MoDOT

Research, Development and Technology

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Laboratory Study-

Laboratory Testing of Bridge Deck Mixes

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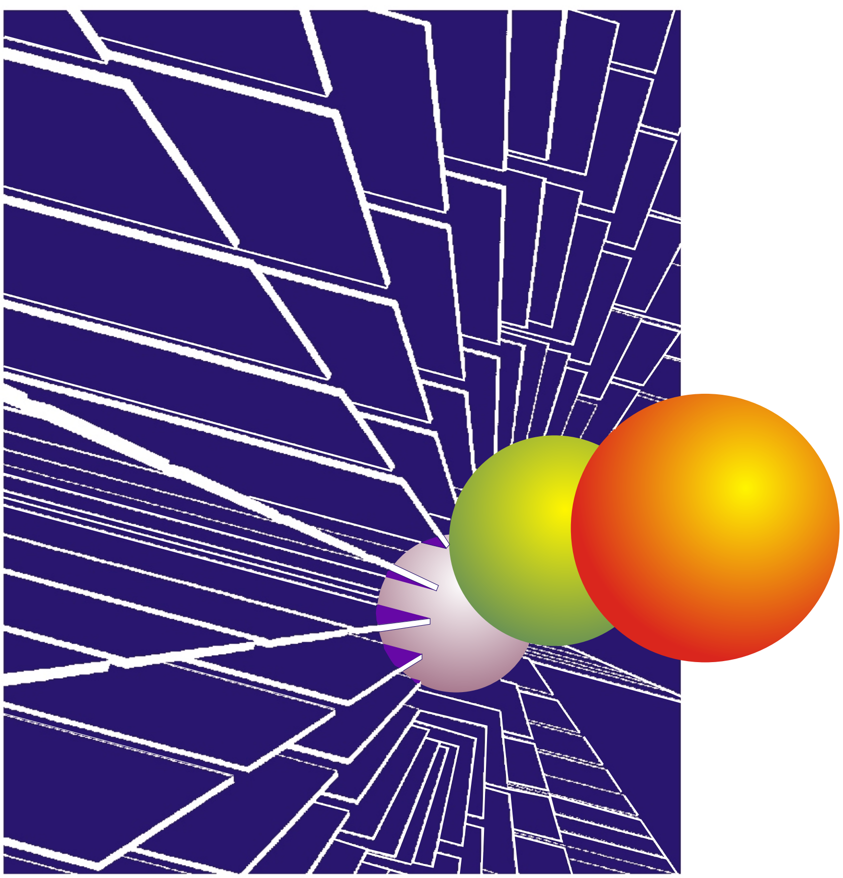

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The investigation was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract
The purpose of this investigation was to develop bridge deck mixes that will improve field performance and minimize cracking potential compared to MoDOT's current (B-2) bridge deck mix design. The mix designs developed in this study were tested and compared to the control B-2 mixes for strength, durability, permeability, and shrinkage potential.

This paper presents laboratory test results from nine different concrete mix designs that will be considered by MoDOT's bridge deck quick action (QA) team to replace the current bridge deck mixes. The mixes differed mainly by the amounts and combinations of supplementary cementitious materials, which included Class C flyash, ground granulated blast furnace slag (GGBFS), silica fume, and ternary combinations of these materials. The research conducted should give MoDOT a bridge deck mix that is more economical, increases the service life, and reduces the maintenance costs of bridge decks in the future.

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LABORATORY STUDY
LABORATORY TESTING OF BRIDGE DECK MIXES

PREPARED BY
MISSOURI DEPARTMENT OF TRANSPORTATION
RESEARCH, DEVELOPMENT, AND TECHNOLOGY

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> Roland Hoover and Bill Buschman, fabricated and tested mortar bars for ASTM C596 and ASTM C151.

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Executive Summary

This study was conducted to develop a new bridge deck mix design that has superior strength, durability, permeability, and shrinkage characteristics. The mix designs developed in this study will improve field performance and minimize cracking potential compared to MoDOT's current (B-2) bridge deck mix design.

This paper presents laboratory-testing results on nine different PCC bridge deck mix designs. Each test mix differed by the type and/or the amount of supplementary cementitious material that replaced Type 1 Portland cement. The supplementary cementitious materials used in this study included Class C flyash, ground granulated blast furnace slag (GGBFS), silica fume, and ternary combinations of these materials. Concrete characteristics from each mix design were evaluated and compared to each other and to MoDOT's B-2 mixes. The main findings and recommendations are summarized as follows:

- All mixes tested in this study achieved acceptable compressive strength and excellent freeze/thaw durability factors.

- Reducing Portland cement content from 7.74 sk/yd^3 to 6.40 sk/yd^3 lowered the ultimate compressive strength by approximately 800 psi., but is well above the design compressive strength requirement for bridge decks.

- Replacing Portland cement with a supplementary cementitious material in the 6.40 sk/yd^3 mixes yielded compressive strengths equivalent to or greater than the control mixes.

- Mixes containing 25% and 50% GGBFS yielded lower early strengths and lower early modulus of elasticity compared to other mixes. Concrete with lower early strength and lower early concrete modulus have less thermal and shrinkage stresses that cause early bridge deck cracking.

- Decreasing total cementitious content and the use of supplementary cementitious materials slightly decreased the salt scale resistance of concrete. However, these results and the results from all mixes tested were found acceptable for bridge deck applications in Missouri.

- The use of flyash, GGBFS, and/or silica fume significantly decreased concrete's permeability. Concrete mixes without a pozzolan or cementitious admixture yielded moderate permeability, which is too high to be acceptable for bridge deck applications in Missouri.

- A laboratory test to compare the shrinkage characteristics between different mix designs was developed, but no conclusions could be made from the test results.

Based on the laboratory results from this study, Research, Development, and Technology makes the following recommendations:

- The minimum total cementitious material in bridge deck mixes should be reduced from 7.50 sk/yd^3 to 6.40 sk/yd^3 to reduce the drying shrinkage potential and thermal stresses that induce cracking in bridge decks.

- The addition of a Type A water reducer should be used in bridge deck mixes to ensure strength, permeability, and workability requirements.

- At least one of the following supplementary cementitious materials should be incorporated into bridge deck mixes at the recommended replacement limits.

Supplementary Cementitious Material	**Maximum Limits**
Max. Flyash Replacement	25 %
Max. GGBFS Replacement	40 %
Max. Total Portland Cement Replacement with Supplementary Cementitious Materials	40 %

- A ternary mix containing Type 1 Portland cement, 15% flyash, and 25% GGBFS (Mix 9 in Table 14) should be encouraged and used whenever possible because of its superior concrete properties, lower cost, and its desired compatibility compared to mixes containing Type 1 Portland and Class C flyash.

- Silica fume is not recommended based upon cost, workability issues, and its plastic shrinkage cracking potential.

- Field documentation and verification should be conducted to verify the performance of the bridge deck mix designs proposed in this study.

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Introduction

Early crack development has been noted in many of MoDOT's bridge decks. These cracks accelerate corrosion of reinforcing steel and lead to concrete deterioration that shorten the service lives and increases the maintenance costs of bridge decks.

MoDOT formed a bridge deck quick action (QA) team to determine the causes and find solutions to mitigate early bridge deck cracking. The QA team conducted a thorough literature search, state DOT survey, and an evaluation of MoDOT's current bridge deck specifications to identify possible solutions to early deck cracking. The QA team concluded that plastic shrinkage cracking, drying shrinkage cracking, and thermal stresses were the primary types of cracking occurring in MoDOT's bridge decks.

Plastic shrinkage cracks occur when water evaporates from the surface faster than it can travel to the surface during the bleeding process. This creates rapid drying shrinkage and tensile stresses in the surface that often result in short, irregular cracks[1]. The most important factors effecting plastic shrinkage cracking are the placement and curing procedures used during construction and the concrete mix design properties.

The tensile strain resulting from the loss of adsorbed water in the capillary pores of concrete causes drying shrinkage cracking. This occurs after the concrete hardens and the concrete is exposed to less than 100% relative humidity. Most drying shrinkage of bridge decks occur within the first year after construction[2].

Thermal stresses that develop within a bridge deck from the heat of hydration of the cementitious materials are also a significant factor causing early bridge deck cracking. Early thermal contraction, temperature gradients, temperature cycles, and seasonal variations also cause thermal cracking.

The QA team developed new placing and curing specifications that are currently being implemented on bridge deck construction projects. The changes made to the new placing and curing specification should mitigate early bridge deck cracking. However, the team decided that research for an improved bridge deck mix was necessary to further mitigate deck cracking. It was proposed that Research, Development, and Technology conduct a laboratory investigation to develop new concrete mix designs with improved concrete properties that are less susceptible to cracking. Material properties of concrete affect deck cracking more than any other factor[2].

This paper presents laboratory test results from nine different concrete mix designs that will be considered by the QA team to replace MoDOT's current bridge deck (B-2) mixes. The research conducted should give MoDOT a bridge deck mix that is more economical, improves the service life, and reduces maintenance costs of bridge decks.

Objective

The objective of this investigation is to develop bridge deck mixes that improve field performance and minimize cracking potential compared to MoDOT's current (B-2) bridge deck mix design. The mix designs developed in this study were tested and compared to the control B-2 mixes for the following concrete properties:

compressive strength (AASHTO T22)
modulus of elasticity (ASTM C469)
freeze/thaw durability (AASHTO T161)
salt scale resistance (ASTM C672)
chloride permeability (AASHTO T277)
90-day ponding test (AASHTO T259)
plastic shrinkage crack tests (research-in-progress)
dry shrinkage of mortar (ASTM C596)
autoclave expansion (ASTM C151)

The mix designs that appeared to have the best performance through laboratory testing would be selected in field projects for further evaluation.

Discussion of Present Conditions

Currently, MoDOT uses the following mix design criteria for its bridge deck (B-2) mixes.

Mix Design Criteria
min. cementitious material: 7.50 sacks/yd^3
max. slump: 3 inches
max. gallons of water: 4.5 gal/sack
percent air content: 5.5% +/- 1.5%
water reducers allowed; not required
max. 15% flyash replacement allowed; not required
max. 25% ground granulated blast furnace slag (GGBFS) replacement allowed; not required
ternary mixes not allowed
silica fume not allowed

This study focuses primarily on improving the B-2 mixes by maintaining strength and durability criteria, decreasing chloride permeability, and reducing cracking potential. Improving the B-2 mixes will increase the service life and decrease maintenance cost of the bridge deck. Also, using different combinations of supplementary cementitious materials should lead to better concrete characteristics at a lower cost.

Technical Approach
Two of the most important factors effecting early bridge deck cracking are placement conditions, curing techniques, and concrete material properties. The bridge deck quick action (QA) team developed new placing and curing specifications and proposed that a laboratory study be conducted to improve the concrete characteristics of the bridge deck (B-2) mix that MoDOT currently uses.

New Placing and Curing Specification
The QA team developed new placing and curing specifications that are currently being implemented on future bridge deck construction projects. The new specifications lowered the maximum placement and concrete mix temperatures, required the application of a curing compound within a minimum time period, and extended the wet cure period. The changes made should help mitigate early crack development in MoDOT's bridge decks. Table 1 highlights primary changes or additions made to the new specifications compared to the old specifications.

Proposed Mix Design Changes
The QA team proposed a laboratory study to test a number of variations of new bridge deck concrete mix designs. The mix designs determined to have the best performance characteristics through various laboratory tests could then be used on field demonstration projects with follow-up field-testing.

The QA team recommended lowering the cement content in MoDOT's bridge deck mixes. After a thorough literature search, a nation wide state DOT survey, and FHWA guidelines, the QA team recommended a reduced cement content of 6.40 sacks/yd^3 for laboratory testing of a new bridge deck mix design. The team also suggested trying different types and percentages of supplementary cementitious materials, varied types and dosages of water reducers, varied water/cement ratios, and use of different fine and coarse aggregate percentages. Appendix A provides the original work plan for this investigation.

Material Sources
The laboratory study was limited by using only one material source for the aggregates, Portland cement, supplementary cementitious materials, and chemical admixtures. The source/manufacturer and description of the materials that were used for this study are as follows:

Coarse Aggregate:	Capital Quarries, Holts Summit 1A Gradation D Limestone (1" Max.) Cedar Valley, Ledges 1-3
Fine Aggregate (38%):	Capital Sand #1, Jefferson City Missouri River Sand, Class A
Cement:	Continental Cement Jefferson City River Terminal Type 1 Portland Cement

Class C Flyash:	Mineral Resource Labadie, MO
Ground Granulated Blast Furnace Slag:	Lonestar St. Louis Terminal
Silica Fume:	Elkem Materials Pittsburgh, PA
Air Entrainment:	Grace – Daravair 1400
Water Reducer:	Grace – Daracem 65

The above aggregate and cement sources were local materials that have a good performance history and are used as a laboratory standard. Supplementary cementitious materials and chemical admixtures were selected from MoDOT's approved materials list.

Mix Designs

The absolute volume method was used in developing the 11 different mix designs. Two mix designs represented MoDOT's standard B-2 mixes and were used as control mixes. Nine test mixes were developed to test the performance of different amounts and combinations of supplementary cementitious materials and to compare the characteristics with the standard B-2 mixes. The supplementary cementitious materials selected for this investigation were Class C flyash, ground granulated blast furnace slag (GGBFS), and silica fume. Table 2 describes the cementitious material content and the description/reference of each mix design investigated in this study. Mixes 1 and 2 were the two control mixes that followed MoDOT's current specifications for a B-2 mix. The other nine mix designs contain a total cementitious content of 6.40 sacks/yd^3, which follows the QA team's initial recommendation. Lowering the cementitious material further would be comparative to MoDOT's PCCP mixes of which much laboratory data is available. A Type A water reducer was used for all test mixes (mixes 3 – 11). The dosage of the water reducer was set for all test mixes by the manufacturer's recommendations (8 oz./yd^3). Although water reducers are allowed by specifications, they were not used in control mixes 1 and 2. Water reducers are generally not used on MoDOT projects because of the increase in costs of a mix design.

Trial Batching and Specimen Fabrication

After the aggregate characteristics, total cementitious contents, supplementary cementitious percentages, and water reducer dosages were determined; numerous trial batches were produced in the development of the 11 mix designs. The unknown variables, which included air entrainment agent and water, were varied in the trial batches until a target slump of 3 – 4 inches and target air content of 6% were achieved for each mix design. The water/cement ratio was established at these target values. One laboratory batch sheet for each final mix design is included in Appendix B.

Once the target slump and air content were established, concrete test specimens were fabricated from each mix design. The concrete test specimens were made according to AASHTO T126, *Making and Curing Concrete Test Specimens in the Laboratory*. The concrete specimens representing the 11 mix designs were tested for strength, durability, permeability, and shrinkage properties following the appropriate AASHTO or ASTM specifications listed in Table 3. The average slump, air content, and water/cement ratio for each mix design can be found in Table 4.

Results and Discussion

This research investigation is a laboratory study on the development and testing of bridge deck mixes. Nine different bridge deck mix designs were laboratory tested and compared to two control mixes for strength, durability, permeability, and shrinkage characteristics. The bridge deck test mixes differed mainly by cementitious material type and percent replacement as listed in Table 2. The average fresh concrete characteristics (slump, percent air, and water/cement ratio) of each mix design are listed in Table 4. The laboratory results from this study are described within the following sections.

Compressive Strength

MoDOT has a minimum 28-day compressive strength requirement of 4000 psi. for its bridge decks. The minimum cementitious material requirement for MoDOT's B-2 mix is 7.50 sk/yd^3. This cementitious amount currently provides MoDOT with an average 28-day compressive strength over 6000 psi[3]. Compressive strength is a very important concrete characteristic, however, it does not indicate a superior mix. The trends of increasing compressive strengths and lowering water/cement ratios in mix designs have led to producing compressive strengths far above the design compressive strengths that are actually needed. The National Cooperative Highway Research Program (NCHRP) report states, "The primary reason for increased cracking are increased cement contents, higher paste volumes, higher early modulus of elasticity, higher hydration temperatures, and much lower creep"[2]. The following material properties were some of the recommendations by the NCHRP report to reduce cracking in bridge decks: low early strength concrete (use 56 or 90 day design compressive strengths), lower amounts of Portland cement, low heat of hydration supplementary cementitious materials, minimum paste volumes and free shrinkage, larger aggregate sizes, good quality low-shrinkage aggregates, and shrinkage-compensating cements.

Compressive strength data were collected from 3, 7, 14, 28, 56, and 90 day concrete test cylinders that represented each laboratory mix design. The fresh concrete characteristics of each mix are listed in Table 4, while the average compressive strengths of each mix design are listed in Table 5. Figure 1 graphically illustrates the compressive strengths of each mix design. Compressive strengths and concrete characteristics for individual specimens are located in Appendix C.

Mix 3, which contained a Type A water reducer, 6.40 sack/yd^3 cement content, and no supplementary cementitious materials, yielded the lowest 28-day, 56-day, and 90-day compressive strengths of all other mixes. The average 90-day compressive strength of Mix 3 was 5740 psi, which is approximately 800 psi lower than the B-2 Control Mix 1. The significance of this is that reducing the cement content from 7.74 to 6.40 sacks/yd^3 will decrease the compressive strength of a mix, despite the addition of a Type A water reducer.

The reduction in compressive strength is not significant enough to hinder the structural performance of a bridge deck mix.

The use of supplementary cementitious materials increased the compressive strength of a mix design. When supplementary cementitious materials and a Type A water reducer were used in a mix containing 6.40 sacks/yd^3 (Mixes 4 –11), the compressive strengths were equivalent or higher than the B-2 control mixes. Also, the B-2 Control Mix 2 with 15% flyash replacement yielded higher compressive strengths than the B-2 Control Mix 1.

GGBFS has a lower heat of hydration than Portland cement and will generally retard the setting time of concrete[1]. The laboratory results likewise indicated that test mixes 6, 7, 9, and 11 that contained ground granulated blast furnace slag (GGBFS) yielded a lower 3 and 7-day compressive strengths compared to all other mixes as listed in Table 5 or illustrated in Figure 1. After 7-days, the compressive strengths of the GGBFS mixes compared similar to the B-2 control mixes.

Modulus of Elasticity (ASTM 469)

The modulus of elasticity affects both thermal and shrinkage stresses more than any other physical concrete property. Increasing the concrete modulus of elasticity increases both shrinkage and thermal stresses[2]. Modulus of elasticity testing was performed on 3, 7, 14, 28, and 56-day cylinders that were fabricated to represent each of the 11 different mix designs. The results from this testing are listed in Table 6 and graphically compared in Figure 2. The intent of this test was to compare early age modulus values of the different mixes to determine which mixes were less susceptible to thermal and shrinkage stresses. The concrete modulus of elasticity is largely affected by aggregate type. All mixes in this study used the same aggregate source. Any differences in the concrete modulus of elasticity would be due to the cementitious amounts and types.

There was a great paradox that occurred with the modulus testing in this study. For Mix 1 versus Mix 3, decreasing the total cement content from 7.74 sacks/yd^3 to 6.40 sacks/yd^3 increased the modulus of elasticity, which in theory makes a mix more cracking susceptible, yet the decrease in cementitous material should decrease total shrinkage, which makes a mix less susceptible to cracking. This paradox is probably caused by the effect of the aggregate on the concrete modulus of elasticity. A decrease in paste content allowed the modulus of the aggregate to dominate, instead of the modulus of the paste. A decrease in paste content would most likely decrease the cracking potential of a mix rather than increasing the cracking potential.

Mixes containing Class C flyash (Mixes 4 and 5) did not have a significant effect on the modulus of elasticity. However, mixes containing GGBFS (Mix 6, 7, and 9) had the lowest early modulus of elasticity compared to all the mixes tested. Despite the reduction of the cementitous material content compared to the control mixes, the GGBFS had the lowest heat of hydration and retarded the set time to produce a low early concrete modulus of elasticity. These mixes should be less susceptible to thermal and shrinkage cracking compared to the other test mixes in this study.

Mix 8, which contained 6% silica fume, resulted in the highest early modulus. Mixes containing silica fume admixtures generally produce high early strengths and high early modulus, which increases the potential for early cracking. However, the ternary mixes containing silica fume (Mix 10 and 11) had equivalent modulus of elasticity compared to the control mixes. Adding a flyash or a GGBFS with silica fume appeared to reduce the early concrete modulus of elasticity.

Freeze/Thaw Durability (AASHTO T161)

Resistance to freezing and thawing is one of the most important concrete characteristics for any structure to have, especially in the severe freezing and thawing conditions that occur in Missouri. Freeze/thaw beams were fabricated from each mix design and tested according to AASTHO T161, Method B. This method is intended to determine the effects of variations in both properties and conditioning of concrete in the resistance to freezing and thawing cycles[4,5]. However, this test method is used extensively in ranking of coarse aggregates as to their effect on concrete freeze/thaw durability, especially where soundness of the aggregate is questionable. The coarse aggregate used in this study was obtained from the same aggregate source with a superior freeze/thaw durability history. The coarse aggregate was also obtained from the same stockpile to ensure consistency in freeze/thaw resistance. Therefore, differences in freeze/thaw durability in the mix designs would result from other concrete mix properties.

The average freeze/thaw durability results for each mix design are presented in Table 7. Freeze/thaw results from individual specimens can be found in Appendix D. All mixes in this study obtained a freeze/thaw durability factor greater than 90, which is considered excellent in freeze/thaw resistance. All changes in the bridge deck mix designs, which included a decrease in cementitious material, different types and dosages of supplementary cementitious material replacements, and use of a Type A water reducer, did not significantly affect the freeze/thaw durability performance of the concrete. The use of silica fume in a mix appeared to decrease the freeze/thaw durability by approximately 3 – 5 units, but still achieved an excellent durability factor. Mixes containing the higher dosages of flyash and GGBFS yielded equivalent freeze/thaw durability factors compared to the control mixes.

Salt Scale Resistance (ASTM C672)

Freezing and thawing cycles can cause the loss of cement paste and mortar from the surface layer of concrete, and this phenomenon is aggravated by the presence of dissolved deicer salts[1]. Decades of field experience have demonstrated that air-entrained concretes containing normal dosages of fly ash, slag, silica fume, calcined clay, or calcined shale are resistant to scaling caused by the application of deicing salts in a freeze-thaw environment[1]. However, previous laboratory work by other researchers has shown that concrete containing either blast-furnace slag or flyash typically have lower resistances to deicer salt scaling than Portland cement concretes[6]. There have been significant differences in durability performance predicted by laboratory testing versus field exposure. Reported field observations have shown satisfactory performance of concretes containing slag despite poor laboratory results[6]. The ASTM C672 is a harsh test in evaluating a concrete mix's salt scale resistance. Laboratory results should be interpreted carefully, and where possible, verified by documented field performance.

Lean concrete with only about 405 lb/yd^3 or less of cementitious material can be especially vulnerable to deicer scaling. The Portland Cement Association recommends a minimum of 564 lb/yd^3 of cementitious material and a maximum water/cement ratio of 0.45. The minimum cementitious material used in this study was 6.40 sack/yd^3 (602 lb/yd^3), which is well within the above recommendation.

Salt scaling resistance testing was conducted on specimens representing all mixes according to ASTM C672. The finishing and curing of the top surface of the specimens are critical when comparing the effects of different concrete mixes. This test was conducted twice to ensure accuracy. In the first batch of testing (Trial 1), the specimens may have been over-finished and were immediately covered with plastic and wet burlap. Bleed water formed on the top surface, which may have skewed the ratings of the mixes. Consequently, salt scale testing was conducted a second time for each mix design (Trial 2). There were some differences within the two trials, but this test is somewhat subjective and the consistency of the finishing operation on the specimens is very critical. Evaporation retarders or curing compounds were not applied to the concrete specimens. This allowed each mix to be rated on its salt scaling resistance without the effects of curing compounds or evaporation retarders. All mixes tested for salt scale resistance in this study achieved a salt scale rating less than or equal to 2, which would be considered acceptable for bridge deck applications in Missouri.

Table 8 lists the salt scale ratings for each mix design. Four concrete specimens were fabricated to represent each mix design. Two were fabricated from the first batch (Trial 1), while two more were fabricated to verify the results (Trial 2). Based upon ASTM C672 laboratory results, decreasing cement from 7.74 sack/yd^3 to 6.40 sack/yd^3 (Mix 1 vs. Mix 3) did not significantly affect the salt scale resistance of the concrete. Both control mixes 1 and 2, which contained 7.74 sacks/yd^3, either had no scaling or only very slight scaling, which is a 0 or 1 rating, respectively. Although Mix 3 had one specimen rated at a 2 (slight to moderate scaling), three specimens performed better or equivalent to the control mix (slight scaling or no scaling).

The addition of the supplementary cementitious materials used in this study appeared to slightly decrease the salt scale resistance of the concrete, but the effect is not considered significant. This correlates with research previously conducted by others. Test mixes 5 – 11, which contain a cementitious content of 6.40 sacks/yd and contain one or more supplementary cementitious materials, had more test specimens with a 2 rating (slight to moderate scaling) compared to the other mixes. Increasing the dosage of Class C flyash and GGBFS to 35% and 50%, respectively, and the use of silica fume did not appear to affect the salt scale resistance of the concrete. Also, the three ternary mixes performed equal or better than the single supplementary cementitious mixes. Test mixes 4 – 11 had salt scale ratings 1 (very slight scaling) or 2 (slight to moderate scaling). A minimum salt scale rating of 2 or less would be considered acceptable for bridge deck applications in Missouri. Figures 3, 4, and 5 illustrate examples of salt scale ratings of 0, 1, and 2, respectively.

Rapid Chloride Permeability (AASHTO T277)
The rapid chloride permeability test is an electrical indication of concrete's ability to resist chloride ion penetration. Lower permeability improves concrete's resistance to freezing and thawing, resaturation, sulfate, and chloride-ion penetration, and other chemical attack[1].

AASHTO T277, *Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, was conducted on 28, 56, and 90-day concrete specimens that were fabricated to represent 11 different mix designs in this study. Table 9 lists the average chloride permeability results for each mix design. Figure 6 compares the permeability results from all mix designs. Average concrete characteristics of each mix are listed in Table 4.

Based upon the laboratory results, control (B-2) Mix 1 and Mix 3 had the highest chloride permeability compared to all the mixes tested. Both Mix 1 and Mix 3, which contained no supplementary cementitious materials, yielded over 2000 Coulombs of electrical charge passing through the specimens on the 28, 56, and 90-day test dates. Mixes 1 and 3 are considered being in the *moderate range* (2000 – 4000 C). All other mixes containing one or more supplementary cementitious materials yielded less than 2000 Coulombs on the 90-day test, which is considered to be the *low permeability range* (1000 – 2000 C). The use of supplementary cementitious materials significantly decreases concrete's permeability.

Mixes containing higher dosages of flyash and GGBFS (Mix 5 and Mix 7) yielded much lower permeability compared to the lower flyash and GGBFS mixes (Mix 4 and Mix 6, respectively). Mix 5 (35% flyash replacement) and Mix 7 (50% GGBFS replacement) both yielded a 90-day chloride permeablility of less than 1000 Coulombs, which is considered the *very low permeability range* (100 – 1000 C). Mix 9, which is a ternary mix containing 15% flyash and 25% GGBFS, was in the *low permeability range* (1000-2000 C) based on the 28, 56, and 90-day permeability tests.

The dosage of silica fume was not varied in this study and was set at 6% replacement based upon recommendations of NCHRP Report 410. Mix 8 (6% silica fume) yielded 28, 56, and 90-day permeability in the *low permeability range* (1000 – 2000 C). Adding flyash or GGBFS with the silica fume, Mixes 10 and 11 (both ternary mixes), yielded very low permeability of less than 1000 C.

Low permeability is a very important concrete characteristic, especially for bridge decks. The durability and service life of concrete exposed to weather is related to the permeability of the cover concrete protecting the reinforcement[1]. High performance concrete typically has very low permeability of less than a 1000 Coulombs. However, without the use of silica fume and/or high dosages of supplementary cementitious materials, very low permeability is difficult to achieve. Total Coulombs passing in excess of 2000 is judged to be undesirable for a bridge deck, especially in severe freezing and thawing conditions with exposure to chlorides. If the maximum 2000 Coulombs passing criteria was used, B-2 control Mix 1 and Mix 3, containing no supplementary cementitious materials, would not be acceptable for bridge deck applications.

Resistance of Concrete to Chloride Ion Penetration (AASHTO T259)

This test method, known as the 90-day ponding test, determines the resistance of concrete specimens to the penetration of chloride ions. It is intended for use in determining the effects of variations in the properties of concrete on the resistance of the concrete to chloride ion penetration. There should have been a correlation with the results from this test compared to AASTHO T227. However, the results obtained from the 90-day ponding tests were inconclusive for mix comparison. Figure 7 illustrates the results. According to this test method, supplementary cementitious materials did not have a significant effect on the penetration of chloride ions. A 1.0-lb/yd^3 maximum chloride limit is recommended to protect reinforcing steel from corroding[7]. At a depth of 1.5 inches, all mixes tested below the maximum chloride content limit. MoDOT requires a 3-inch concrete cover for its reinforcing steel. According to AASTHO T227, all mixes tested in this study would not have allowed chloride ion penetration to the reinforcing steel. No significant chloride ion penetration comparisons could be made among the 11 different mix designs, however.

Potential Shrinkage Crack Tests

One goal of this study was to develop new bridge deck mix designs that would be less susceptible to shrinkage cracking. Currently, there are no approved standard specifications to evaluate and compare the shrinkage cracking potential of a concrete mix in the laboratory. Through the literature review conducted for this investigation, two shrinkage test methods are being used by other state agencies to determine and compare cracking potential of different mixes. *The Proposed Standard Method for Testing Cracking Tendency of Concrete* and *The Slab Cracking Potential Test Method* are the two test methods that Research, Development, and Technology tried to implement in this study.

The Proposed Method of Testing Cracking Tendency of Concrete was proposed to AASHTO for specification review, but was not approved. The proposed test method was used in this study for evaluating bridge deck mixes. This method is intended for determining the relative likelihood of early concrete cracking due to free shrinkage and for aiding in the selection of concrete mixtures that are less likely to crack[2]. This method involved fabricating a concrete specimen around a steel inner ring. Strain gages were attached to the inner ring and strain readings were taken as the surrounding concrete ring shrinks until the concrete cracks. Figure 8 illustrates the testing apparatus. Unfortunately, no valuable data was retrieved from this test method and no cracking was noticed after two-weeks of monitoring the concrete rings. This test method has been effective for other researchers and deserves further development and evaluation.

The New York State Department of Transportation (NYSDOT) developed *The Slab Crack Potential Test Method*. This method compares the plastic shrinkage cracking potential of different concrete mixes with the surface cracking of a control concrete panel[8]. This method involves fabricating concrete specimens and subjecting them to a harsh curing environment to induce cracking. The time-of-cracking and crack lengths are determined after a 24-hour period. Figure 9 illustrates the concrete form inside the environmental chamber that creates the harsh curing environment. Testing results in this study were inconsistent. The same mix design under the same evaporation conditions would crack during one test, but would not crack during a different time. No comparisons of mix designs could be made when the same mix design yielded conflicting results.

Autoclave Expansion (ASTM C151)

This test method covers determination of the autoclave expansion of Portland cement by means of a test on a neat cement specimen. The autoclave expansion test provides an index of potential delayed expansion caused by the hydration of CaO, or MgO, or both, when present in Portland cement[9]. The testing procedure was varied from the specification to include representative amounts of supplementary cementitious materials. Results from this testing are listed in Table 10. The maximum limit on autoclave expansion is 0.8%. The highest percent expansion resulted from this testing was .04%, which is well below the maximum limit. The expansion of cementitious materials may vary considerably from source to source, but the sources of cementitious materials used in this study were not expansive and indicated good compatibility when intermixed.

Dry Shrinkage of Mortar (ASTM C596)

This test method determines the change in length on drying of mortar bars containing hydraulic cement and graded standard sand. This test was modified to include proportions of the cementitious materials to represent the 11 different mix designs. Table 11 lists the results from this test method. Mortar bars containing GGBFS had slightly higher shrinkage results compared to the other mixes. Including either flyash or GGBFS generally increases shrinkage of mortar bars, however, Swayze has shown that a higher shrinkage of neat cement paste does not necessarily mean a higher shrinkage of concrete made with the cement[10]. This test method does not appear to be effective for comparing the actual dry shrinkage characteristics of different concrete mix designs.

Cost Analysis

The cost of the 11 different mix designs were estimated and compared to determine the most cost effective mix design. The eleven mix designs differed mostly by type and amounts of cementitious material and the addition of a Type A water reducer. The prices of cementitious materials vary considerably and depend on project location, project size, and available shipping means. Tables 12 and 13 list one cost comparison of only the cementitous materials and the water reducing admixtures. All other common ingredients were taken out of the estimate, assuming that the costs are comparable.

All mixes containing Class C flyash are less expensive than the other mixes. Class C flyash was quoted at $22/ton while the cost of Type 1 Portland cement is $83/ton. Missouri has an ample supply of Class C flyash and MoDOT should be able to capitalize on this cost savings for its bridge decks.

GGBFS is less abundant in Missouri, but prices in some areas are less expensive than Type 1 Portland cement. GGBFS has shown excellent laboratory performance and should be competitive as a suitable cement replacement.

Silica fume is more expensive compared to the other supplementary cementitious materials. The cost of mixes containing silica fume were considerably higher. If new sources become available in the future and silica fume price becomes more competitive, then silica fume could be used in MoDOT's concrete bridge decks, as long as appropriate curing methods are used.

Summary of Mix Performance and Evaluation

The quality of the aggregate is the primary constituent in a concrete mix that will greatly influence mix performance. This study used aggregate that has an outstanding performance history. Unfortunately, some aggregate sources in Missouri will not perform as well compared to the results reflected in this study, especially in freeze/thaw durability. For optimum freeze/thaw durability, bridge decks should use only good quality aggregates.

Table 14 lists the advantages and disadvantages for each mix design developed in this investigation. Shrinkage and thermal cracking potential of a mix was determined through the recommendations given by literature review, since the laboratory cracking tests were inconclusive. All mix designs had excellent compressive strength and freeze/thaw durability factors that were comparable to each other.

Mixes 1 and 2 should have the highest drying shrinkage potential due to the cement content in the mixes, and both mixes did produce high early concrete modulus of elasticity. However, both have excellent salt scale resistance and finishing characteristics.

Mixes 1 and 3 have moderate permeability in which over 2000 Coulombs passed. The moderate permeability range is not acceptable for bridge deck applications in Missouri. Mix 3 also had a high early modulus, but may be attributed to the decreased paste content.

Mixes 4 and 5, which contain Class C flyash, are the least expensive mixes. The mixes had higher early concrete moduli, but again may be attributed to the decrease in paste content. Class C flyash has also been recognized by other researchers to have some incompatibility issues, especially when used at higher dosages[1]. Mainly, early stiffening and alkali silica reactions (ASR) issues have been noted in Class C flyash mixes. However, no incompatibility issues were found during the mixing performed in this investigation.

Mixes 6, 7, and 9, which contained GGBFS, had the best overall concrete characteristics compared to the other mixes. These mixes exhibited good finishability, lower early concrete moduli, lower hydration temperatures, lower chloride permeability, and lower costs. One disadvantage was the decrease in salt scale resistance, which occurred to all mixes containing a supplementary cementitious material. However, it is well known that concretes containing supplementary cementitious materials have demonstrated excellent scaling resistance in the field despite poor laboratory scaling results[6].

Mix 8, which contained 6% silica fume, was the hardest mix to finish. It also obtained the highest early concrete modulus of elasticity, which correlates with literature review on having higher cracking potential. However, when silica fume is added with a flyash or GGBFS (mixes 10 and 11), these affects are reduced. The major advantage of silica fume is it provides a very dense mix, which yields a very low permeability. The cost of silica fume, however, may limit its choice as an additive for Missouri.

Conclusions
This paper presents a laboratory performance evaluation of PCC mixes for use in bridge decks. Eleven different mix designs were developed and tested for strength, durability, permeability, and shrinkage characteristics. The mixes varied mainly by the type and dosage of supplementary cementitious materials that replaced the Portland cement. Table 2 describes the different cementitious contents of each mix design. The main findings of this study are summarized as follows:

<u>Strength</u>

1. Through literature review performed for this study, other research has indicated that low early strength concrete, low amounts of Portland cement, low heat of hydration supplementary cementitious materials, minimum paste volumes, and free shrinkage, will help reduce plastic shrinkage cracking in bridge decks. Ultimately, lower compressive strengths are desirable as long as design factors and design safety factors are achieved.
2. Reducing total cementitious material from 7.74 sk/yd^3 (Mix 1) to 6.4 0sk/yd^3 (Mix 3) decreased the ultimate compressive strength, despite the addition of a Type A water reducer. This study indicated a 56 and 90-day compressive strength loss of approximately 800 psi between Mix 1 and Mix 3.
3. Replacing Portland cement with supplementary cementitious materials in the 6.4 sk/yd^3 mixes (Mixes 4-11) yielded ultimate compressive strengths equivalent or greater than the 7.74 sk/yd^3 mixes (Mix 1).
4. Mixes 6, 7, 9, and 11 containing GGBFS yielded lower 3 and 7-day compressive strengths compared to the other mixes. This was expected since GGBFS has a lower heat of hydration and retards the setting time of concrete[1].
5. Reducing total cementitious materials from 7.74 sk/yd^{3}to 6.40 sk/yd^3 increased the early modulus of elasticity, but total shrinkage potential of a mix should decrease.
6. Mixes containing GGBFS appeared to have lower 3-day modulus of elasticity, which corresponds to the compressive strength results. Reducing the concrete modulus of elasticity reduces shrinkage and thermal stresses in concrete.
7. Mix 8 containing 6% silica fume replacement yielded the highest early concrete modulus. However, adding a Class C flyash or GGBFS to the silica fume yielded lower concrete modulus values that were equivalent to the control mixes.

<u>Durability</u>

1. Decreasing the amount of cementitious materials (7.74 to 6.40 sk/yd^3), use of different dosages of Class C flyash, GGBFS, and/or silica fume, and the addition of a type A water reducer did not significantly affect the freeze/thaw durability results of all mixes evaluated in this study. All mix designs achieved a freeze/thaw durability greater than 90.
2. The use of silica fume in a mix appeared to slightly decrease the freeze/thaw durability by approximately 3 – 5 units, but still achieved an excellent durability factor.
3. Decreasing total cementitious content and the use of supplementary cementitious materials slightly decreased the salt scale resistance of concrete. However, the results from all mixes were found acceptable for bridge deck applications in Missouri.

4. The use of supplementary cementitious materials slightly decreased the salt scale resistance of the concrete. Increased dosages of supplementary cementitious materials did not decrease the concrete's salt scale resistance compared to lower dosages. Mixes 5 – 11, which all contained one or more supplementary cementitious materials, had at least one test specimen rated at a 2 (slight to moderate scaling), which is still considered acceptable for bridge deck applications in Missouri.

<u>Permeability</u>

1. The use of supplementary cementitious materials significantly decreases concrete's permeability when tested according to AASHTO T277, *Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*.
    a. Mixes containing no supplementary cementitious materials (Mix 1 and 3) yielded over 2000 Coulombs of electrical charge passing through the specimens on the 90-day tests. Mixes 1 and 3 are considered *moderate permeability range* (2000 – 4000 C).
    b. Mixes containing lower dosages of supplementary cementitious materials (Mixes 2, 4, and 6) yielded less than 2000 Coulombs on the 90-day test, which is considered *low permeability range* (1000 – 2000 C).
    c. Mixes containing higher dosages of supplementary cementitious materials and/or silica fume (Mixes 5, 7, 8, 9, 10, and 11) yielded less than 1000 Coulombs on the 90-day test, which is considered *very low permeability range* (100 – 1000 C).
2. The permeability results obtained from AASHTO T259, *Resistance of Concrete to Chloride Ion Penetration*, did not correlate with the results obtained from AASTHTO T277. The maximum chloride limit to protect reinforcing steel from corroding is 1 lb/yd^3. All mix designs tested in this study were below this limit at a 1-½ inch depth.

<u>Shrinkage Characteristics</u>

1. *The Proposed Method of Testing Cracking Tendency of Concrete* was submitted for trial use for evaluating cracking tendency in bridge deck mixes. This method is intended for determining the relative likelihood of early concrete cracking and for aiding in the selection of concrete mixtures that are less likely to crack. The test results from this test were not conclusive. No cracking was noticed after two-weeks of monitoring the concrete rings.
2. *The Slab Crack Potential Test Method* compares the surface cracking of different concrete mixes with the surface cracking of a control concrete panel. The results from this test were also not conclusive. Repeatability of the same mix designs could not be achieved, which made comparisons of different mix designs impossible.

Recommendations
Based upon research from the literature review and laboratory test results and observations; Research, Development, and Technology presents the following recommendations:

1. The following concrete characteristics are recommended to be the performance criteria for MoDOT's concrete bridge deck mixes. Some of the testing methods and procedures are not feasible to implement into performance specifications at this time. It is recommended that the mix design be method based, unless industry can perform all of the required testing. Presently, these criteria can serve as a guide for MoDOT in developing and/or approving other bridge deck mixes.

Concrete Characteristic	**Test Method**	**Performance Criteria**
Air content	AASHTO T152	Minimum = 6.0 %
Slump	AASHTO T119	Max. 4 inches
Water/cement Ratio	-	Max. w/c ratio = .45 (5.0 gal/sk.)
56-day Compressive Strength	AASHTO T22	Min. 56-day = 5000 psi
Freeze/thaw Durability Factor	AASHTO T161	Min. Durability Factor = 85
Salt Scale Resistance	ASTM C672	2 rating or less
90-day Chloride Permeability	AASHTO T277	Max. 2000 Coulombs
90-day Ponding Test	AASHTO T259	Max. 1.0 lb/yd^3 Chloride Ion Content @ 2 inches

2. Mix 2 and mixes 4 - 11 met or exceeded the criteria specified above. The chloride permeability results for Mixes 1 & 3 were greater than 2000, which exceeded the maximum chloride permeability limit. It is recommended that mixes 1 and 3 are not considered acceptable for concrete in bridge deck applications in Missouri.

3. Based upon laboratory results from this study, it is recommended that the new concrete bridge deck mix designs replace MoDOT's current B-2 bridge deck mix with the following specification changes:

    a. Reduce the minimum total cementitious material from 7.50 sk./yd^3 to 6.40 sk./yd^3.

    b. Type A water reducers must be included in the new mix designs to maintain proper water/cement ratio, strength, durability, and permeability requirements.

c. High range water reducers may have to be incorporated in the some of the new mix designs to stay within the maximum water/cement ratio of 0.45, especially in higher evaporation conditions.
d. At least one supplementary cementitious replacement, such as flyash, GGBFS, and/or combinations (ternary mixes) must be incorporated in the new bridge deck mix designs, as long as the following appropriate replacement limits are followed:

Supplementary Cementitious Material Replacement	Maximum Limits
Maximum Flyash Replacement	25%*****
Maximum GGBFS Replacement	40%
Maximum Cement Replacement for Ternary Mixes	40%**

***** *Although 35% Class C flyash was used in this study and had achieved desirable concrete properties, some concerns have been recognized through literature review and conferences since this study began. Class C flyash contains higher contents of aluminates, which may cause early stiffening problems of the concrete. Also, Class C flyash in combination with high silica aggregates may lead to alkali silica reaction (ASR), which causes early deterioration problems. MoDOT uses limestone aggregates (low silica) for a majority of its projects, thus ASR has never been noted or recognized. In order to mitigate the chance of having ASR problems, it is recommended that GGBFS be used in combination with the flyash because this chemically diminishes any ASR potential. A research investigation is currently underway to investigate ASR in high silica sands and coarse aggregates and how combinations of different supplementary materials can mitigate this phenomenon.*

*** Supplementary cementitious materials in a ternary mix shall not exceed its own single maximum replacement limit.*

4. Ternary mixes containing Type 1 Portland cement, flyash, and GGBFS (Mix 9) should be encouraged and used whenever possible because of its superior concrete properties, lower cost, and its desired compatibility compared to mixes containing Type 1 Portland cement and Class C flyash.

5. Silica fume is not recommended at this time based on cost, workability issues, and its plastic shrinkage potential. If the price of silica fume gets more competitive with other cementitious materials, it could be considered in MoDOT's concrete bridge deck mixes, especially in ternary mixes.

6. Laboratory results indicate that GGBFS could be used as high as 50% without significant scaling issues. However, it is recommended that the maximum replacement limit for Type 1 Portland cement be 40% in a bridge deck, thus GGBFS replacement limits were lowered accordingly.

7. Field documentation and verification should be conducted to verify the performance of concrete bridge deck mixes proposed for this study.

8. Based upon the laboratory compressive strength results and literature review, total cementitious material could be reduced further. It is suggested that minimum cementitious material could be reduced to 6.0 sk/yd^3, if the maximum aggregate size is increased to 1-½ inches (Gradation A or B). This would give contractors incentives on using larger sized aggregates, which would decrease shrinkage cracking potential significantly, as long as contructibility and placeability requirements are not hindered.

9. The development of a laboratory test method to successfully determine the cracking tendency of a concrete mix did not get accomplished during this study. It is recommended that laboratory tests be developed by an outside entity (university, consultant, etc.) to correlate the laboratory test results with field performance.

10. Through literature review, decreased cementitious material content, low heat-of-hydration pozzolans, decreased paste content, and improvements of the curing specifications should decrease the shrinkage cracking experienced in MoDOT's bridge decks. Further laboratory testing of bridge deck performance is recommended on mix designs containing fibers, shrinkage compensating cements, shrinkage reducing admixtures, and other new products.

Subject	Old Specifications	New Curing Specifications
Max. placement temperature	90^o F	85^o F
Max. concrete temperature	90^o F	85^o F
Curing compound	No requirements	Curing compound applied immediately
Time Limits on Wet Curing	No requirements	Wet burlap cover in 90 minutes or less
Wet Cure Period	5 days	7 days

Table 1 – New Curing Specifications

Mix No.	Cementitious Materials	Description/Reference
1	**Control**, 728 lb/yd^3, No Water Reducer	Typical mix from current specifications
2	**Control**, 728 lb/yd^3- 15% FlyAsh, No Water Reducer	Typical mix from current specifications
3	602 lb/yd^3, Type A Water Reducer	Decreased cement without supplementary cementitious materials
4	602 lb/yd^3- 15% FlyAsh, Type A Water Reducer	Follows current MoDOT flyash replacement limits
5	602 lb/yd^3- (35% FlyAsh) Type A Water Reducer	Typical range (15-35%), use of higher end. **(ACI)**
6	602 lb/yd^3- (25% Slag) Type A Water Reducer	Follows current MoDOT slag replacement limits
7	602 lb/yd^3- (50% Slag) Type A Water Reducer	No scaling found using 50%, Scaling observed when high slag contents >50% and high w/c ratios. **(ACI)**
8	602 lb/yd^3- (6% Silica Fume) Type A Water Reducer	Optimum content (6-8%), **NCHRP 410** (Note: MoDOT limit = 10%)
9	602 lb/yd^3- (15% FlyAsh & 25% Slag) Type A Water Reducer	Follows current MoDOT flyash & slag replacement limits, but in combination.
10	602 lb/yd^3- (15% FlyAsh & 6% Silica Fume) Type A Water Reducer	Follows current MoDOT flyash limit & optimum silica fume, but in combination.
11	602 lb/yd^3- (25% Slag & 6% Silica Fume) Type A Water Reducer	Follows current MoDOT slag limit & optimum silica fume, but in combination.

Table 2 – Description of Mix Designs

Specimens per Mix Design	Test Description	Specification Method
18 (3 per testing date)	3,7,14,28,56,90 Day Compressive Strength	AASHTO T22
5 (1 per testing date)	3,7,14,28,56 Day Modulus of Elasticity	ASTM C469
4	Freeze/Thaw Durability	AASHTO T161
4	Salt Scale Resistance	ASTM C672
9	Rapid Chloride Permeability	AASHTO T277
6	90-Day Ponding Test	AASHTO T259
1	Cracking Tendency of Concrete (Ring Test)	Under Development
1	Plastic Shrinkage Crack Test (New York Test)	Under Development
2	Autoclave expansion	ASTM C151
2	Dry shrinkage of Mortar	ASTM C596

Table 3 – Strength, Durability, and Shrinkage Tests

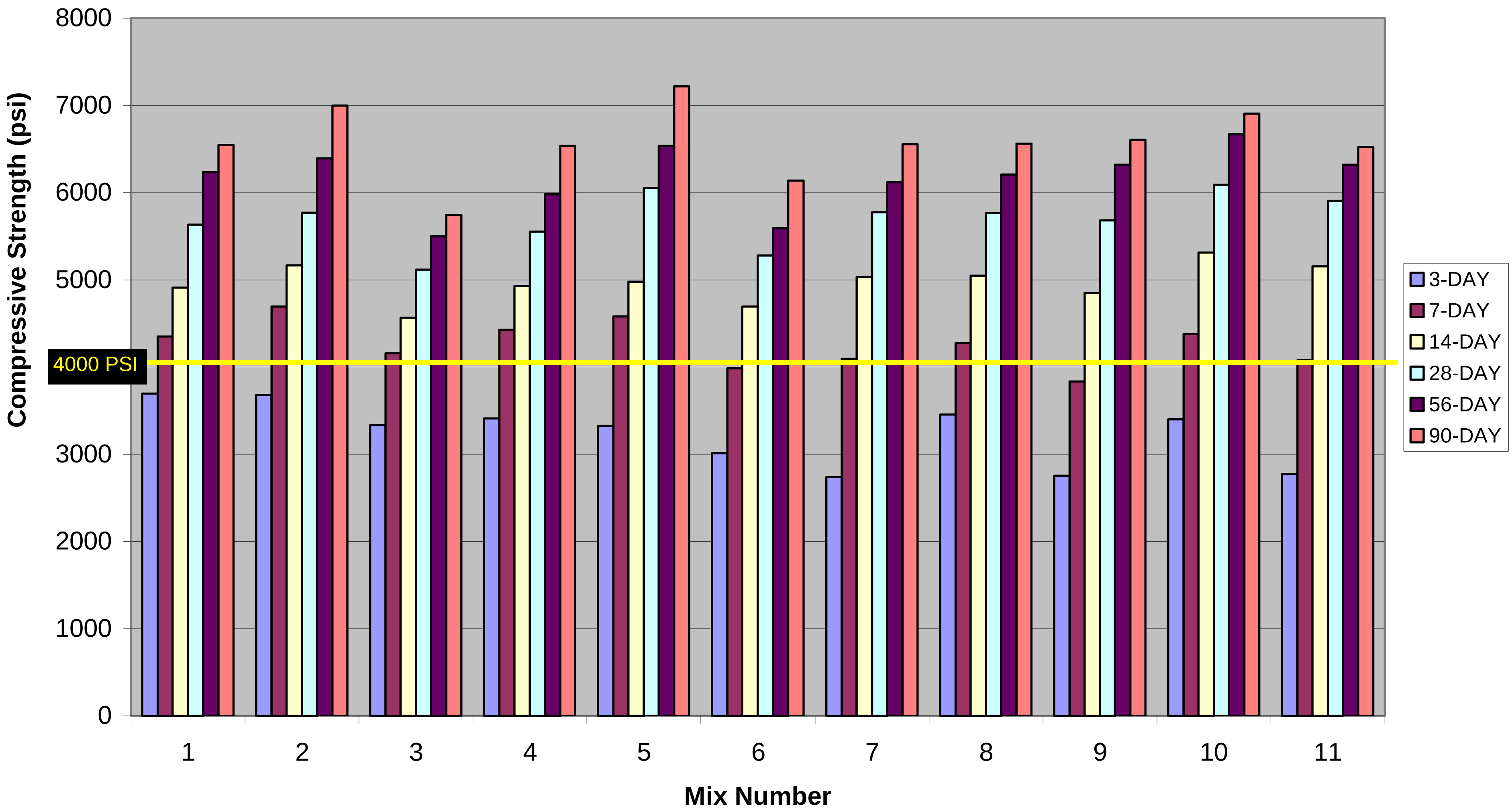
Mix No.	Mix Description	Cementitious Content (sacks/yd^3)	Avg. w/c ratio	Avg. Slump (in)	Avg. Air (%)
1	Control	7.74	.389	3.50	6.3
2	Control (15% Flyash)	7.74	.369	3.63	6.2
3	No Supplementary Cemetitious Materials	6.40	.412	3.40	6.4
4	15% Flyash	6.40	.390	3.25	6.0
5	35% Flyash	6.40	.370	3.20	5.9
6	25% GGBFS	6.40	.412	3.15	6.1
7	50% GGBFS	6.40	.420	3.70	5.6
8	6% Silica Fume (SF)	6.40	.428	4.05	6.0
9	15% Flyash, 25% GGBFS	6.40	.398	4.13	6.4
10	15% Flyash, 6% SF	6.40	.420	3.55	5.8
11	25% GGBFS, 6% SF	6.40	.442	3.85	5.8

Table 4 – Fresh Concrete Characteristics

Mix No.	Mix Description	Avg. 3-Day Compressive Strength (psi)	Avg. 7-Day Compressive Strength (psi)	Avg. 14-Day Compressive Strength (psi)	Avg. 28-Day Compressive Strength (psi)	Avg. 56-Day Compressive Strength (psi)	Avg. 90-Day Compressive Strength (psi)
1	Control	3690	4350	4910	5630	6260	6540
2	Control (15% Flyash)	3680	4700	5170	5770	6400	7000
3	No Supplementary Cemetitious Materials	3330	4160	4570	5120	5450	5740
4	15% Flyash	3410	4430	4930	5550	5980	6530
5	35% Flyash	3330	4580	4980	5990	6620	7220
6	25% GGBFS	3010	3990	4700	5320	5690	6140
7	50% GGBFS	2740	4090	5030	5840	6270	6560
8	6% Silica Fume (SF)	3460	4270	5050	5750	6210	6560
9	15% Flyash, 25% GGBFS	2750	3830	4850	5670	6280	6600
10	15% Flyash, 6% SF	3400	4380	5310	6120	6570	6900
11	25% GGBFS, 6% SF	2770	4080	5150	5920	6270	6520

Table 5– Compressive Strengths

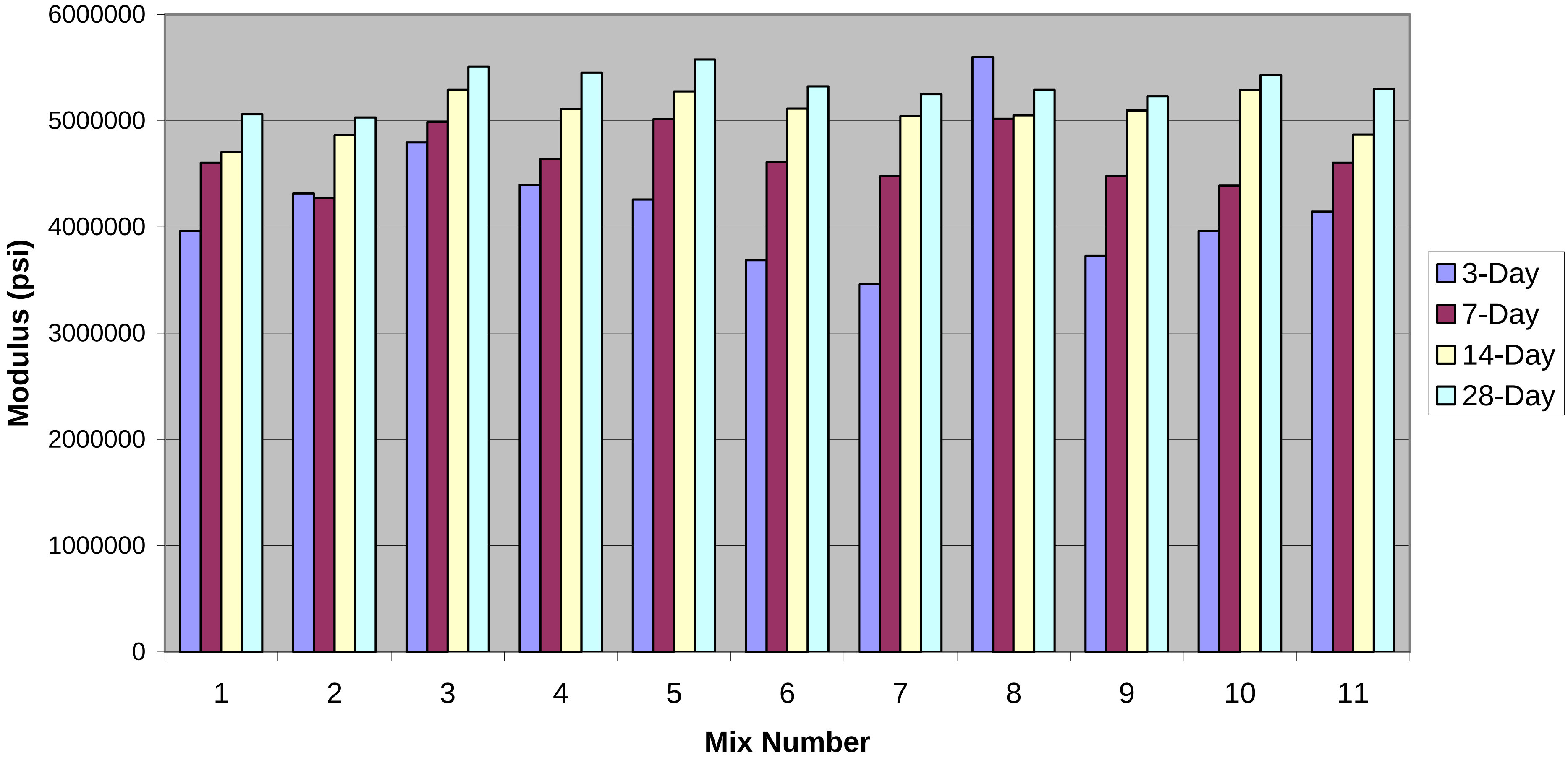
Figure 1 - Compressive Strength



Mix No.	Mix Description	Avg. 3-Day Modulus (psi)	Avg. 7-Day Modulus (psi)	Avg. 14-Day Modulus (psi)	Avg. 28-Day Modulus (psi)	Avg. 56-Day Modulus (psi)
1	Control	3,960,000	4,604,000	4,701,000	5,060,000	5,017,000
2	Control (15% Flyash)	4,320,000	4,272,000	4,864,000	5,031,000	5,256,000
3	No Supplementary Cemetitious Materials	4,795,000	4,987,000	5,290,000	5,508,000	5,542,000
4	15% Flyash	4,397,000	4,640,000	5,110,000	5,453,000	5,551,000
5	35% Flyash	4,265,000	5,015,000	5,274,000	5,575,000	5,863,000
6	25% GGBFS	3,688,000	4,609,000	5,114,000	5,323,000	5,269,000
7	50% GGBFS	3,459,000	4,480,000	5,043,000	5,249,000	5,454,000
8	6% Silica Fume (SF)	5,598,000	5,019,000	5,051,000	5,291,000	5,518,000
9	15% Flyash, 25% GGBFS	3,727,000	4,480,000	5,096,000	5,229,000	5,563,000
10	15% Flyash, 6% SF	3,962,000	4,389,000	5,288,000	5,430,000	5,551,000
11	25% GGBFS, 6% SF	4,145,000	4,603,000	4,868,000	5,298,000	5,354,000

Table 6 – Modulus of Elasticity

Figure 2 - Static Modulus



Mix No.	Mix Description	Avg. Freeze/Thaw Durability
1	Control	97
2	Control (15% Flyash)	97
3	No Supplementary Cemetitious Materials	97
4	15% Flyash	96
5	35% Flyash	96
6	25% GGBFS	97
7	50% GGBFS	95
8	6% Silica Fume (SF)	94
9	15% Flyash, 25% GGBFS	96
10	15% Flyash, 6% SF	92
11	25% GGBFS, 6% SF	93

Table 7 – Freeze/Thaw Results

Mix No.	Mix Description	1st Trial		2nd Trial	
		Specimen 1 Salt Scale Rating (0-5)	Specimen 2 Salt Scale Rating (0-5)	Specimen 3 Salt Scale Rating (0-5)	Specimen 4 Salt Scale Rating (0-5)
1	Control	0	1	0	1
2	Control (15% Flyash)	0	0	1	0
3	No Supplementary Cemetitious Materials	1	0	2	1
4	15% Flyash	1	1	2	2
5	35% Flyash	1	2	2	1
6	25% GGBFS	1	1	1	2
7	50% GGBFS	1	2	*	2
8	6% Silica Fume (SF)	2	1	1	1
9	15% Flyash, 25% GGBFS	1	2	1	2
10	15% Flyash, 6% SF	2	1	1	1
11	25% GGBFS, 6% SF	2	1	1	1

Table 8 – Salt Scaling Results

***Specimen taken out of test**

Figure 3 – Salt Scale Rating (0)

Figure 4 – Salt Scale Rating (1)

Figure 5 – Salt Scale Rating (2)

Mix Identification		Average Chloride Permeability		
Mix No.	Mix Description	Avg. 28-Day Chloride Permeability (Coulombs)	Avg. 56-Day Chloride Permeability (Coulombs)	Avg. 90-Day Chloride Permeability (Coulombs)
1	Control	**3458**	**2547**	**2387**
2	Control (15% Flyash)	**2996**	**1898**	**1614**
3	No Supplementary Cemetitious Materials	**2760**	**2439**	**2282**
4	15% Flyash	**2855**	**2172**	**1747**
5	35% Flyash	**2516**	**1391**	**959**
6	25% GGBFS	**2567**	**1836**	**1845**
7	50% GGBFS	**1256**	**886**	**865**
8	6% Silica Fume (SF)	**1390**	**1033**	**992**
9	15% Flyash, 25% GGBFS	**1825**	**1111**	**1143**
10	15% Flyash, 6% SF	**1274**	**693**	**539**
11	25% GGBFS, 6% SF	**913**	**551**	**524**

Table 9 – Average Chloride Permeability

Figure 6 - Chloride Permeability Results

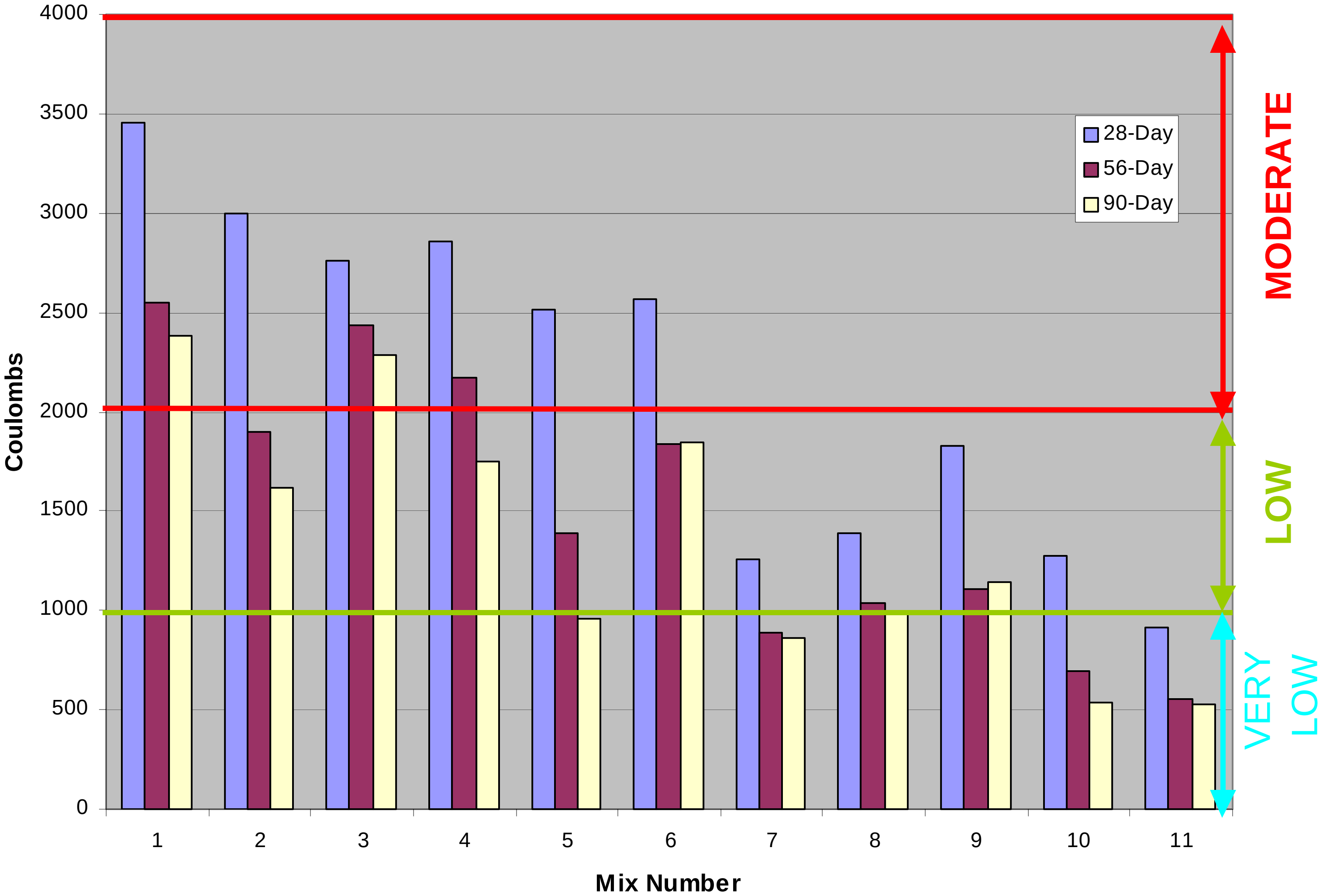
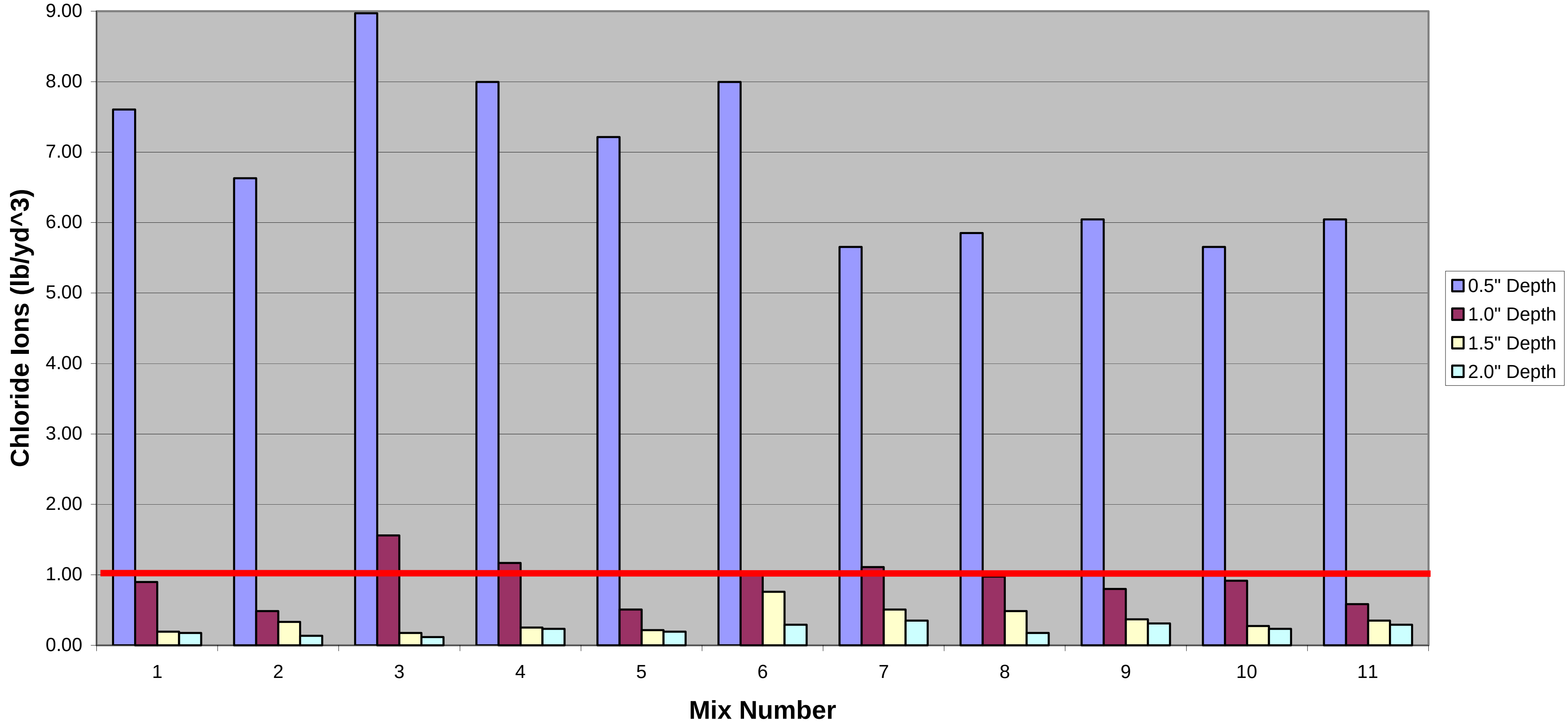


Figure 7 - 90-Day Ponding Results



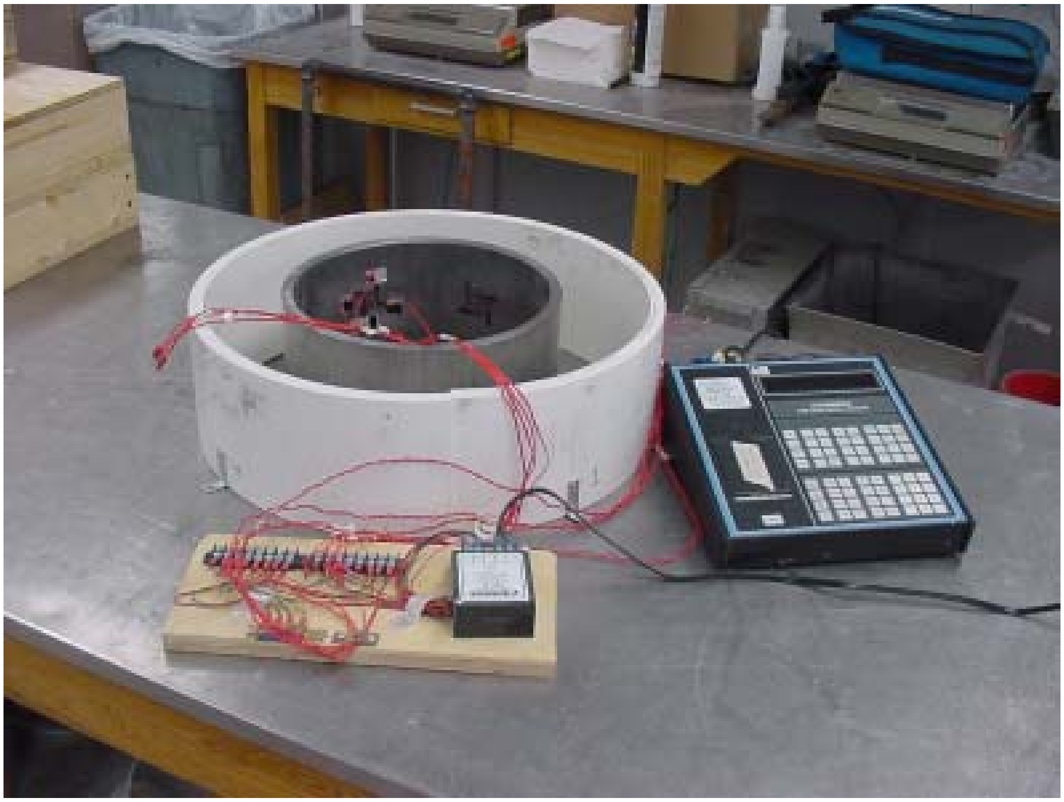


Figure 8 – Cracking Tendency Test

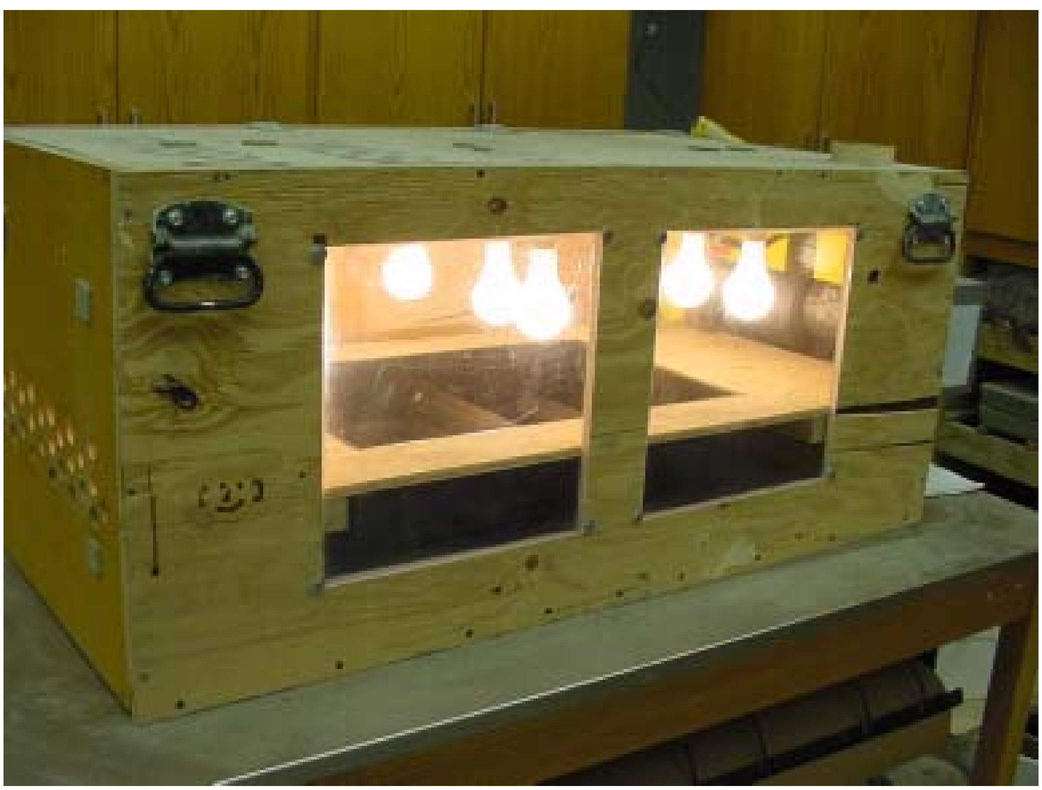


Figure 9 – Slab Cracking Test

Mix No.	Mix Description	Autoclave Expansion (%)
1	Control	**.04**
2	Control (15% Flyash)	**.04**
3	No Supplementary Cemetitious Materials	**.04**
4	15% Flyash	**.04**
5	35% Flyash	**.02**
6	25% GGBFS	**.02**
7	50% GGBFS	**.01**
8	6% Silica Fume (SF)	**.04**
9	15% Flyash, 25% GGBFS	**.03**
10	15% Flyash, 6% SF	**.03**
11	25% GGBFS, 6% SF	**.02**

Table 10 – Autoclave Expansion

Mix No.	Mix Description	Shrinkage (%)
1	Control	**.087**
2	Control (15% Flyash)	**.089**
3	No Supplementary Cemetitious Materials	**.090**
4	15% Flyash	**.083**
5	35% Flyash	**.077**
6	25% GGBFS	**.106**
7	50% GGBFS	**.111**
8	6% Silica Fume (SF)	**.096**
9	15% Flyash, 25% GGBFS	**.097**
10	15% Flyash, 6% SF	**.094**
11	25% GGBFS, 6% SF	**.112**

Table 11 – Shrinkage of Mortar Bars

Cementitious Material	Price ($/ton)	Price ($/lb.)
Type 1 Cement	$83	$0.0415
Class C Flyash	$22	$0.0110
GGBFS	$60	$0.0300
Silica Fume	$800	$0.4000
Type A Water Reducer	$5.50	per gallon

Table 12 - Cementitious Estimates

Mix Number	Type 1 Cement lb/yd^3	Class C Flyash lb/yd^3	GGBFS lb/yd^3	Silica Fume lb/yd^3	Type A WR gal/yd^3	Total $/yd^3
Mix 1	728	0	0	0	0	**$30.21**
Mix 2	620	108	0	0	0	$26.92
Mix 3	602	0	0	0	0.4	$27.18
Mix 4	512	90	0	0	0.4	$24.44
Mix 5	391	211	0	0	0.4	**$20.75**
Mix 6	452	0	150	0	0.4	$25.46
Mix 7	301	0	301	0	0.4	$23.72
Mix 8	566	0	0	36	0.4	**$40.09**
Mix 9	362	90	150	0	0.4	$22.71
Mix 10	476	90	0	36	0.4	$37.34
Mix 11	416	0	150	36	0.4	$38.36

Table 13 - Mix Design Estimates

Mix No.	Mix Description	Advantages*	Disadvantages
1	Control	Excellent Finishability Excellent Scaling Resistance	High Drying Shrinkage Potential Higher Chloride Permeability Higher Early Modulus Higher Cost
2	Control (15% Flyash)	Excellent Finishability Excellent Scaling Resistance Low chloride permeability	Higher Shrinkage Potential Higher Early Modulus
3	No Supplementary Cemetitious Materials	Good Finishability	Lower Salt Scale Resistance Higher Chloride Permeability Higher Early Modulus
4	15% Flyash	Good Finishability Lower Thermal Stresses Low Chloride Permeability	Lower Salt Scale Resistance Higher Early Modulus
5	35% Flyash	Good Finishability Lower Thermal Stresses Very Low Chloride Permeability Lower Cost	Lower Salt Scale Resistance Potential for Incompatibility Higher Early Modulus
6	25% GGBFS	Good Finishability Lower Thermal Stresses Low Chloride Permeability Lower Early Modulus	Lower Salt Scale Resistance
7	50% GGBFS	Good Finishability Lower Thermal Stresses Very Low Chloride Permeability Lower Early Modulus Lower Costs	Lower Salt Scale Resistance
8	6% Silica Fume (SF)	Very Low Chloride Permeability	Harder to finish Higher Plastic Drying Shrinkage Potential Lower Salt Scale Resistance Higher Early Modulus Higher Cost
9	15% Flyash, 25% GGBFS	Good Finishability Lower Thermal Stresses Low Chloride Permeability Lower Early Modulus Lower Cost	Lower Salt Scale Resistance
10	15% Flyash, 6% SF	Lower Thermal Stresses Very Low Chloride Permeability	Harder to finish Lower Salt Scale Resistance Higher Early Modulus Higher Costs
11	25% GGBFS, 6% SF	Lower Thermal Stresses Very Low Chloride Permeability	Harder to finish Lower Salt Scale Resistance Higher Early Modulus Higher Costs

Table 14 – Summary of Mix Performance

*** All mix designs had good strength and freeze/thaw durability characteristics that were comparable to each other.**

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APPENDIX A
WORKPLAN

RESEARCH WORK PLAN

***Date:* 11/19/01**

***Project Number:* RI01-044**

LABORATORY TESTING OF PCC BRIDGE DECK MIXES

Research Agency: **Missouri Department of Transportation**
Research, Development, and Technology

Principal Investigator: **Jason Blomberg, Senior R&D Assistant**

Objective:
The objective of this investigation is to develop and test different PCC mix designs for MoDOT bridge decks to minimize shrinkage cracking while maintaining other performance and workability characteristics. Less shrinkage cracking would increase the life and performance of bridge decks.

Background and Significance of Work:
Early shrinkage cracking is the primary problem with newly constructed bridge decks in Missouri. This research is needed to do develop a PCC mix that mitigates early shrinkage cracking under normal curing conditions and provides the needed strength, durability, and workability requirements.

Action Plan

Obtaining and testing materials
Fine and coarse aggregate sources, cementitious material sources, and admixture sources will be selected and tested for a variety of material characteristics.

Trial mixing
Trial mixing will be necessary to establish desirable mixes that meet air content and consistency (slump) requirements. Different combinations of cement/flyash/slag and water reducer dosages will be used.

Concrete batching
After the mix designs have been verified, concrete batching will be conducted. Concrete test specimens will be fabricated to measure the characteristics of each mix design.

Specimen testing
Concrete specimens will be cured and tested according to the applicable specifications. The specimens from each mix design will be evaluated and compared for strength, durability, and shrinkage characteristics.

Final report
Results from the laboratory test will be summarized in a report and presented to the bridge deck cracking quick action team and management.

Literature Search
A literature search was conducted by the author and by the task force and will be included in the final report.

Method of Implementation
The bridge deck quick action team will review the findings from this investigation and propose new guidelines for MoDOT PCC bridge deck mixes.

Anticipated Benefits
The changes made to the concrete bridge deck design are proposed to mitigate early cracking observed in MoDOT bridge decks. Less cracking will decrease the rate of deterioration and increase the life of the bridge. Also, the bridge mix proposed has less cement, which should mean a less expensive mix and more friendly to the environment.

Research Period
The research will commence in November 2001 and is estimated to be completed by October 2002.

Funding
This project will be funded by SPR funds.

Laboratory Study Procedure:
The source/manufacturer and description of the materials that will be used for the laboratory study are as follows:

Coarse Aggregate:	Capital Quarries, Holts Summit 1A Gradation D Limestone Cedar Valley, Ledges 1-3
Fine Aggregate:	Capital Sand #1, Jefferson City Missouri River Sand, Class A
Cement:	Continental Cement J.C. River Terminal Type 1 Cement
Flyash:	Mineral Resouce Labadie Class C
Slag (GGBFS):	Lonestar St. Louis Teminal

Silica Fume: Elchem

Air Agent: Grace – Darair 1400

Water Reducer: Grace – Daracem 65

November - December:

Testing materials

After obtaining all materials for mixing, they will be tested for material characteristics as follows:

- Coarse and fine aggregate will be tested for specific gravity and absorption characteristics and gradation.
- All cementitious materials and concrete additives will undergo a chemical analysis. Specific gravity of each material will also be determined.

Trial batching

After completed testing, trial batching will commence. Ten different concrete mix designs will be developed for testing. The proposed mix designs are given in Appendix A. Table 1 describes the combination of cementitious materials of each mix design. Mixes 1 and 2 are current bridge deck mixes that MoDOT uses. Mix 3 has a lower cement content, and contains no pozzolan replacements. This mix will be used to compare other mixes of lower cement contents with different pozzolan additives. Mixes 4 – 11 will replace a percentage of Type 1 Portland cement (602 lb/yd^3) with a pozzolan. Trial batching will be performed for each mix design to ensure the air content and slumps are within appropriate limits.

Mix No.	Cementitious Materials	Description/Reference
1	Control, 728 lb/yd^3- (No pozzolans)	Typical mix from current specifications
2	Control, 728 lb/yd^3- (15% FlyAsh)	Typical mix from current specifications
3	602 lb/yd^3 - (No pozzolans)	Decreased cement without pozzolans
4	602 lb/yd^3- (15% FlyAsh)	Follows current flyash replacement limits
5	602 lb/yd^3- (35% FlyAsh)	ACI - typical range (15-35), use of higher end.
6	602 lb/yd^3- (25% Slag)	Follows current slag replacement limits
7	602 lb/yd^3- (50% Slag)	ACI – (No scaling found using 50%, Scaling observed when high slag contents >50% and high w/c ratios.)
8	602 lb/yd^3- (6% Silica Fume)	Optimum content (6-8%), NCHRP 410
9	602 lb/yd^3- (15% FlyAsh & 25% Slag)	Follows current flyash & slag replacement limits
10	602 lb/yd^3-(15% FlyAsh & 6% Silica Fume)	Follows current flyash limit & optimum silica fume
11	602 lb/yd^3-(25% Slag & 6% Silica Fume)	Follows current slag limit & optimum silica fume

Table 1 – Cementitious

Jan – March

<u>Fresh and hardened concrete mix properties</u>

Each mix design will be tested for fresh and hardened concrete properties. Tables 2 and 3 lists the tests that will be performed on fresh concrete and on specimens fabricated from each mix design. Tests that require the most curing and testing time will have specimens fabricated first. An estimated time for curing and testing from fabrication for test specimens is given in Table 3.

Fresh Concrete Properties
Handling and Workability
• Slump – AASHTO T119 (Target Slump 3" – 6 ")
• Finishing characteristics – Laboratory observation
Design Characteristics
• Air Content – AASHTO T152
• Unit Weight – AATHTO T121
• Water/Cement Ratio – Laboratory determined

Table 2 – Fresh Concrete Properties

Hardened Concrete Properties	
Strength / Heat of Hydration	**Curing & Testing Time**
• Compressive Strength @ 3, 7, 14, 28, 56, 90 days – AASHTO T22	3 – 90 days
• Elastic Modulus @ 3, 7, 28, 56 days– ASTM	3 – 90 days
• Maturity Tests (Rate of Strength Gain) – ASTM	3 – 90 days
Permeability Tests	
• Rapid Chloride Permeability @ 28, 56, and 90 days – AASHTO T277	28 – 90 days
• 90-Day Ponding – AASHTO T259	120 days
Durability Tests	
• Freeze/Thaw Durability – AASHTO T161	106 days
• Salt Scaling Panels – ASTM C672	120 days
Resistance to Cracking	
• Plastic Shrinkage Cracks in Slabs - (Research Tests)	24-hours
• Ring Tests – (Research Tests)	28 - days
• Dry Shrinkage of Mortar Bars – ASTM C596 & ASTM C151	75- days

Table 3 – Concrete Testing

April – June

Durability testing will continue throughout this period. All strength and shrinkage cracking tests will be completed and documented.

July – October

Testing results of the different mixes will be completed. The mixes will be compared for cracking resistance, permeability, durability, and strength characteristics. A report will summarize the findings from the investigation.

Staffing

Laboratory Trial Mixing
Jason Blomberg, Int. R&D Assistant
Steve Clark, Int. R&D Tech.
Scott Breeding, Int. R&D Tech.

Laboratory Mixing
Jason Blomberg, Int. R&D Assist.
Steve Clark, Int. R&D Tech.
Scott Breeding, Int. R&D Tech.
Eric Burks, Sr. R&D Tech.

Permeability Testing
Scott Breeding, Int. R&D Tech

Compressive Strength Testing
1 Physical Lab Tech

Freeze/Thaw Durability
3 Physical Lab Techs

Maturity Testing
Jason Blomberg and Dave Amos, Sr. R&D Assistants

Shrinkage Testing
Jason Blomberg, Sr. R&D Assistant
2 – Chemical Lab Techs

Equipment

Air meter – RD&T inventory
Slump cone-RD&T inventory
Concrete Mixer & Supplies-RD&T, Phy. Lab inventory
Compression machine-Phy. Lab inventory
Freeze/Thaw machine-Phy. Lab inventory
Strain Gage Equipment – New Equipment
Concrete Rings – New Equipment
Permeability equipment-RD&T inventory
R&D Truck-RD&T inventory

BUDGET

Item	Quantity	Unit Cost ($/hr)	Hours	Subtotal
TRIAL MIXING				
Sr. R&D Assist	1	$23.18	160	$3,709
Inter. R&D Tech.	1	$15.20	160	$2,432
TEST MIXING				
Sr. R&D Assist	1	$23.18	320	$7,418
Inter. R&D Tech.	2	$15.20	320	$9,728
PHYSICAL LAB TESTING				
Lab Technician - Comp. Str.	1	$18.75	50	$938
Lab Technician - F/T	3	$18.75	50	$2,813
RESEARCH TESTING				
Sr. R&D Assist - Ring Test	1	$23.18	120	$2,782
Sr. R&D Assist - Shrink Test	1	$23.18	120	$2,782
Inter. R&D Tech. - RCP	1	$15.20	120	$1,824
CHEMICAL TESTING				
Lab Technician - Mortar Bars	2	$15.20	120	$3,648
MACHINIST LABOR	1	$16.71	80	$1,337
RESEARCH REPORT (2003 Program)				
Sr. R&D Assist	1	$23.18	300	$6,954
			Subtotal	$46,362
			Benefits	1.67
			Total Labor Cost	$77,425
EQUIPMENT COSTS				
Ring Molds	12	$50		$600
Strain Gage	1	$2,000		$2,000
		GRAND TOTAL COST		**$80,025**
		2002	Budget	68,000
		2003	Program	12,000

APPENDIX B
MIX DESIGN SHEETS

7.5 sack mix, 0Flyash **CONCRETE BATCHING PROGRAM** Mix No. 1

COARSE AGGREGATE: CEDAR VALLEY, CAPITAL QUARRY 1A, HOLT SUMMIT, LEDGES 1-3
GRADATION "D"

W/C Ratio: 0.389

	SP. GR.	LBS / CU. YD	DESIGN LBS/CU. YD	DESIGN AIR	ABSOLUTE VOLUME	SCALE WEIGHT (1.0 Ft^3)	SCALE WEIGHT 1.80 (Ft^3)	
CEMENT	3.15	728			0.1372	26.96	48.53	Lbs.(Cement)
Flyash	2.62	0			0.0000	0.00	0.00	lbs. (Flyash)
GGBFS	2.88	0			0.0000	0.00	0.00	lbs. (Slag)
Silicia Fume	2.24	0			0.0000	0.00	0.00	lbs.(Silicia Fume)
DESIGN WATER		728	283		0.1681	11.12	19.98	Lbs.(Water)
DESIGN AIR			4.38	6%	0.0600			
					0.3653			

MISSOURI RIVER - CAPITIAL SAND #1
SAND: % Sand= 38.0

SP. GR. (DRY)	DESIGN ABS. VOL.	ABSOLUTE VOLUME	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) 1.80 (FT^3)	SCALE WEIGHT (AIR DRY) 1.80 (FT^3)	
2.629	0.2412	0.2412	39.57	39.57	0.00	0.3	71.22	71.22	Lbs.(Sand)

COARSE AGGREGATE (AIR DRIED):

FRACTION	SP. GR. (DRY)	PERCENT CA FRACT.	DESIGN ABS. VOL.	ABSOLUTE VOLUME	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	SCALE WEIGHTS (AIR DRY) 1.80 (FT^3)	
1" - #4	2.647	100.0	0.3935	0.3935	0.00	0.8	65.00	65.00	117.00	
	2.647	100.0		0.3935	0.00	0.80	65.00	65.00	117.00	Lbs.(CA)

AIR METER:

	Run 1	Run 2
Reading =	6.6	6.6
Aggr.Corr =	0.3	0.3
%Air =	6.3	6.3

Slump = 3.50 in.

Assumed 65% Wate

WATER REDUCER:		AIR AGENT:	
0.000	OZ/100 LBS CEMENT	0.889	OZ/100 lb. cement
0.000	CC	12.760	CC
0.000	lbs. (water correction)	0.026	lbs. (water correction)

7.5 sack mix, 15% Flyash **CONCRETE BATCHING PROGRAM** Mix No. 2

COARSE AGGREGATE: CEDAR VALLEY, CAPITAL QUARRY 1A, HOLT SUMMIT, LEDGES 1-3
GRADATION "D"

W/C Ratio 0.369

	SP. GR.	LBS / CU. YD	DESIGN LBS/CU. YD	DESIGN AIR	ABSOLUTE VOLUME	SCALE WEIGHT (1.0 Ft^3)	SCALE WEIGHT 1.80 (Ft^3)	
CEMENT	3.15	620			0.1168	22.96	41.33	Lbs.(Cement)
Flyash	2.62	109			0.0247	4.04	7.27	lbs. (Flyash)
GGBFS	2.88	0			0.0000	0.00	0.00	lbs. (Slag)
Silicia Fume	2.24	0			0.0000	0.00	0.00	lbs.(Silicia Fume)
DESIGN WATER		729	269		0.1597	10.59	19.04	Lbs.(Water)
DESIGN AIR			4.16	6%	0.0600			
					0.3612			

MISSOURI RIVER - CAPITIAL SAND #1
SAND: % Sand= 38.0

SP. GR. (DRY)	DESIGN ABS. VOL.	ABSOLUTE VOLUME	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) 1.80 (FT^3)	SCALE WEIGHT (AIR DRY) 1.80 (FT^3)	
2.629	0.2428	0.2428	39.82	39.82	0.00	0.3	71.68	71.68	Lbs.(Sand)

COARSE AGGREGATE (AIR DRIED):

FRACTION	SP. GR. (DRY)	PERCENT CA FRACT.	DESIGN ABS. VOL.	ABSOLUTE VOLUME	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	SCALE WEIGHTS (AIR DRY) 1.80 (FT^3)	
1" - #4	2.647	100.0	0.3961	0.3961	0.00	0.8	65.42	65.42	117.76	
	2.647	100.0		0.3961	0.00	0.80	65.42	65.42	117.76	Lbs.(CA)

AIR METER:

	Run 1	Run 2
Reading =	6.5	6.5
Aggr.Corr =	0.3	0.3
%Air =	6.2	6.2

Slump = 3.63 in.

	WATER REDUCER:		AIR AGENT:	
	0.000	OZ/100 LBS CEMENT	0.880	OZ/100 lb. cement
Assumed	0.000	CC	12.648	CC
65% Wate	0.000	lbs. (water correction)	0.026	lbs. (water correction)

6.4 sack mix, 0 pozzolin **CONCRETE BATCHING PROGRAM** Mix No. 3

COARSE AGGREGATE: CEDAR VALLEY, CAPITAL QUARRY 1A, HOLT SUMMIT, LEDGES 1-3
GRADATION "D"

W/C Ratio: 0.412

	SP. GR.	LBS / CU. YD	DESIGN LBS/CU. YD	DESIGN AIR	ABSOLUTE VOLUME	SCALE WEIGHT (1.0 Ft^3)	SCALE WEIGHT 1.80	
CEMENT	3.15	601			0.1132	22.26	40.07	Lbs.(Cement)
Flyash	2.62	0			0.0000	0.00	0.00	lbs. (Flyash)
GGBFS	2.88	0			0.0000	0.00	0.00	lbs. (Slag)
Silicia Fume	2.24	0			0.0000	0.00	0.00	lbs.(Silicia Fume)
DESIGN WATER		601	247.61		0.1470	9.77	17.42	Lbs.(Water)
DESIGN AIR			4.64	6%	0.0600			
					0.3202			

MISSOURI RIVER - CAPITIAL SAND #1
SAND: % Sand= 38.0

SP. GR. (DRY)	DESIGN ABS. VOL.	ABSOLUTE VOLUME	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) 1.80 (FT^3)	SCALE WEIGHT (AIR DRY) 1.80 (FT^3)	
2.629	0.2583	0.2583	42.38	42.42	0.10	0.3	76.28	76.36	Lbs.(Sand)

COARSE AGGREGATE (AIR DRIED):

FRACTION	SP. GR. (DRY)	PERCENT CA FRACT.	DESIGN ABS. VOL.	ABSOLUTE VOLUME	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	SCALE WEIGHTS (AIR DRY) 1.80 (FT^3)	
1" - #4	2.647	100.0	0.4215	0.4215	0.05	0.8	69.62	69.65	125.37	
	2.647	100.0		0.4215	0.05	0.80	69.62	69.65	125.37	Lbs.(CA)

AIR METER:

	Run 1	Run 2
Reading =	6.6	6.6
Aggr.Corr =	0.3	0.3
%Air =	6.3	6.3

Slump = 3.40 in.

Assumed 65% Wate

WATER REDUCER:

8.000	OZ/100 LBS CEMENT
94.793	CC
0.136	lbs. (water correction)

AIR AGENT:

0.700	OZ/100 lb. cement
8.294	CC
0.017	lbs. (water correction)

15% Flyash **CONCRETE BATCHING PROGRAM** Mix No. 4

COARSE AGGREGATE: CEDAR VALLEY, CAPITAL QUARRY 1A, HOLT SUMMIT, LEDGES 1-3
GRADATION "D"

W/C Ratio 0.390

	SP. GR.	LBS / CU. YD	DESIGN LBS/CU. YD	DESIGN AIR	ABSOLUTE VOLUME	SCALE WEIGHT (1.0 Ft^3)	SCALE WEIGHT 1.80 (Ft^3)	
CEMENT	3.15	511			0.0963	18.93	34.07	Lbs.(Cement)
Flyash	2.62	90			0.0204	3.33	6.00	lbs. (Flyash)
GGBFS	2.88	0			0.0000	0.00	0.00	lbs. (Slag)
Silicia Fume	2.24	0			0.0000	0.00	0.00	lbs.(Silicia Fume)
DESIGN WATER		601	234		0.1391	9.28	16.55	Lbs.(Water)
DESIGN AIR			4.39	6%	0.0600			
					0.3158			

MISSOURI RIVER - CAPITIAL SAND #1
SAND: % Sand= 38.0

SP. GR. (DRY)	DESIGN ABS. VOL.	ABSOLUTE VOLUME	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) 1.80 (FT^3)	SCALE WEIGHT (AIR DRY) 1.80 (FT^3)	
2.629	0.2600	0.2600	42.65	42.70	0.10	0.3	76.77	76.85	Lbs.(Sand)

COARSE AGGREGATE (AIR DRIED):

FRACTION	SP. GR. (DRY)	PERCENT CA FRACT.	DESIGN ABS. VOL.	ABSOLUTE VOLUME	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	SCALE WEIGHTS (AIR DRY) 1.80 (FT^3)	
1" - #4	2.647	100.0	0.4242	0.4242	0.05	0.8	70.07	70.10	126.18	
	2.647	100.0		0.4242	0.05	0.80	70.07	70.10	126.18	Lbs.(CA)

AIR METER:

	Run 1	Run 2
Reading =	6.3	6.3
Aggr.Corr =	0.3	0.3
% Air =	6.0	6.0

Slump = 3.25 in.

	WATER REDUCER:		AIR AGENT:	
	8.000	OZ/100 LBS CEMENT	0.720	OZ/100 lb. cement
Assumed	94.793	CC	8.531	CC
65% Wate	0.136	lbs. (water correction)	0.017	lbs. (water correction)

35 % Flyash **CONCRETE BATCHING PROGRAM** Mix No. 5

COARSE AGGREGATE: CEDAR VALLEY, CAPITAL QUARRY 1A, HOLT SUMMIT, LEDGES 1-3
GRADATION "D"

W/C Ratio 0.370

	SP. GR.	LBS / CU. YD	DESIGN LBS/CU. YD	DESIGN AIR	ABSOLUTE VOLUME	SCALE WEIGHT (1.0 Ft^3)	SCALE WEIGHT 1.80 (Ft^3)	
CEMENT	3.15	391			0.0737	14.48	26.07	Lbs.(Cement)
Flyash	2.62	210			0.0477	7.80	14.03	lbs. (Flyash)
GGBFS	2.88	0			0.0000	0.00	0.00	lbs. (Slag)
Silicia Fume	2.24	0			0.0000	0.00	0.00	lbs.(Silicia Fume)
DESIGN WATER		601	223		0.1321	8.84	15.76	Lbs.(Water)
DESIGN AIR			4.17	6%	0.0600			
					0.3135			

MISSOURI RIVER - CAPITIAL SAND #1
SAND: % Sand= 38.0

SP. GR. (DRY)	DESIGN ABS. VOL.	ABSOLUTE VOLUME	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) 1.80 (FT^3)	SCALE WEIGHT (AIR DRY) 1.80 (FT^3)	
2.629	0.2609	0.2609	42.80	42.84	0.10	0.3	77.04	77.11	Lbs.(Sand)

COARSE AGGREGATE (AIR DRIED):

FRACTION	SP. GR. (DRY)	PERCENT CA FRACT.	DESIGN ABS. VOL.	ABSOLUTE VOLUME	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	SCALE WEIGHTS (AIR DRY) 1.80 (FT^3)	
1" - #4	2.647	100.0	0.4257	0.4257	0.05	0.8	70.31	70.34	126.62	
	2.647	100.0		0.4257	0.05	0.80	70.31	70.34	126.62	Lbs.(CA)

AIR METER:

	Run 1	Run 2
Reading =	6.2	6.2
Aggr.Corr =	0.3	0.3
% Air =	5.9	5.9

Slump = 3.20 in.

	WATER REDUCER:		AIR AGENT:	
	8.000	OZ/100 LBS CEMENT	0.750	OZ/100 lb. cement
Assumed	94.870	CC	8.894	CC
65% Wate	0.136	lbs. (water correction)	0.018	lbs. (water correction)

25 % Slag **CONCRETE BATCHING PROGRAM** Mix No. 6

COARSE AGGREGATE: CEDAR VALLEY, CAPITAL QUARRY 1A, HOLT SUMMIT, LEDGES 1-3
GRADATION "D"

W/C Ratio: 0.412

	SP. GR.	LBS / CU. YD	DESIGN LBS/CU. YD	DESIGN AIR	ABSOLUTE VOLUME	SCALE WEIGHT (1.0 Ft^3)	SCALE WEIGHT 1.80 (Ft^3)	
CEMENT	3.15	451			0.0849	16.69	30.05	Lbs.(Cement)
Flyash	2.62	0			0.0000	0.00	0.00	lbs. (Flyash)
GGBFS	2.88	150			0.0310	5.56	10.02	lbs. (Slag)
Silicia Fume	2.24	0			0.0000	0.00	0.00	lbs.(Silicia Fume)
DESIGN WATER		601	248		0.1470	9.76	17.42	Lbs.(Water)
DESIGN AIR			4.64	6%	0.0600			
					0.3229			

MISSOURI RIVER - CAPITAL SAND #1
SAND: % Sand= 38.0

SP. GR. (DRY)	DESIGN ABS. VOL.	ABSOLUTE VOLUME	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) 1.80 (FT^3)	SCALE WEIGHT (AIR DRY) 1.80 (FT^3)	
2.629	0.2573	0.2573	42.21	42.25	0.10	0.3	75.98	76.06	Lbs.(Sand)

COARSE AGGREGATE (AIR DRIED):

FRACTION	SP. GR. (DRY)	PERCENT CA FRACT.	DESIGN ABS. VOL.	ABSOLUTE VOLUME	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	SCALE WEIGHTS (AIR DRY) 1.80 (FT^3)	
1" - #4	2.647	100.0	0.4198	0.4198	0.05	0.8	69.34	69.38	124.88	
	2.647	100.0		0.4198	0.05	0.80	69.34	69.38	124.88	Lbs.(CA)

AIR METER:

	Run 1	Run 2
Reading =	6.4	6.4
Aggr.Corr =	0.3	0.3
% Air =	6.1	6.1

Slump = 3.15 in.

Assumed 65% Wate

WATER REDUCER:		AIR AGENT:	
8.000	OZ/100 LBS CEMENT	0.795	OZ/100 lb. cement
94.793	CC	9.420	CC
0.136	lbs. (water correction)	0.019	lbs. (water correction)

50 % Slag **CONCRETE BATCHING PROGRAM** Mix No. 7

COARSE AGGREGATE: CEDAR VALLEY, CAPITAL QUARRY 1A, HOLT SUMMIT, LEDGES 1-3
GRADATION "D"

W/C Ratio 0.420

	SP. GR.	LBS / CU. YD	DESIGN LBS/CU. YD	DESIGN AIR	ABSOLUTE VOLUME	SCALE WEIGHT (1.0 Ft^3)	SCALE WEIGHT 1.80 (Ft^3)	
CEMENT	3.15	301			0.0566	11.13	20.03	Lbs.(Cement)
Flyash	2.62	0			0.0000	0.00	0.00	lbs. (Flyash)
GGBFS	2.88	301			0.0619	11.13	20.03	lbs. (Slag)
Silicia Fume	2.24	0			0.0000	0.00	0.00	lbs.(Silicia Fume)
DESIGN WATER		601	252		0.1498	9.94	17.73	Lbs.(Water)
DESIGN AIR			4.73	6%	0.0600			
					0.3284			

MISSOURI RIVER - CAPITIAL SAND #1
SAND: % Sand= 38.0

SP. GR. (DRY)	DESIGN ABS. VOL.	ABSOLUTE VOLUME	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) 1.80 (FT^3)	SCALE WEIGHT (AIR DRY) 1.80 (FT^3)	
2.629	0.2552	0.2552	41.87	41.91	0.10	0.3	75.36	75.44	Lbs.(Sand)

COARSE AGGREGATE (AIR DRIED):

FRACTION	SP. GR. (DRY)	PERCENT CA FRACT.	DESIGN ABS. VOL.	ABSOLUTE VOLUME	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	SCALE WEIGHTS (AIR DRY) 1.80 (FT^3)	
1" - #4	2.647	100.0	0.4164	0.4164	0.05	0.8	68.78	68.81	123.86	
	2.647	100.0		0.4164	0.05	0.80	68.78	68.81	123.86	Lbs.(CA)

AIR METER:

	Run 1	Run 2
Reading =	5.9	5.9
Aggr.Corr =	0.3	0.3
% Air =	5.6	5.6

Slump = 3.70 in.

	WATER REDUCER:		AIR AGENT:	
	8.000	OZ/100 LBS CEMENT	0.910	OZ/100 lb. cement
Assumed	94.793	CC	10.783	CC
65% Wate	0.136	lbs. (water correction)	0.022	lbs. (water correction)

6 % Silicia Fume **CONCRETE BATCHING PROGRAM** Mix No. 8

COARSE AGGREGATE: CEDAR VALLEY, CAPITAL QUARRY 1A, HOLT SUMMIT, LEDGES 1-3
GRADATION "D"

W/C Ratio 0.428

	SP. GR.	LBS / CU. YD	DESIGN LBS/CU. YD	DESIGN AIR	ABSOLUTE VOLUME	SCALE WEIGHT (1.0 Ft^3)	SCALE WEIGHT 1.80 (Ft^3)	
CEMENT	3.15	565			0.1065	20.93	37.67	Lbs.(Cement)
Flyash	2.62	0			0.0000	0.00	0.00	lbs. (Flyash)
GGBFS	2.88	0			0.0000	0.00	0.00	lbs. (Slag)
Silicia Fume	2.24	36			0.0096	1.34	2.40	lbs.(Silicia Fume)
DESIGN WATER		601	257		0.1527	10.11	18.06	Lbs.(Water)
DESIGN AIR			4.82	6%	0.0600			
					0.3287			

MISSOURI RIVER - CAPITIAL SAND #1

SAND: % Sand= 38.0

SP. GR. (DRY)	DESIGN ABS. VOL.	ABSOLUTE VOLUME	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) 1.80 (FT^3)	SCALE WEIGHT (AIR DRY) 1.80 (FT^3)	
2.629	0.2551	0.2551	41.85	41.89	0.10	0.3	75.33	75.40	Lbs.(Sand)

COARSE AGGREGATE (AIR DRIED):

FRACTION	SP. GR. (DRY)	PERCENT CA FRACT.	DESIGN ABS. VOL.	ABSOLUTE VOLUME	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	SCALE WEIGHTS (AIR DRY) 1.80 (FT^3)	
1" - #4	2.647	100.0	0.4162	0.4162	0.05	0.8	68.75	68.78	123.80	
	2.647	100.0		0.4162	0.05	0.80	68.75	68.78	123.80	Lbs.(CA)

AIR METER:

	Run 1	Run 2
Reading =	6.3	6.3
Aggr.Corr =	0.3	0.3
% Air =	6.0	6.0

Slump = 4.05 in.

	WATER REDUCER:		AIR AGENT:	
	8.000	OZ/100 LBS CEMENT	0.560	OZ/100 lb. cement
Assumed	95	CC	6.6	CC
65% Wate	0.136	lbs. (water correction)	0.014	lbs. (water correction)

15% FlyAsh/25% Slag **CONCRETE BATCHING PROGRAM** Mix No. 9

COARSE AGGREGATE: CEDAR VALLEY, CAPITAL QUARRY 1A, HOLT SUMMIT, LEDGES 1-3
GRADATION "D"

W/C Ratio 0.398

	SP. GR.	LBS / CU. YD	DESIGN LBS/CU. YD	DESIGN AIR	ABSOLUTE VOLUME	SCALE WEIGHT (1.0 Ft^3)	SCALE WEIGHT 1.80 (Ft^3)	
CEMENT	3.15	361			0.0680	13.37	24.07	Lbs.(Cement)
Flyash	2.62	90			0.0204	3.33	6.00	lbs. (Flyash)
GGBFS	2.88	150			0.0309	5.56	10.00	lbs. (Slag)
Silicia Fume	2.24	0			0.0000	0.00	0.00	lbs.(Silicia Fume)
DESIGN WATER		601	239		0.1420	9.45	16.86	Lbs.(Water)
DESIGN AIR			4.48	6%	0.0600			
					0.3213			

MISSOURI RIVER - CAPITIAL SAND #1
SAND: % Sand= 38.0

SP. GR. (DRY)	DESIGN ABS. VOL.	ABSOLUTE VOLUME	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) 1.80 (FT^3)	SCALE WEIGHT (AIR DRY) 1.80 (FT^3)	
2.629	0.2579	0.2579	42.31	42.35	0.10	0.3	76.16	76.23	Lbs.(Sand)

COARSE AGGREGATE (AIR DRIED):

FRACTION	SP. GR. (DRY)	PERCENT CA FRACT.	DESIGN ABS. VOL.	ABSOLUTE VOLUME	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	SCALE WEIGHTS (AIR DRY) 1.80 (FT^3)	
1" - #4	2.647	100.0	0.4208	0.4208	0.05	0.8	69.50	69.54	125.17	
	2.647	100.0		0.4208	0.05	0.80	69.50	69.54	125.17	Lbs.(CA)

AIR METER:

	Run 1	Run 2
Reading =	6.7	6.7
Aggr.Corr =	0.3	0.3
% Air =	6.4	6.4

Slump = 4.13 in.

Assumed 65% Wate

WATER REDUCER:		AIR AGENT:	
8.000	OZ/100 LBS CEMENT	0.780	OZ/100 lb. cement
94.793	CC	9.242	CC
0.136	lbs. (water correction)	0.019	lbs. (water correction)

15 % Flyash/6 % SF **CONCRETE BATCHING PROGRAM** Mix No. 10

COARSE AGGREGATE: CEDAR VALLEY, CAPITAL QUARRY 1A, HOLT SUMMIT, LEDGES 1-3
GRADATION "D"

W/C Ratio 0.420

	SP. GR.	LBS / CU. YD	DESIGN LBS/CU. YD	DESIGN AIR	ABSOLUTE VOLUME	SCALE WEIGHT (1.0 Ft^3)	SCALE WEIGHT 1.80 (Ft^3)	
CEMENT	3.15	475			0.0895	17.59	31.67	Lbs.(Cement)
Flyash	2.62	90			0.0204	3.34	6.01	lbs. (Flyash)
GGBFS	2.88	0			0.0000	0.00	0.00	lbs. (Slag)
Silicia Fume	2.24	36			0.0096	1.34	2.41	lbs.(Silicia Fume)
DESIGN WATER		601	253		0.1499	9.94	17.74	Lbs.(Water)
DESIGN AIR			4.73	6%	0.0600			
					0.3294			

MISSOURI RIVER - CAPITIAL SAND #1
SAND: % Sand= 38.0

SP. GR. (DRY)	DESIGN ABS. VOL.	ABSOLUTE VOLUME	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) 1.80 (FT^3)	SCALE WEIGHT (AIR DRY) 1.80 (FT^3)	
2.629	0.2548	0.2548	41.81	41.85	0.10	0.3	75.25	75.33	Lbs.(Sand)

COARSE AGGREGATE (AIR DRIED):

FRACTION	SP. GR. (DRY)	PERCENT CA FRACT.	DESIGN ABS. VOL.	ABSOLUTE VOLUME	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	SCALE WEIGHTS (AIR DRY) 1.80 (FT^3)	
1" - #4	2.647	100.0	0.4158	0.4158	0.05	0.8	68.68	68.71	123.68	
	2.647	100.0		0.4158	0.05	0.80	68.68	68.71	123.68	Lbs.(CA)

AIR METER:

	Run 1	Run 2
Reading =	6.1	6.1
Aggr.Corr =	0.3	0.3
% Air =	5.8	5.8

Slump = 3.55 in.

	WATER REDUCER:		AIR AGENT:	
	8.000	OZ/100 LBS CEMENT	0.620	OZ/100 lb. cement
Assumed	94.832	CC	7.350	CC
65% Wate	0.136	lbs. (water correction)	0.015	lbs. (water correction)

25 % Slag/6 % SF **CONCRETE BATCHING PROGRAM** Mix No. 11

COARSE AGGREGATE: CEDAR VALLEY, CAPITAL QUARRY 1A, HOLT SUMMIT, LEDGES 1-3
GRADATION "D"

W/C Ratio 0.442

	SP. GR.	LBS / CU. YD	DESIGN LBS/CU. YD	DESIGN AIR	ABSOLUTE VOLUME	SCALE WEIGHT (1.0 Ft^3)	SCALE WEIGHT 1.80 (Ft^3)	
CEMENT	3.15	415			0.0782	15.37	27.67	Lbs.(Cement)
Flyash	2.62	0			0.0000	0.00	0.00	lbs. (Flyash)
GGBFS	2.88	150			0.0310	5.56	10.02	lbs. (Slag)
Silicia Fume	2.24	36			0.0096	1.34	2.41	lbs.(Silicia Fume)
DESIGN WATER		601	266		0.1578	10.42	18.61	Lbs.(Water)
DESIGN AIR			4.98	6%	0.0600			
					0.3365			

MISSOURI RIVER - CAPITIAL SAND #1
SAND: % Sand= 38.0

SP. GR. (DRY)	DESIGN ABS. VOL.	ABSOLUTE VOLUME	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) 1.80 (FT^3)	SCALE WEIGHT (AIR DRY) 1.80 (FT^3)	
2.629	0.2521	0.2521	41.36	41.40	0.10	0.3	74.45	74.53	Lbs.(Sand)

COARSE AGGREGATE (AIR DRIED):

FRACTION	SP. GR. (DRY)	PERCENT CA FRACT.	DESIGN ABS. VOL.	ABSOLUTE VOLUME	PERCENT MOIST.	PERCENT ABSORP.	WEIGHT (DRY) (1.0 FT^3)	WEIGHT (AIR DRY) (1.0 FT^3)	SCALE WEIGHTS (AIR DRY) 1.80 (FT^3)	
1" - #4	2.647	100.0	0.4114	0.4114	0.05	0.8	67.95	67.98	122.37	
	2.647	100.0		0.4114	0.05	0.80	67.95	67.98	122.37	Lbs.(CA)

AIR METER:

	Run 1	Run 2
Reading =	6.1	6.1
Aggr.Corr =	0.3	0.3
%Air =	5.8	5.8

Slump = 3.85 in.

	WATER REDUCER:		AIR AGENT:	
	8.000	OZ/100 LBS CEMENT	0.650	OZ/100 lb. cement
Assumed	94.848	CC	7.706	CC
65% Wate	0.136	lbs. (water correction)	0.016	lbs. (water correction)

APPENDIX C

COMPRESSIVE

STRENGTH RESULTS

COMPRESSIVE STRENGTH RESULTS

Mix 1- 7.5 sacks/yd^3				**Portland**						**3-DAY**	**7-DAY**	**14-DAY**	**28-DAY**	**56-DAY**	**90-DAY**
	Cementitious			**Cement**	**WR**	**Air Agent**	**W/C**	**Slump**							
SM Number	**Materials**			**(lb/yd^3)**	**(oz./yd^3)**	**(oz./yd^3)**	**Ratio**	**(in)**	**Air (%)**						
2RJ5B128	728			728	0.0	7.4	0.390	3.50	5.7	3910	4500	5230	5870	6300	6700
2RJ5B161	728			728	0.0	7.4	0.390	3.50	6.2	3800	4080	5380	5450	6370	6540
2RJ5B276	728			728	0.0	7.2	0.390	3.00	6.7	3370	4230	4640	5320	6220	6390
Modulus	728			728	0.0	6.5	0.387	4.25	6.6		4590	4390	5648	6144	
Extra	728			728	0.0	7.4	0.390	3.25	6.5				5620	6150	
Extra	728			728	0.0	6.5	0.387	3.50	6.3				5890		
AVERAGE				**7.74**	sk/yd^3		0.389	3.50	6.3	**3693**	**4350**	**4910**	**5633**	**6237**	**6543**
								Std. Deviation		285	236	471	225	98	155
Mix 2- 7.5 sk/yd^3, 15% Flyash			**15%**	**Portland**						**3-DAY**	**7-DAY**	**14-DAY**	**28-DAY**	**56-DAY**	**90-DAY**
	Cementitious		**Flyash**	**Cement**	**WR**	**Air Agent**	**W/C**	**Slump**							
SM Number	**Materials**		**(lb/yd^3)**	**(lb/yd^3)**	**(oz./yd^3)**	**(oz./yd^3)**	**Ratio**	**(in)**	**Air (%)**						
2RJ5B131	728		109	620	0.0	7.3	0.370	2.50	5.7	4100	4780	5660	6150	6550	7050
2RJ5B163	728		109	620	0.0	6.9	0.370	3.50	6.0	3590	4720	5250	5860	6190	6770
2RJ5B278	728		109	620	0.0	6.9	0.370	3.50	6.2	3330	4790	4880	5730	6350	7170
Modulus	728		109	620	0.0	6.6	0.365	4.25	6.7	3705	4488	4870	5490	6374	
Extra	728		109	620	0.0	6.9	0.370	4.00	6.1				5590	6500	
Extra	728		109	620	0.0	6.9	0.370	4.00	6.2				5800		
AVERAGE							0.369	3.63	6.2	**3681**	**4695**	**5165**	**5770**	**6393**	**6997**
								Std. Deviation		320	141	374	231	141	205
Mix 3- 6.4 sacks/yd^3				**Portland**						**3-DAY**	**7-DAY**	**14-DAY**	**28-DAY**	**56-DAY**	**90-DAY**
	Cementitious			**Cement**	**WR**	**Air Agent**	**W/C**	**Slump**							
SM Number	**Materials**			**(lb/yd^3)**	**(oz./yd^3)**	**(oz./yd^3)**	**Ratio**	**(in)**	**Air (%)**						
2RJ5B134	601			601	48.1	4.5	0.410	2.75	5.7	3410	4430	4790	5200	5680	5840
2RJ5B200	601			601	48.1	4.5	0.412	3.75	6.7	3310	4080	4450	5000	5350	5630
2RJ5B280	601			601	48.1	4.4	0.412	4.25	6.9	3130	3860	4410	4930	5340	5760
Modulus	601			601	48.1	4.2	0.400	3.00	5.7	3470	4250	4614	5340	5702	
Extra	601			601	48.1	4.5	0.412	3.25	6.9				5110	5430	
AVERAGE							0.409	3.40	6.4	**3330**	**4155**	**4566**	**5116**	**5500**	**5743**
								Std. Deviation		149	243	173	162	178	106

COMPRESSIVE STRENGTH RESULTS

Mix 4- 15% Flyash SM Number	Cementitious Materials		15% Flyash (lb/yd^3)	Portland Cement (lb/yd^3)	WR (oz./yd^3)	Air Agent (oz./yd^3)	W/C Ratio	Slump (in)	Air (%)	3-DAY	7-DAY	14-DAY	28-DAY	56-DAY	90-DAY
2RJ5B137	601		90	511	48.1	4.5	0.390	3.50	6.1	3630	4430	4740	5550	5830	6350
2RJ5B202	601		90	511	48.1	4.5	0.390	3.50	6.1	3340	4420	4880	5180	5920	6400
2RJ5B282	601		90	511	48.1	4.3	0.390	2.50	5.2	3330	4530	5320	5980	6140	6850
Modulus	601		90	511	48.1	4.3	0.390	3.75	6.3	3350	4330	4780	5530	5984	
Extra	601		90	511	48.1	4.5	0.390	3.00	6.5				5520	6020	
AVERAGE							0.390	3.25	6.0	**3413**	**4428**	**4930**	**5552**	**5979**	**6533**
								Std. Deviation		145	82	267	284	115	275

Mix 5- 35% Flyash SM Number	Cementitious Materials		35% Flyash (lb/yd^3)	Portland Cement (lb/yd^3)	WR (oz./yd^3)	Air Agent (oz./yd^3)	W/C Ratio	Slump (in)	Air (%)	3-DAY	7-DAY	14-DAY	28-DAY	56-DAY	90-DAY
2RJ5B140	601		210	391	48.1	4.5	0.370	3.25	5.4	3390	4490	5350	5840	6460	7420
2RJ5B204	601		210	391	48.1	4.5	0.370	3.00	6.2	2850	4500	4860	5600	6190	6960
2RJ5B283	601		210	391	48.1	4.5	0.370	2.75	6.0	3740	4640	5050	6090	6570	7270
Modulus	601		210	391	48.1	4.5	0.370	4.25	6.2	3320	4690	4660	6316	6211	
Extra	601		210	391	48.1	4.5	0.370	2.75	5.7				6430	7250	
AVERAGE							0.370	3.20	5.9	**3325**	**4580**	**4980**	**6055**	**6536**	**7217**
								Std. Deviation		366	100	294	340	431	235

Mix 6- 25% Slag SM Number	Cementitious Materials		25% Slag (lb/yd^3)	Portland Cement (lb/yd^3)	WR (oz./yd^3)	Air Agent (oz./yd^3)	W/C Ratio	Slump (in)	Air (%)	3-DAY	7-DAY	14-DAY	28-DAY	56-DAY	90-DAY
2RJ5B143	601		150	451	48.1	4.9	0.415	3.00	6.0	3110	4220	4830	5540	5910	6380
2RJ5B206	601		150	451	48.1	4.9	0.415	3.75	6.1	2730	3960	4610	5100	5460	6060
2RJ5B284	601		150	451	48.1	4.8	0.410	3.00	6.4	3260	4020	4700	5220	5550	5980
Modulus	601		150	451	48.1	4.8	0.410	3.00	6.2	2948	3750	4640	5102	5192	
Extra	601		150	451	48.1	4.8	0.410	3.00	5.7				5430	5840	
AVERAGE							0.412	3.15	6.1	**3012**	**3988**	**4695**	**5278**	**5590**	**6140**
								Std. Deviation		227	193	97	199	292	212

COMPRESSIVE STRENGTH RESULTS

Mix 7- 50% Slag			50%	Portland						3-DAY	7-DAY	14-DAY	28-DAY	56-DAY	90-DAY
	Cementitious		Slag	Cement	WR	Air Agent	W/C	Slump							
SM Number	Materials		(lb/yd^3)	(lb/yd^3)	(oz./yd^3)	(oz./yd^3)	Ratio	(in)	Air (%)						
2RJ5B173	601		301	301	48.1	5.3	0.420	4.25	5.6	2700	4420	5040	5700	6070	6300
2RJ5B208	601		301	301	48.1	5.3	0.420	3.25	5.9	2340	3860	5080	5750	6160	6530
2RJ5B285	601		301	301	48.1	5.3	0.420	3.00	5.0	3520	4440	5200	6010	6580	6840
Modulus	601		301	301	48.1	5.5	0.420	4.50	6.1	2382	3650	4810	5534	5666	
Extra	601		301	301	48.1	5.3	0.420	3.50	5.4				5880		
AVERAGE							0.420	3.70	5.6	**2736**	**4093**	**5033**	**5775**	**6119**	**6557**
								Std. Deviation		547	399	163	181	375	271

Mix 8 - 6% Silica Fume			6%	Portland						3-DAY	7-DAY	14-DAY	28-DAY	56-DAY	90-DAY
	Cementitious		Silica	Cement	WR	Air Agent	W/C	Slump							
SM Number	Materials		Fume	(lb/yd^3)	(oz./yd^3)	(oz./yd^3)	Ratio	(in)	Air (%)						
2RJ5B175	601		36	565	48.1					3490	4230	5100	5490	6090	6280
2RJ5B210	601		36	565	48.1					3110	4230	5120	5550	6250	
2RJ5B286	601		36	565	48.1	3.5	0.430	3.75	5.9	3940	4170	5290	5940	6380	6900
2RJ5B302	601		36	565	48.1	3.5	0.430	4.50	6.2	3300	4080	4760	5520	6060	6440
2RJ5B304	601		36	565	48.1	3.5	0.425	4.00	6.1	3450	4360	5130	5810	6250	6620
Modulus	601		36	565	48.1	3.4	0.425	4.50	6.1	3440	4570	4890	5882		
Extra	601		36	565	48.1	3.5	0.430	3.50	5.5				6170		
AVERAGE							0.428	4.05	6.0	**3455**	**4273**	**5048**	**5766**	**6206**	**6560**
							Standard	**Std. Deviation**		276	172	190	256	131	266

Mix 9 - 15% Flyash, 25% Slag				Portland						3-DAY	7-DAY	14-DAY	28-DAY	56-DAY	90-DAY
	Cementitious	15%		Cement	WR	Air Agent	W/C	Slump							
SM Number	Materials	Flyash	25% Slag	(lb/yd^3)	(oz./yd^3)	(oz./yd^3)	Ratio	(in)	Air (%)						
2RJ5B177	601	90	150	361	48.1	4.8	0.400	4.00	6.7	2810	3610	4820	5500	6160	6530
2RJ5B212	601	90	150	361	48.1	4.8	0.400	4.50	7.0	2240	3600	4660	5330	6000	6320
2RJ5B287	601	90	150	361	48.1	4.6	0.400	5.00	6.8	3310	3890	4900	5500	6320	6530
2RJ5B306	601	90	150	361	48.1	4.6	0.395	3.75	5.4	2420	3820	5090	5800	6630	7030
Modulus	601	90	150	361	48.1	4.7	0.395	3.50	6.7	2970	4240	4770	5764	6476	
Extra	601	90	150	361	48.1	4.6	0.400	4.00	5.6				6200		
AVERAGE							0.398	4.13	6.4	**2750**	**3832**	**4848**	**5682**	**6317**	**6603**
								Std. Deviation		429	261	161	310	249	302

COMPRESSIVE STRENGTH RESULTS

Mix 10- 15% Flyash, 6% Silica Fume			6%	Portland						3-DAY	7-DAY	14-DAY	28-DAY	56-DAY	90-DAY
	Cementitious	15%	Silica	Cement	WR	Air Agent	W/C	Slump							
SM Number	Materials	Flyash	Fume	(lb/yd^3)	(oz./yd^3)	(oz./yd^3)	Ratio	(in)	Air (%)						
2RJ5B179	601	90	36	475	48.1	3.8	0.420	3.25	5.3	3540	4370	5400	6050	6570	6970
2RJ5B214	601	90	36	475	48.1	3.8	0.420	3.50	5.4	2890	4490	5220	5900	6560	6790
2RJ5B288	601	90	36	475	48.1	3.8	0.420	3.75	6.3	3850	4310	5110	6100	6580	6950
Modulus	601	90	36	475	48.1	3.7	0.420	4.50	6.6	3330	4350	5520	5990	6970	
Extra	601	90	36	475	48.1	3.8	0.420	2.75	5.4				6410		
AVERAGE							0.420	3.55	5.8	**3403**	**4380**	**5313**	**6090**	**6670**	**6903**
								Std. Deviation		403	77	183	194	200	99

Mix 11- 25% Slag, 6% Silicia Fume			6%	Portland						3-DAY	7-DAY	14-DAY	28-DAY	56-DAY	90-DAY
	Cementitious	25%	Silica	Cement	WR	Air Agent	W/C	Slump							
SM Number	Materials	Slag	Fume	(lb/yd^3)	(oz./yd^3)	(oz./yd^3)	Ratio	(in)	Air (%)						
2RJ5B181	601	150	36	415	48.1	4.0	0.445	4.50	5.8	2880	3830	5080	5440	6040	6480
2RJ5B215	601	150	36	415	48.1	4.0	0.445	4.50	6.1	2350	4020	5000	5960	6250	6310
2RJ5B289	601	150	36	415	48.1	4.0	0.445	3.5	5.9		4130	5230	6080	6520	6780
Modulus	601	150	36	415	48.1	3.8	0.43	3.75	5.6	3080	4330	5300	5870	6470	
Extra	601	150	36	415	48.1	4.0	0.445	3.00	5.7				6190		
AVERAGE							0.442	3.85	5.8	**2770**	**4078**	**5153**	**5908**	**6320**	**6523**
								Std. Deviation		377	209	137	288	220	238

APPENDIX D
FREEZE/THAW DURABILITY RESULTS

FREEZE/THAW DURABILITY					
MIX DESCRIPTION/SPECIMEN ID	**Durability Factor (%)**	**% Weight Change**	**MIX DESCRIPTION/SPECIMEN ID**	**Durability Factor (%)**	**% Weight Change**
MIX 1 - 7.5 sack, 0 Flyash			**MIX 6 - 6.4 sack, 25 % Slag**		
2RJ5B003	97.0	-0.082	2RJ5B033	96.3	-0.003
2RJ5B004	96.9	-0.130	2RJ5B034	96.7	0.020
2RJ5B068	97.1	-0.023	2RJ5B243	96.4	-0.040
2RJ5B069	96.3	-0.029	2RJ5B244	96.4	-0.028
2RJ5B218	96.5	-0.075	**AVG.**	**96.5**	**-0.013**
2RJ5B219	96.2	-0.080			
AVG.	**96.7**	**-0.070**	**MIX 7 - 6.4 sack, 50% Slag**		
			2RJ5B039	95.2	0.008
MIX 2 - 7.5 sack, 15% Flyash			2RJ5B040	95.4	0.003
2RJ5B009	97.6	-0.045	2RJ5B248	95.0	0.023
2RJ5B010	97.3	-0.038	2RJ5B249	95.2	0.072
2RJ5B223	96.3	-0.155	**AVG.**	**95.2**	**0.027**
2RJ5B224	94.9	-0.138			
AVG.	**96.5**	**-0.094**	**MIX 8 - 6.4 sack, 6% Silicia Fume**		
			2RJ5B045	94.3	0.036
MIX 3 - 6.4 sack, 0 Pozzilan			2RJ5B046	94.3	0.019
2RJ5B015	96.7	-0.073	2RJ5B254	94.0	0.218
2RJ5B016	97.7	-0.065	2RJ5B255	94.3	0.183
2RJ5B228	96.2	-0.124	**AVG.**	**94.2**	**0.114**
2RJ5B229	96.6	-0.126			
AVG.	**96.8**	**-0.097**	**MIX 9 - 6.4 sk,15%Flyash,25%Slag**		
			2RJ5B051	96.0	-0.062
MIX 4 - 6.4 sack,15% Flyash			2RJ5B052	95.4	-0.042
2RJ5B021	96.3	-0.074	2RJ5B260	95.8	0.007
2RJ5B022	97.8	-0.078	2RJ5B261	95.2	0.007
2RJ5B233	95.5	-0.186	**AVG.**	**95.6**	**-0.023**
2RJ5B234	95.9	-0.203			
AVG.	**96.4**	**-0.135**	**MIX 10 - 6.4 sk,15%Flyash,6%SF**		
			2RJ5B057	92.4	0.066
MIX 5 - 6.4 sack, 35% Flyash			2RJ5B058	93.5	0.037
2RJ5B027	96.2	-0.227	2RJ5B266	90.2	-0.040
2RJ5B028	95.1	-0.212	2RJ5B267	91.2	-0.021
2RJ5B238	95.8	-0.296	**AVG.**	**91.8**	**0.011**
2RJ5B239	95.1	-0.246			
AVG.	**95.6**	**-0.245**	**MIX 11 - 6.4 sk, 25%Slag,6%SF**		
			2RJ5B063	91.6	0.171
			2RJ5B064	92.0	0.090
			2RJ5B272	94.4	0.069
			2RJ5B273	92.5	0.098
			AVG.	**92.6**	**0.107**