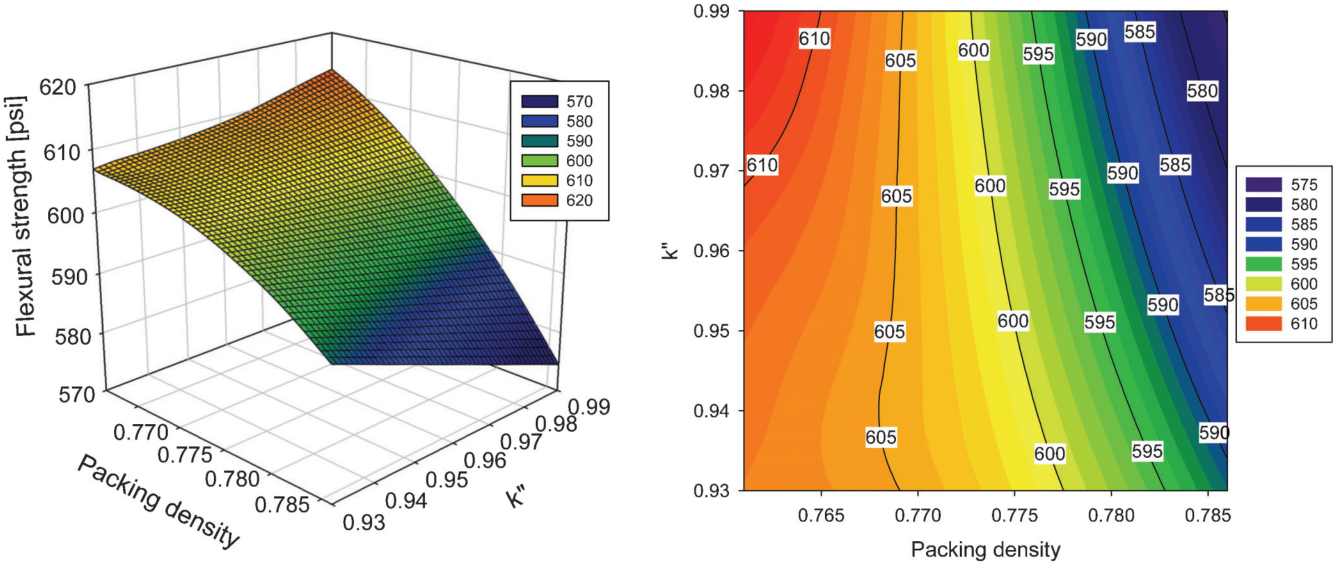
a) b)

Figure 5.25 Correlation between (k″) and free shrinkage for concrete mixtures with (a) gradations No. 2, No. 5 and No. 6, and (b) gradations No. 1, No. 3 and No. 4.

type of aggregate used. The reduction of k″ value, although desirable from shrinkage reduction perspective, creates overall problems with concrete workability and finishability. This eventually leads to durability problems (see previously discussed results of scaling and sorptivity). Such contradicting results regarding the influence of k″ on scaling (sorptivity) and shrinkage seem to indicate that is would be possible to establish "optimized" values of k″ with respect to these properties.

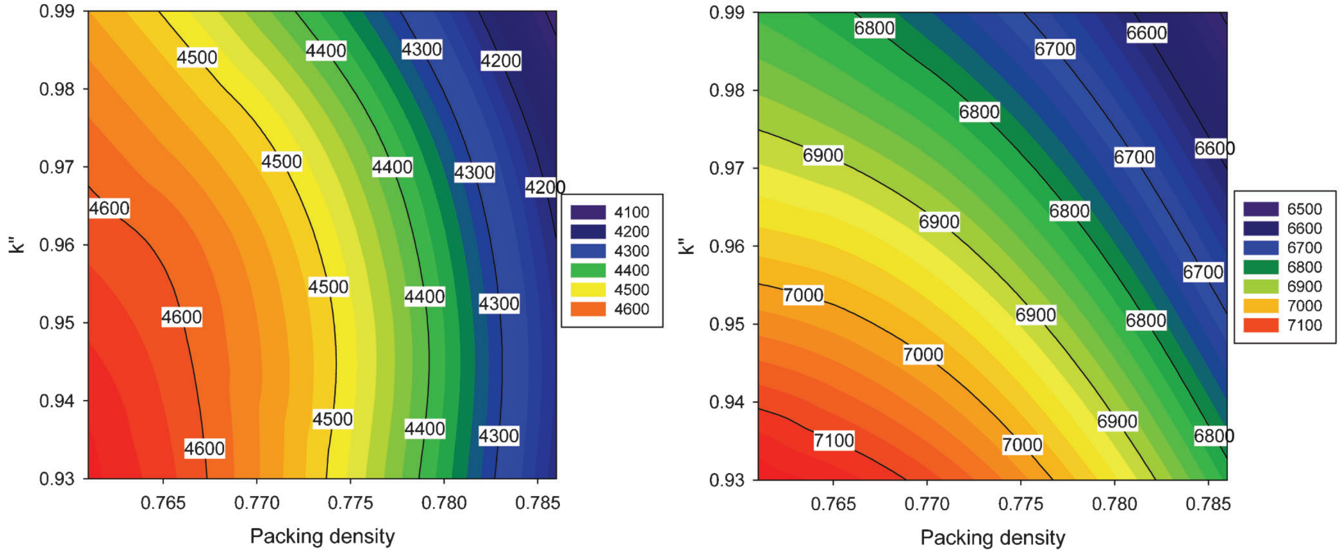
5.4. Optimization of Aggregate Packing Density (Φ) and Air Void Free Paste-Aggregate Void Saturation Ratio (k″)

The same type of analysis as that used for predicted results of optimization for binary and ternary mixtures studied in Phase I can be applied to optimization of aggregate packing density and aggregate void saturation ratio. Figures 5.26 through 5.30 present the predicted values for combinations of aggregate packing



a) b)

Figure 5.26 Predicted 7 day flexural strength for Phase III research variables: (a) 3D plot and (b) contour plot.



a)

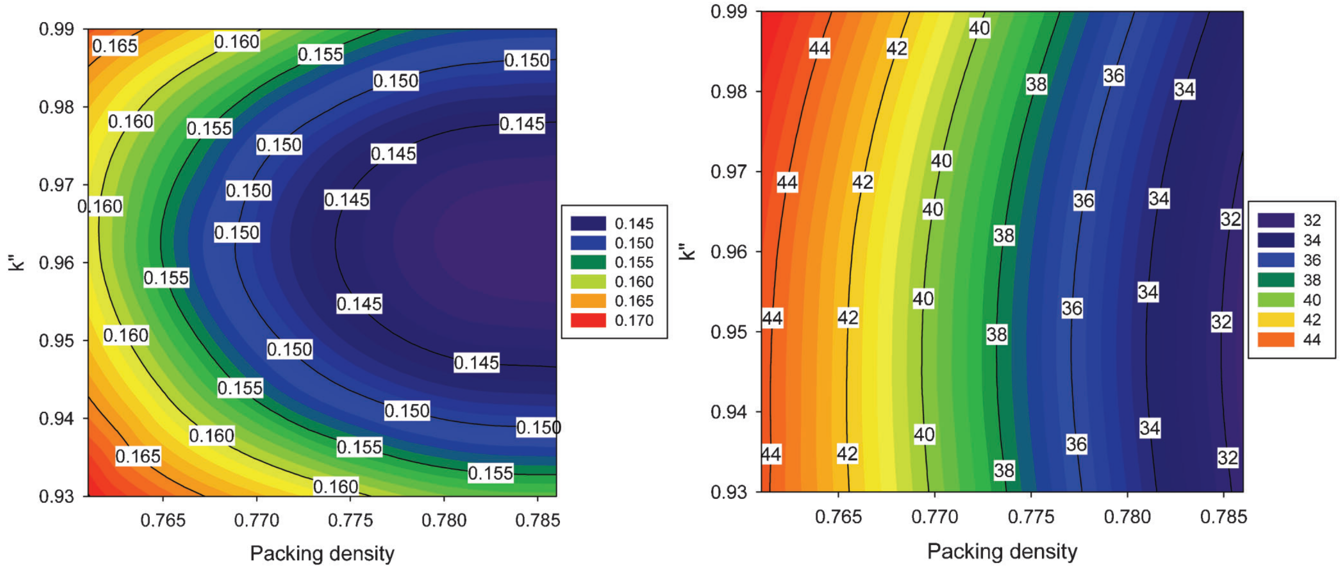
b)

Figure 5.27 Predicted compressive strength for Phase III research variables: (a) after 7 days and (b) after 28 days.

density and aggregates void saturation ratio with non-zero overall desirability for all concrete properties used in the optimization process.

As indicated in Figure 5.26, the highest predicted 7 days flexural strength exists for mixtures with aggregate packing density in the range from 0.760 to about 0.775 (what is in the upper-middle range studied) and k″ from 0.930 to 0.99 (what is in the middle of the range studied). Using equation 6, the range of paste content corresponding to all possible combinations between Φ and k″ described above can be calculated. The highest flexural strength values exist for paste content from 20.9% to 23.8%. This range is in good agreement with the results presented in Figure 5.3 for fly ash mixtures. Similar analysis can be performed for 7 and 28 days compressive strength results. Figure 5.27 shows the results of predicted compressive strength for Phase III mixtures.

After 7 days, the highest compressive strength results were obtained for the same range of research variables as described for flexural strength. On the other hand, after 28 days, the highest strength was associated with



a)

b)

Figure 5.28 Predicted amount of scaling (a) and rate of water absorption (b) for Phase III research variables.

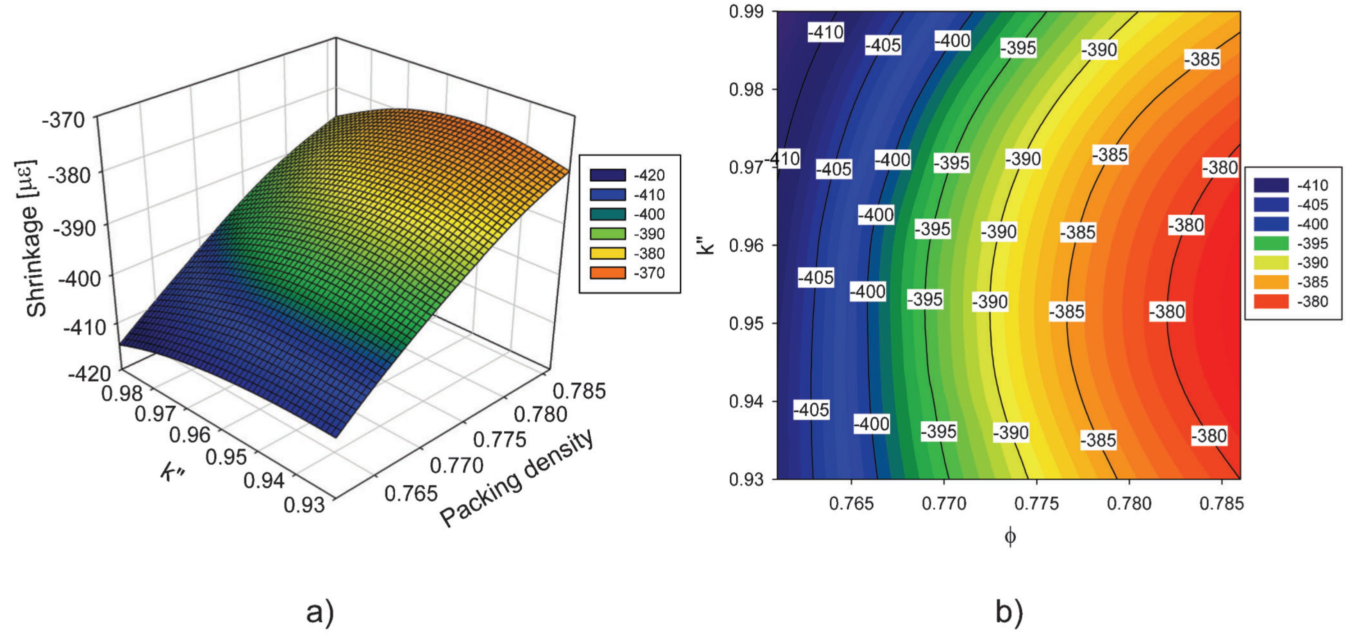


Figure 5.29 Predicted shrinkage for Phase III research variables: (a) 3D plot and (b) contour plot.

narrower range of k″ values (0.93 to 0.975) and broader range of Φ values (0.76 to 0.782). The amount of paste corresponding to that ranges changes from 20.3% to 23.2%. The amount of paste calculated for presented strength results stays in a good agreement with optimum paste content found for fly ash mixtures studied in Phase I (Figure 5.4).

Following the same analysis, the predicted results for scaling and water absorption for Phase III mixtures are presented in Figure 5.28.

As indicated above, both low amount of scaling and low water absorption can be obtained for mixtures with high packing density (0.780 and above.) At the same time, with respect to scaling the k″ values have to stay within the range from 0.95 to 0.97. This range of k″ corresponds to low amount of paste (from 20.3% to 21.3%). In the case of water absorption, the k″ can change within entire range of k″ (from 0.93 to 0.99). The results obtained for Phase III mixtures for scaling and water absorption support conclusions summarized

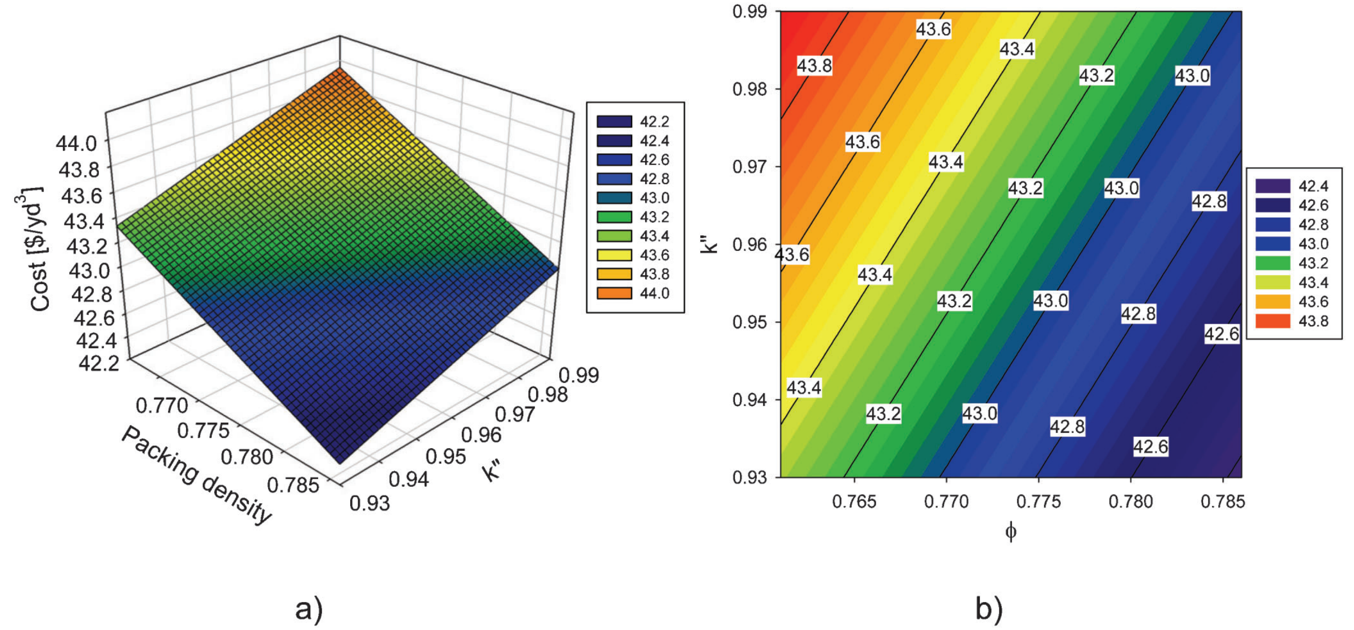


Figure 5.30 Predicted cost for Phase III mixtures: (a) 3D plot and (b) contour plot.

during optimization process for fly ash mixtures. The results of predicted shrinkage for Phase III research variables are shown in Figure 5.29.

In general, the predicted shrinkage for combinations of Phase III variables with non-zero overall desirability is far below the critical value of 550 $\mu\varepsilon$. The most preferable combination of Phase III variables, resulting in lowest shrinkage, exists for Φ in the range from 0.775 to 0.786 and the entire range of k'' (corresponding values to paste content from 19.9% to 21.8%). This range of paste content is in good agreement with the results described for fly ash mixtures. The predicted cost of PHASE III mixtures is provided in Figure 5.30.

The predicted results of cost for Phase III mixtures indicate that the lowest cost of concrete mixtures is associated with mixtures with high packing density and low amount of paste (also low k''). These results are in good agreement with predicted costs of fly ash mixtures.

5.5 Influence of Φ and k'' on Cracking Potential

As presented in Table 4.10, mixtures with low level of values of Φ and high values of k'' developed relatively high (over 500 $\mu\varepsilon$) shrinkage and were, therefore, selected for evaluation of the cracking potential. These mixtures included the following: 0.715_0.975, 0.726_0.900, 0.726_1.050, 0.751_1.081.

Immediately after the mixing cycle was completed, all concrete mixtures were tested for slump and air content. Following these tests, each concrete mixture was cast in the dual-ring mold as per AASHTO PP 34 specification (*52*). Two ring specimens per mixture were produced. The geometry of the restrained shrinkage specimen is presented in Figure 5.31.

The AASHTO PP 34 procedure allows for testing of concrete mixtures with maximum aggregate size (d_{max}) up to 1 in. (25 mm). The concrete specimen is placed between the interior steel ring and the exterior removable ring (mold). After the designated amount of time, the exterior mold is removed, thus initiating drying from the outside toward the interior steel ring. As the concrete dries, it shrinks and induces compressive deformations into the steel ring. These deformations are recorded (as strains) by strain gages mounted on the interior of the steel ring and can be converted to stress in concrete. Typically, the test continues until the first crack appears on the concrete wall (this event is also visible as a significant drop of the strain value) or until no further change in strain values is observed. In case of cracking potential measurements described in this chapter, the removed of outer ring mold was performed right after the final concrete setting time.

The results of restrained shrinkage test for concrete mixtures with different aggregate packing density (φ) and air void free paste-aggregate void saturation ratio (k'') are presented in Figure 5.32.

The first observation that can be made from Figure 5.32 is that the "age at cracking" depended on the k'' value rather than aggregate on packing density (φ). For two concrete mixtures with highest k'' ratio (Figure 5.32 (c) and (d)) both ring specimens cracked at about the same time. In addition, it can also be seen that for concrete mixture with k'' ratio lower than 1.0, only one of the ring specimens cracked (see Figure 5.32 (a) and (b), respectively). The average "age at cracking" for all mixtures is presented in Table 5.3.

The "age at cracking" can be related to the total amount of paste used to produce concrete mixtures subjected to restrained shrinkage test. The data of total paste content used for these mixtures are listed in Table 5.3. It can be clearly seen that mixtures 0.726_1.050 containing 28.8% of paste cracked earlier that mixture 0.751_1.081, which contained 26.8% of paste.

Finally, it is interesting to note that there seem to be only limited correlation between free shrinkage and the cracking potential data. Referring to Table 4.10, it can be observed that mixtures 0.715_0.975, 0.726_0.900 and 0.726_1.050 all had similar free shrinkage values. However, the cracking tendency for these mixtures

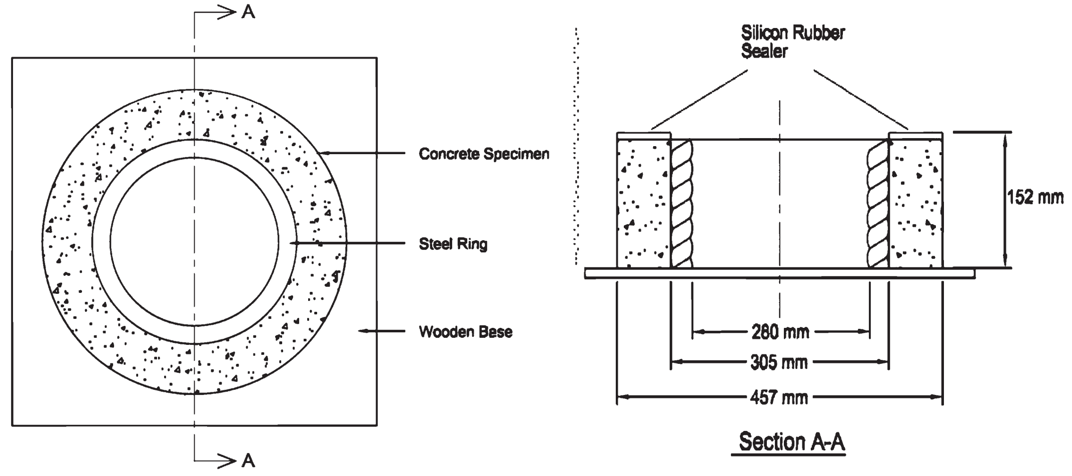


Figure 5.31 The restrained shrinkage test apparatus (*52*).

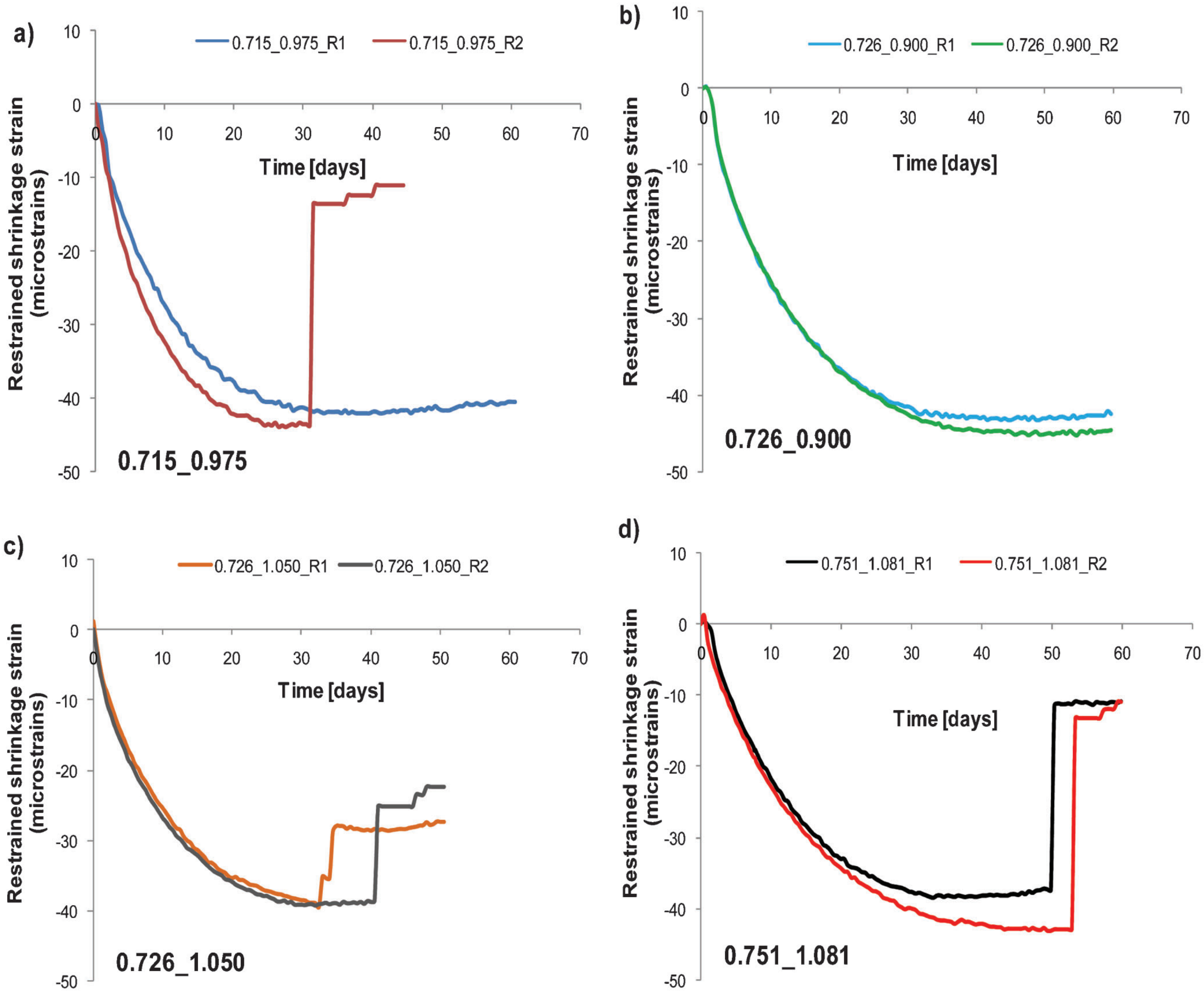


Figure 5.32 The results of restrained shrinkage test for concrete mixtures with different aggregate packing density (Φ) and void saturation ratio (k″).

was completely different. Mixtures 0.726_1.050 and 0.715_0.975 developed cracking, whereas mixture 0.726_0.900 did not crack at all. Based on these observations, it seems important to further evaluate the relationships between cracking potential and free shrinkage to better evaluate potential volumetric stability problems.

TABLE 5.3
Age of cracking for tested concrete mixtures

	0.715_0.975	0.726_0.900	0.726_1.050	0.751_1.081
Mix	Time to crack [days]			
Ring #1	n/a	n/a	31.5	48.7
Ring #2	30.0	n/a	39.5	51.8
Average	30.0	n/a	35.5	50.3

6. SUMMARY AND CONCLUSIONS

The research study presented in this document was divided into three main Phases. Each of these Phases explored different aspects of design of concrete for pavement applications. The summary of major findings for each of these Phases is provided is next three sections.

6.1 Summary of Major Findings from Phase I

6.1.1 Binary Systems with Fly Ash and GGBFS

- Fly ash concrete mixtures with paste content below 22% (about 480 lb/yd^3 of total cementitious materials) were difficult to produce and required extremely high dosage of water reducing admixture (from 100% to 200% over what was recommended by producer), thus they are not recommend for field applications.

- Slag mixtures with paste content below 23% (about 500 lb/yd^3 of total cementitious materials) were difficult to produce and required extremely high dosage of water reducing admixture (from 100% to 200% over what was recommended by producer), thus they are not recommend for field applications.
- For all fly ash and GGBFS concrete mixtures measured flexural strength satisfied INDOT's 7 days required 570 psi. After 56 days of curing most of fly ash and all GGBFS mixtures resulted in higher bending strength than reference (plain cement) mixture, showing benefit of utilization of supplementary cementitious materials.
- Compressive strength results showed relatively high variability for both fly ash and GGBFS mixtures (probably partially as a result of using sawed-off parts of beams as test specimens). The rate of strength gain between 7 and 90 days for all fly ash and GGBFS mixtures was higher than that for reference mixture.
- The non-linear relationship was found to exist between scaling resistance and paste content for both fly ash and GGBFS mixtures. Concrete mixtures with GGBFS showed better resistance to scaling than fly ash mixtures. The increase in fly ash content can impair scaling resistance more than increase in GGBFS content.
- Sorptivity and absorptivity data measured for both fly ash and GGBFS mixtures also followed non-linear trend similar to that observed for scaling results. Linear correlation between sorptivity (absorptivity) and scaling was established for fly ash and GGBFS systems.
- For fly ash mixtures, the highest desirability (0.973) value was located near one of the corners of the desirability surface and is defined by the combination of about 21.75% of paste and about 29.5% of fly ash, whereas for GGBFS mixtures the highest desirability (0.988) exists for combination of about 21% of paste and about 37% of slag.
- In order to assure proper workability and to avoid problems with consolidation of the mixtures the optimum proportions of fly ash, GGBFS and paste were adjusted as follows:
  - mixture with 22% of paste and 29% of fly ash (desirability level 0.970)-fly ash system,
  - mixture with 23% of paste and 37% of slag (desirability level 0.968)-slag system,
- Instead of selecting the single value corresponding to optimum combination of variables studied, it is proposed to use a concept of the "desirability windows" which represents broader, but still nearly optimal combinations of paste content and supplementary cementitious material.
- For mixtures with fly ash as supplementary cementitious material the desirability window has following coordinates: paste content from 22% to 22.75% and fly ash content from 16% to 27%.
- For mixtures with GGBFS as supplementary cementitious material the desirability window has following coordinates: paste content from 23% to 23.75% and slag content from 27% to 36%.

6.1.2 Ternary binder systems

- Ternary concrete mixtures showed the same trends with respect to workability and requirements for dosage of water reducing admixture as those with fly ash. However, addition of GGBFS into ternary systems with 24% and higher paste contents improved their resistance to "bleeding "and increased their cohesiveness.
- Flexural strength measured for all ternary mixtures satisfied INDOT's 7 days minimum requirement of 570 psi. Similar to what was observed for fly ash and GGBFS mixtures, significant increase between 7 to 56 days flexural strength was also noted in ternary systems.
- 7 days compressive strength values for ternary mixtures were low (sometimes below 3000 psi). However, starting from 28 days, constant increase in strength was observed for all ternary mixtures. These observations were in agreement with previously reported data for ternary concrete mixtures with fly ash and GGBFS.
- The scaling resistance of ternary mixtures was somewhat low. Only mixtures with 21% and some mixtures with 22% of paste resulted in amount of scaled material lower than maximum allowable 0.164 lb/ft^2. Similarly, to binary mixtures with fly ash and GGBFS, the overall scaling showed non-linear increase in mass scaled with the increase in the amount of supplementary cementitious materials (SCMs) and paste volume.
- Sorptivity and absorptivity data measured for ternary mixtures followed the same (non-linear) trend as scaling results. Linear correlation between sorptivity (absorptivity) and scaling was established for these mixtures.
- The most desirable combination of variables studied was one containing 15% of fly ash, 26% of GGBFS and 21.5% of paste (desirability value of 0.975).
- For mixtures with ternary binders (cement + fly ash + GGBFS), it was not easy to establish "desirability window". For practical reasons, it is suggested to select a range of paste content that assures adequate workability and adjust fly ash and GGBFS contents in order to find the most desirable proportions with respect to strength, durability and shrinkage.
- The broadest area of high desirability (the most desire mixtures) exists for various combinations of fly ash and GGBFS at paste content of 22%, For this reason, it is proposed to design ternary mixtures around this paste value.
- For ternary mixtures with 22% of paste, the most desirable combinations included 15% of fly ash and up to 27% of GGBFS.

6.2 Summary of Major Findings from Phase II

The major findings from Phase II can be summarized in the following way:

- Aggregate gradations significantly affect concrete finishability, placement and consolidation abilities. The increase in maximum nominal aggregate size improves workability (gradation No. 4), whereas combination of high sand content and intermediate aggregate size makes concrete mixtures dry and difficult to work with (gradation No. 1).
- The most desired gradation should have about 36 to 43% of sand, about 40% cumulative retaining on ⅜ in. sieve (based on results obtained from gradation No. 4 and No. 5).
- Shilstone's gradation chart was found to be useful in identifying some of the problematic combined gradation; however it must be always supported by "8-to-18" and 0.45 power plots. The most desired gradation had

coarseness factor (CF) and workability factor (WF) equal 67 and 40, respectively, which is different from Shilstone recommendations (*11*).
- The durability related properties (i.e., scaling, shrinkage and sorptivity) can be related to the amount of voids between aggregate particles (packing density) and paste content used to produce concrete mixture.

6.3 Summary of Major Findings from Phase III

The final part of the research involved investigation of the effect of aggregate packing density and air void free paste-aggregates void saturation ratio (k″) on concrete performance and optimization of concrete mixtures with respect to these two parameters. The major outcomes of this part of the study can be summarized as follows:

- Both packing density (Φ) and k″ ratio affected concrete properties. However, in case of mechanical properties, the influence of k″ is more important. On the other hand, durability related properties are more dependent on packing density.
- Numerical optimization revealed that the most desirable concrete mixtures were produced with k″ value in the range from 0.925 to 1.000 and packing density in the range from 0.755 to 0.786.
- Due to potential workability problems, the most desired combination of k″ and packing density values should be probably selected to be, respectively, about 0.975 and 0.776.

Lastly, it was observed that concrete mixtures with (k″) ratio higher than 1.0 cracked after 45.8 and 52.2 days after initiation of drying.

7. RECOMMENDATIONS AND GUIDELINES FOR PAVING MIXTURES

7.1 Recommended Paste Content

Since the paste content of the mixture was one of the research variables studied in Phase I and in Phase III, it will be useful to compare statistically optimized contents of pastes resulting from both Phases. Such comparison is presented in Figure 7.1.

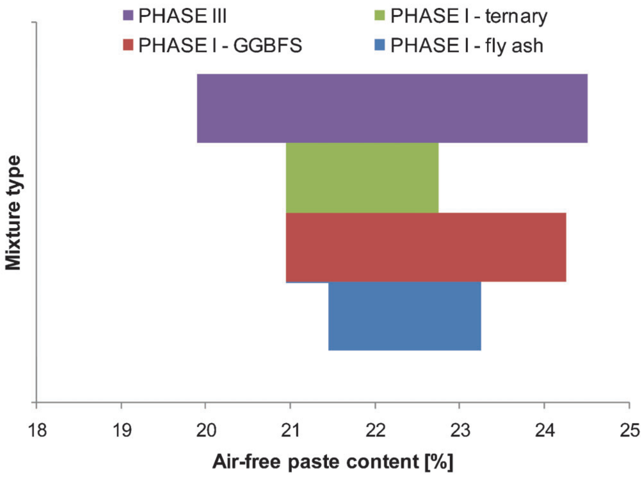


Figure 7.1 Summary of optimum air-free paste content for different mixtures from Phase I and Phase III.

The results of optimum paste contents indicate that by selecting well graded aggregates (with packing densities from 0.755 to 0.786 and k″ values from 0.925 to 1.000) the desired paste content for paving mixtures can range from 19.8% to 24.5%. This range of paste contents is wider than any other obtained from Phase I, thus indicating the importance of selection of proper aggregate gradation. Further, this graph also indicates that the most desirable paste content for fly ash mixtures (found as the result of Phase I study) is located in the middle of paste content range defined as the optimum by combined values of Φ and k″ in Phase III. Based on this observation, it is believed that paste content in the range from 21.5% to 23.25% represents the combined optimum paste content for fly ash and GGBFS (binary) paving mixtures when well graded aggregates are utilized. In case of ternary mixtures, this range must be shrunk slightly from 21.5% to 22.75% (as the result of statistical optimization discussed in section 2.6).

Paste content in the range from 21.5% and 23.25% corresponds to the total cementitious materials content from about 469 to 507 lb/yd^3 (for binary mixtures), whereas paste content from 21.5% to 22.75% corresponds to the amount of total cementitious materials from 469 to 495 lb/yd^3 (for ternary mixtures). For each of these ranges the maximum (based on statistical optimization) amount of supplementary materials incorporated will result in minimum cement content required to produce satisfactory paving mixture. The minimum calculated amount of cement required to produce satisfactory binary paving mixtures with optimum combined paste content from 21.5% to 23.25% is provided in Figure 7.2.

The data presented in Figure 7.2 indicate that the minimum amount of cement needed to obtain satisfactory paving mixtures can be as low as 295 lb/yd^3 for GGBFS mixtures and 347 lb/yd^3 for fly ash mixtures. The amount of cement in satisfactory binary mixtures indicated by this analysis is much lower than that required by current INDOT specification (*5*).

Similar analysis of minimum cement content for satisfactory ternary mixtures for selected range of combined optimum paste contents can be found in Figure 7.3. In case of ternary systems, the analysis is more complicated due to introduction of third variable. However it can be seen that for concrete mixtures studied in Phase I the amount of cement can be even lower than that indicated for binary systems. The values of minimum cement for ternary mixtures vary in the range from 280 to 337 lb/yd^3, depending on the amount of SCM's utilized.

Although the analysis presented in Figures 7.2 and 7.3 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

Supplementary cementitious materials		21.5% of paste	23.25% of paste
Fly ash	GGBFS	Min. cement	Min. cement
21.0% min.*			398
24.5% max.**			383
18.0% min.*		385	
28.5% max.**		347	
	25.5% min.*	349	
	37.0% max.**	295	
	24.0% min.*		385
	37.0% max.**		319

*Minimum allowed value of SCM for selected paste content based on optimization results in Chapter 3.
**Maximum allowed value of SCM for selected paste content based on optimization results in Chapter 3.

Figure 7.2 The minimum amount of cement required to produce satisfactory binary paving mixtures for selected range of combined optimum paste contents.

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.

7.2 Final Conclusions and Recommendations for Paving Mixtures

The ultimate goals of this study were to investigate the optimal ranges for paste content, amount of cementitious materials and aggregate gradation for concrete paving mixtures. In general, the optimum concrete mixtures developed in this study contained low paste content (below 23%), and were characterized by low scaling and sorptivity. In addition to that, it was possible to maintain high cement replacement level for these mixtures. Lastly, concrete mixtures developed with optimum ranges of variables studied in this research contained low cement content. That reduction in cement content made these mixtures more economical with respect to traditional concrete paving mixtures produced using on typical ranges of cement and supplementary cementitious materials contents discussed in Chapter 2 and at the beginning of Chapter 3.

As the final outcome from this study, the following modifications to the existing specifications for concrete paving mixtures used in Indiana are proposed:

Supplementary cementitious materials		21.50% of paste	21.75% of paste	22.00% of paste	22.25% of paste	22.5% of paste	22.75% of paste
Fly ash	GGBFS	Min. cement	Min. cement	Min. cement	Min. cement	Min. cement	Min. cement
14.0%	26.0% max.**	281					
10.0% min.*	24% min.*	310					
10.0% min.*	27.0% max.**	295					
15.0%	26.0% max.**		280				
10.0% min.*	23% min.*		318				
10.0% min.*	27.5% max.**		296				
15.0%	26.0% max.**			306			
10.0% min.*	22% min.*			325			
10.0% min.*	27.5% max.**			299			
15.0%	26.0% max.**				286		
10.0% min.*	21.5% min.*				332		
10.0% min.*	28.0% max.**				300		
14.0%	27.0% max.**					289	
11.0% min.*	21.0% min.*					333	
11.0% min.*	28.0% max.**					299	
12.0%	24.5% max.**						314
11.0% min.*	21.0% min.*						337
11.0% min.*	28.5% max.**						302

*Minimum allowed value of SCM for selected paste content based on optimization results in Chapter 3.
**Maximum allowed value of SCM for selected paste content based on optimization results in Chapter 3.

Figure 7.3 The minimum amount of cement required to produce satisfactory ternary paving mixtures for selected range of combined optimum paste contents.

- Allow the utilization of ternary concrete mixtures (incorporation PC + GGBFS + fly ash) for pavement construction.
- Figures 7.1 and 7.2 can be used by mixture designer as a guide to select the initial mixture proportions for both binary and ternary systems. In each case, the contractor should be required to successfully demonstrate that durable mixture of adequate strength can be produced.
- Design the concrete mixtures with 22% to 23.5% of paste using aggregate gradation with packing density between 0.755 and 0.786.
- Utilize up to three (one fine and maximum two coarse) aggregates to establish well-graded combined gradation characterized by CF of 60 ± 5 and WF of 36 to 40.
- Produce combined aggregate blends with fine aggregate content from 35% to 42% (by mass) of total aggregate.
- Allow utilization of aggregate gradations with maximum nominal aggregate size of 1 in.

7.3 Benefits of the Study

The benefits of this research include

- 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 can be used directly by mix designers to reduce the amount of cement, thus making the mixtures more economical.
- Confirmation of technical feasibility of using ternary mixtures in the construction of concrete pavements.

8. FUTURE RESEARCH STUDIES

The research study presented in this document covered broad range of variables associated with paving mixtures (i.e., content of supplementary cementitious materials, amount of paste), discussed the effect of different aggregate gradations on performance of concrete, and linked paste requirements with packing density of aggregate.

All results obtained during this study were based on mixtures produced in the laboratory and thus did not include the variables associated with field productions. In order to verify the results of concrete optimization described in this document, a group of concrete mixtures should be designed based on combined recommendations from Phase I and Phase III and produced in the field in order to address issues of different mixing, placement and curing conditions typically encountered in the field.

Although ternary concrete mixtures with GGBFS and fly ash satisfied strength, shrinkage and sorptivity requirements defined for this research study, they showed poor resistance to scaling. Before this type of mixtures will be allowed for paving construction, some additional research must be performed to identify causes of such reduced scaling performance.

Finally, the results of Phase I and Phase III showed that concrete mixtures with paste content below 21% resulted in good hardened properties. However, despite very high dosage of water reducing admixture used they still exhibited difficulties with respect to workability which can potentially limit limits their application in the field. It would be of interest to explore if the use of high-range water reducer may help to improve workability of mixtures with paste content below 21%, increase their thixotropy, and enhance cement hydration rate. If successful, use of superplasticizers will allow for further reduction in the amount of cement in the paving mixtures.

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