Expanding the Informational Catalog of TDOT Lower Permeability Bridge Deck Mixtures

Final Report

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16. Abstract

Building on the success of RES 2011-09 Development of a TDOT Class D-LP (Lower Permeability) Concrete Mixture, a study was conducted to expand the Tennessee Department of Transportation (TDOT) informational catalog of concrete mixtures that have a high probability of meeting the proposed new 1,200 coulomb specification. Four examples of lower rapid chloride permeability (RCP) concrete mixture designs for Tennessee bridge decks were developed and tested. All materials used in the new lower RCP mixtures are widely available in Tennessee. The four mixtures were:

1. 5% silica fume and 25% Class C fly ash substitution for portland cement
2. 5% metakaolin and 25% Class C fly ash substitution for portland cement
3. 35% slag and 15% Class F fly ash substitution for portland cement
4. 3% metakaolin and 35% Class F fly ash substitution for portland cement

Eleven batches of each mixture were produced. The plastic and hardened properties of all batches of all mixtures met TDOT 604.03 Class D requirements. Further, the hardened properties of all mixtures were similar to, or superior to, a typical TDOT Class D mixture from RES 2010-07. The mean RCPs of all four mixtures were significantly lower than 1,200 coulombs at 56 days at the 5% significance level.

The authors further recommend that TDOT continue the development of an informational catalog that provides examples of concrete mixtures that have a high probability of meeting the proposed new specification. The catalog would not be a recipe book or a complete list of mixtures that could meet the specification, but would rather provide laboratory-tested ideas for experienced mixture designers attempting to produce concrete mixtures that meet the proposed new specification.

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CHAPTER 1 : INTRODUCTION

A key step for increasing bridge deck service life is to develop lower rapid chloride permeability (RCP) concrete mixtures. In RES 2010-07 Optimum Air Content Range (Plastic and Hardened) for TDOT Class D PCC, a typical Class D portland cement concrete (PCC) mixture was found to have an RCP value of about 1,540 coulombs (independent of air content) at 56 days, based on 100 samples tested. TDOT Materials and Tests (M&T) Division is currently considering developing a new lower permeability bridge deck concrete specification. In RES 2011-09, three new lower permeability concrete mixtures were developed to address the possible new lower permeability bridge deck concrete specification. The three lower permeability mixtures developed formed the initial portion of an informational catalog to support the possible new specification. However, no mixtures were developed that included Class C fly ash. Further, no mixtures were developed that contained both slag and fly ash. Building on RES 2011-09, additional lower permeability concrete mixtures will be developed that will make access to low permeability concrete for bridge decks easier, more economical, and, thus, more efficient.

Benefits to TDOT

Delaying chlorides from reaching the critical reinforcement in bridge decks will extend their service life and reduce costs to TDOT. Specifically:

1. Longer service life of bridge decks will lower their life cycle costs.
2. Less frequent need for maintenance / rehabilitation / reconstruction incursions into traffic will result in fewer traffic delays.

3. Less frequent need for maintenance / rehabilitation / reconstruction incursions into traffic will result in reduced risks for TDOT and contractor personnel, as well as the motoring public.

Purpose of the Research

The proposed project will develop four new lower permeability bridge deck concrete mixtures to make access to low permeability concrete for bridge decks easier, more economical, and, thus, more efficient. All materials used in the new lower permeability mixtures will be widely available in Tennessee. The additional example mixture designs would serve as further support for TDOT management implementing a newer lower permeability bridge deck concrete PCC specification.

CHAPTER 2 : LITERATURE REVIEW

Introduction

A new literature review was not a required task in the Catalog project since the current project builds directly on RES 2011-09 Development of a TDOT Class D-LP (Lower Permeability) Concrete Mixture. The literature review for RES 2011-09 is repeated below.

One of the key issues constantly facing transportation departments in the United States is the durability of bridge decks throughout the current and future infrastructure systems. The American Concrete Institute (ACI) defines durability of concrete as "its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration" (1). There are numerous aspects of a concrete mixture that can directly impact durability such as compressive strength, water-to-cement ratio (w/cm), permeability, shrinkage, thermal cracking, and many more (2). Specifically in bridge decks, however, the service life is closely related to the permeability of the concrete. The ease with which water and other substances can travel through the pore structure causes chemical reactions to occur which eventually weaken the structure internally. This happens most often in the form of chloride ion ingress, which causes corrosion on the reinforcing steel; this results in a volume expansion within the concrete and ultimately produces enough tensile stress to cause cracking, delamination, and spalling (3; 4). Because of the damage it can cause and the safety issues it presents, the ability of concrete to resist chloride penetration is an important topic of research within the community.

Supplementary Cementitious Materials

How to best combat chloride permeability in bridge decks is unsettled with different agencies throughout the country adopting different procedures. One of the main ways to decrease permeability of bridge decks comes in the form of adding supplementary cementing materials (SCM) to concrete mixes in lieu of portland cement (PC) (5). Three of the most predominant SCMs used are silica fume, metakaolin, and ground blasted furnace slag (GGBFS). Each of these materials has their advantages and disadvantages and corresponding research to support both.

Since its first application in Scandinavia in the 1970s, silica fume has been used in various states across the U.S., starting with an Ohio bridge overlay in 1984 (6). It is produced as a byproduct of silicon alloy production most commonly found in the steel, aluminum, and computer chip industries (4). One of the important characteristics of silica fume is its extremely small particle size; this property contributes to the densification of concrete's microstructure in that the silica fume particles can fill in the voids between the cement molecules (4). Not only do its physical characteristics play a role in concrete durability, but it also has chemical properties that make it an advantageous SCM in high performance concrete (HPC). Silica fume reacts with calcium hydroxide to form silica hydrate, increasing the binder material that improves hardened properties of concrete (4). As with any material, silica fume's advantages are met with challenges as well. This SCM significantly decreases bleeding, which means that water will not accumulate under the steel reinforcement and aggregate will be less likely to segregate; however, this lack of extra water in the concrete can lead to early drying of the surface and eventually to the formation of plastic shrinkage cracks (4). These benefits and challenges have served as starting points for research spurred on across the nation. From the review of prior research, silica fume appears to be the SCM predominantly used for controlling permeability in HPC.

Another popular SCM is GGBFS, a byproduct of the steel industry. It was first developed in Germany in approximately 1853 and has been used since the early 1900s as a cementitious material (7). It has high contents of silicates and is cooled quickly by means of water or air to form a glossy surface appearance that is eventually ground down to a similar state as PC. When GGBFS comes into contact with water in the concrete, it reacts chemically to produce calcium silica hydrate (C-S-H), contributing to its hardened durability (8; 9; 10). One of the main problems associated with large amounts of slag incorporated into concrete mixes is the possibility of salt scaling where the top layers of concrete flake off after repeated freeze-thaw cycles and exposure to harsh deicing salts (11).

Metakaolin is also another SCM used to achieve low permeability. Its use began in the 1960s in Brazil for dam construction in order to improve the concrete resistance to alkali-silica reactions (ASR); however, it also helps densify the microstructure of concrete and ultimately decreases its permeability (12). Unlike slag and silica fume, metakaolin is not a byproduct of industry. It is produced by heating kaolin, a natural aluminosilicous mineral, to extremely high temperatures; after doing so it becomes a highly reactive and consistent pozzolan (13). Small quantities of this SCM are needed in order to achieve higher compressive strength as well as lower permeability due to its relatively high degree of reactivity and large surface area. Just like the aforementioned pozzolans, metakaolin reacts with the calcium hydroxide produced during cement hydration to improve both hardened and plastic properties.

Silica Fume Research

One study was conducted to create optimal ternary blends of PC, fly ash, and silica fume (14). Three separate types of fly ash were used in conjunction with silica fume in an attempt to improve both plastic and hardened properties at two w/cm ratios of 0.34 and 0.40. The various mixes were not only compared to each other, but also to a control mix design that contained no fly ash and no silica fume. The authors found that even when the w/cm ratio or the type of fly ash used was altered the HPC drastically outperformed the control mix in permeability (14). It was concluded that 4% and 8% silica fume additions significantly decreased the permeability into the low and very low ranges, respectively, as per ASTM C 1202 (15). The lowest permeability at 28 days was 190 coulombs with a 28-day compressive strength of 48.9 MPa (7,092 psi); this was achieved using 8% silica fume, 40% fly ash from North Dakota, and a w/cm ratio of 0.34 (14).

The Colorado Department of Transportation sponsored a study that was intended to create new mix designs for bridge decks within the state that could resist cracking and chloride ion ingress (16). This research was broken into two phases in which trial mixtures were formulated that met qualifications needed for HPC and then the best performing of these mixes were trialed and edited to produce better field conditions. The final specimens were tested for compressive strength, permeability, drying shrinkage, and cracking resistance. The final mixes that were deemed "best" all had 4% silica fume; the permeability values at 28 days ranged from 2,747 to 4,657 coulombs and the 28-day compressive strength results ranged from 4,634 to 5,645 psi. This study concluded that class F ash results in lower permeability than class C ash, and that permeability was almost proportional to the w/cm ratio.

Following the collapse of the I35W bridge in Minneapolis, the consulting firm charged with designing its replacement decided to create a bridge that was not only aesthetically pleasing but also extremely durable (17). The mix for the bridge superstructure contained 25% fly ash and 4% silica fume as decreasing permeability was one of the main goals in this project. Samples taken from the placement had permeability values ranging from 90-150 coulombs at various ages after 28 days; compressive strength at 28 days averaged 8,000 psi, which was well over the specified 6,500 psi required.

A major study, fueled by many different state departments of transportation as well as large entities within the concrete industry, was undertaken at Iowa State University to develop optimal mix designs using portions of slag, silica fume, fly ash, metakaolin, and PC for HPC (18). A total of 12 control mixtures and 105 ternary mixtures were made with various combinations of the SCMs being evaluated. Although the mix design with the lowest permeability was a ternary mixture of cement, metakaolin, and GGBFS, all the mixes that included silica fume had permeability values under 2,000 coulombs with the lowest being 935 coulombs. Although all of the silica fume mixes met compressive strength requirements, it was noted that during the durability testing, these mixtures exhibited moderate to severe scaling after 5 freeze-thaw cycles. Further results of this study will be discussed in other parts of this report.

Despite its ability to drastically increase a concrete's resistance to ingress of solutions, silica fume also brings challenges, particularly to the curing process needed after placement to prevent drying and shrinkage cracking (4; 19). The Oregon Department of Transportation invested in a study to evaluate the possibility of a fairly new type of self-curing admixture (SCA) developed by Dr. Wen-Chen Jau that would take the place of wet curing in the field (19). Tests were conducted on both cylinders cast in the laboratory as well as slabs cast in the field. All specimens that were made including silica fume as an SCM and that used the SCA had permeability values falling within the low to very low ranges as per ASTM C 1202 (15). This study concluded that in concretes where silica fume is used in place of PC, this admixture could effectively reduce the time needed for wet curing from 14 days to 3 days. The authors state that as long as the SCA is compatible with the other elements in the mix, required compressive strengths as well as increased durability can be achieved. This new admixture may prove to make silica fume a more viable option for HPC given that the possibility of encountering shrinkage cracking is reduced by its addition.

Slag Research

The Virginia Department of Transportation (VDOT) sponsored a study conducted at Virginia Polytechnic Institute and State University in which a model was developed to predict service life estimates for concrete bridge decks based on extent of chloride corrosion as well as other factors (20). In order to do this, they surveyed over 40 bridge decks within the state indicating what type of reinforcement was used and its cover depth, the bridge age, as well as the use of different SCMs particularly slag and fly ash. Cores were taken from the selected bridges, which ranged across six climactic zones in Virginia, and used to determine time to corrosion initiation, time from initiation to cracking, and time for corrosion damage to propagate to a limit state. These time frames were calculated using chloride titration data that was input to service life software called Bridge Corrosion Analysis. Based on the finalized model, the authors concluded that adding fly ash or slag to a bridge deck concrete mixture dramatically reduced the chloride diffusivity of concrete and therefore provided protection for the reinforcement from corrosion. Studies such as this provide motivation for further research to determine exactly what affect slag has on decreased permeability.

VDOT also conducted a similar study to evaluate cores taken from Virginia bridge decks that had been in service for longer than 20 years (21). This time stamp marks the beginning use of SCMs essentially as a requirement by the state; before this time, SCMs were either optional or not allowed in concrete at all in Virginia. In similar fashion as before, cores were obtained from bridges placed from 1968 to 1991. After being tested and examined for various durability measures such as absorption, electrical conductivity, scaling, and hardened air content, VDOT concluded that both fly ash and slag should continue to be used in concrete bridge decks. Unfortunately, this study did not address each individual mix design used and evaluated so its results are difficult to compare with other research efforts.

One example of such research was conducted in Shanghai, China as chloride ingress is particularly important in coastal marine environments (22). One of the major issues that must be addressed when using slag in concrete is the need for proper curing to avoid drying and cracking due to early strength gain (6). Heat curing was used in this study in order to be able to measure the effects of mature concrete containing slag; specifically the maximum curing temperature was 167°F for accelerated curing conditions and 68°F for standard curing conditions. The specimens made for permeability testing were cured using both methods with three cylinders being cast for each method. Each mixture had 70% slag and 30% Type I PC while the w/cm ratio varied between 0.28 and 0.52. It was concluded that within this range, high volumes of slag perform well with respect to permeability as all of the samples had less than 1,000 coulombs passed. It was also determined that the correlation between the accelerated heat curing and the standard curing was extremely good with a correlation coefficient above 0.90.

In the aforementioned study conducted at Iowa State University, in which ternary mixtures were created using different combinations of fly ash, slag, silica fume, cement and metakaolin, permeability results were not as promising (18). The mix design that faired the best was a ternary mixture with 35% Grade 120 slag and 5% metakaolin; the average permeability was 698 coulombs passed after testing was concluded on all the specimens. Unlike the silica fume results in this study, throughout the durability testing Grade 120 slag performed well with only moderate scaling occurring in certain ternary mixtures, but not in all of them. The compressive strength results varied throughout the mix designs as expected due to the different combinations of SCMs; the 28-day values ranged from 5,180 to 8,040 psi.

Overall, GGBFS is a valuable addition to concrete mix designs particularly when durability is an issue. It only has minor effects on the plastic state of the concrete and therefore does not decrease workability. It can also increase compressive strength and decrease permeability with substitution rates between 25-35% (23).

Metakaolin Research

As mentioned earlier, metakaolin is a slightly more economical alternative than silica fume when used as a SCM in HPC (13). This next study was conducted in India in order that understanding the effects of metakaolin in concrete would increase its use throughout the country (24). Various mix designs were created using 0, 10, 20, and 30% metakaolin substitution for PC. The lowest permeability as tested by ASTM C 1202 (15) was 490 coulombs with 30% metakaolin and a w/cm ratio, referred to as the water-to-binder ratio in this study, of 0.30. Despite the observation that compressive strength decreased with increasing metakaolin contents at every w/cm ratio tested, the 28-day compressive strengths met the standards for structural applications.

Another study conducted in 2005 experimented with different quantities of two types of metakaolin and silica fume (25). The main focus of this research was to evaluate the effect that metakaolin fineness would have on durability, mechanical and fresh concrete properties, which is why two different types of metakaolin were used from the same regional supplier. The different mixes were evaluated at an 8% replacement by weight for PC and at w/cm ratios of 0.40, 0.50, and 0.60; they were compared to a control mixture made at these same ratios without the use of any SCMs and mixes made using silica fume as an SCM at the same substitution rate. After 28 days of moist curing, three specimens were tested for permeability per ASTM C 1202 (15). Results showed that the control mixtures all had permeability values in the high range above 4,000 coulombs and the other three mixes using different SCMs all had permeability values ranging from moderate to very low permeability. The most effective mix with respect to permeability was the design using the coarser metakaolin with less than 2,000 coulombs passed although the finer metakaolin used was not far behind. It was also found that the silica fume replacement did not produce permeabilities as low as the metakaolin replacements at the same w/cm ratios. This study would seem to indicate that metakaolin is a better substitute for PC by mass than silica fume; however, this study was only conducted at one replacement percentage and other research has proven that silica fume reduces permeability at lower replacement rates and when it is used in conjunction with fly ash (14; 17; 18).

Combinations of SCMs

As with many aspects of concrete, one material does not necessarily provide the best solution for every application. Many researchers have found that using multiple SCMs can lead to even further reduced permeability in different applications. Ozyildirim conducted a study for the Virginia Transportation Research Council to evaluate different combinations of silica fume and slag for both economical and permeability benefits (26). Specimens were tested for compressive strength at 1, 7 and 28 days. They were tested for RCP at both 28 days and 1 year; the 1 year samples were stored in outdoor conditions to mimic field exposure conditions present in the state. The authors found that the 28-day compressive strength results showed the plain PCC with no silica fume or slag had the lowest strength of all the mixtures. Its strength was 6,430 psi. This obviously means that the concrete batches made with extra SCM combinations were all above the stipulated 4,000 psi strength requirement. The relatively poorer strength performance of plain concrete relative to mixtures with silica fume or slag was also exhibited with the property of permeability. The maximum value of 3,814 coulombs, which is considered moderate permeability (15), was obtained for plain concrete. The lowest permeability was achieved with a mix design having 50% cement, 43% slag, and 7% silica fume; it had 645 coulombs passed which puts it in the very low range (15). This low permeability was achieved at w/cm ratios of 0.40 and 0.45; however Type III PC was necessary at the latter ratio. It was concluded that all of the concrete mixes containing slag and silica fume were in the low permeability range with only one exception. When tested at 1 year, the samples had approximately a half of their corresponding coulomb value passed at 28 days. All of the 1 year permeability values obtained were below 1,000 coulombs passed, which is the upper limit for the “low permeability” category (15). It was observed that with increase in the content of silica fume, the permeability of the concrete decreased. However, Khayat and Nasser note that silica fume replacements over 7% can induce early cracking and therefore defeat its purpose of improving durability through lowered permeabilities (27).

A methodology was developed by a group of researchers in order to statistically predict the optimal SCM combinations using experimental design methods (28). They first defined the input parameters which consisted of performance requirements and material properties, then used a design matrix to determine different mix designs, tested the concrete batches and then ultimately determined the concrete mixes that were expected to produce the best results based on a statistical analysis. To test this methodology, a case study was undertaken in which different batches were made with C and F ash, silica fume and slag. The only percentages of silica fume tested were 0, 5 and 8% in combination with different percentages of the other SCMs at various w/cm ratios. After testing, it was found that the lowest 56-day permeability mix contained 25% slag, 8% silica fume and had a w/cm ratio of 0.37. A matrix was then designed to depict the desirability of each mix based on 12 different characteristics of both the plastic and hardened concrete. The best predicted mix was then designed and properties were predicted based on the previous mix design values. With regards to permeability, the method's prediction for the optimal mix was 397 coulombs while the actual permeability test resulted in a value of 244 coulombs, a 38.5% difference. Other properties often times did not exhibit such high differences between the predicted and experimentally determined values. For instance, the 28-day compressive strength was predicted to be 7,731 psi while the laboratory test resulted in a value of 7,710 psi, producing a negligible difference. This method could prove to be a way of economically testing the durability properties of concrete by using time and materials efficiently.

Not only can slag and silica fume be combined to achieve even greater decreases in permeability, but silica fume and metakaolin combinations are also a prevalent topic of research within the field of concrete durability. The next study was conducted to find optimal combinations of the two SCMs (29). The tested silica fume replacement values for PC were 0, 5, 6, 7, 8, 9, and 10% while the replacement values for the metakaolin were higher at 0, 10, 15, 20, and 25%. Each combination of SCM replacements was trialed producing 24 different mix designs and one overall control mix with no SCM substitution. The highest compressive strength was 7,885 psi with 6% silica fume and 15% metakaolin. Unfortunately, permeability was not investigated in this study. However, this gives rise to a future research opportunity.

There have been other research attempts to compare silica fume and metakaolin to determine which is the most cost-effective cement replacement while at the same time providing reduced permeability. One such study was conducted in an effort to undermine silica fume's hold on the concrete industry. The opinion of the authors was that the abundance of research proving that silica fume provided reduced permeability made it the obvious choice over metakaolin in HPC, despite its higher price (30). Concrete mixtures were made at a w/cm ratio of 0.35 using SMC replacements for PC of 5, 10, and 15% of both silica fume and highly reactive metakaolin. Specimens were tested for compressive strength, shrinkage, and chloride diffusivity instead of permeability. With respect to compressive strength, the 15% replacement of metakaolin behaved almost identically to the mix containing 15% silica fume replacement. While the silica fume behaved better with respect to cracking, both SCM mixes exhibited earlier cracking than did the control cement-only mix. It was also observed that at the 15% replacement level, the silica fume performed best with regard to chloride ion diffusivity. Overall, the authors concluded that each of the two SCMs examined performed almost equally as well as the other with silica fume having a slight upper hand.

Summary

The use of SCMs has become common place within HPC applications. As demonstrated in the aforementioned literature, there are various opinions and research that attempt to quantify the promising effects of these different SCMs with respect to permeability and compressive strength. However encouraging these results may be concerning the improved durability and performance of concrete, it is important to note that there is by no means a universally appealing solution across every HPC-warranted situation. Particularly in the achievement of low permeability, there are various methods and materials that can be used to obtain desirable results. The quality of locally available materials and their internal reactivity can affect not only short term properties, but also the long term durability of concrete mixes. The field conditions and geographical region can also directly impact the quality of concrete placed and the needs for any given project. For reasons such as these, testing and research should be conducted not only on a national level, but also on a local level to ensure the quality of materials and in turn their part to play in HPC bridge decks.

CHAPTER 3 : MATERIALS

The coarse aggregate used in the research was a No. 57 stone from a local aggregate producer. The fine aggregate was river sand commonly used throughout middle Tennessee. Sieve analyses were conducted in triplicate on both coarse and fine aggregate as per AASHTO T 27 and AASHTO T 11 (31; 32). The average results of the sieve analysis on the aggregates are shown in Table 3.1. The analysis showed that the coarse aggregate met specifications for a No. 57 stone as per ASTM C 33 (33). The fine aggregate met the specifications for use in concrete as per TDOT 903.01 (34). Specific gravity and absorption tests were also conducted in triplicate on the coarse and fine aggregate as per AASHTO test methods T 85 and T 84 (35; 36). The average results for the aggregates are shown in Table 3.2.

TABLE 3.1: Average Results from Sieve Analysis

Sieve Size (in)	**Sieve Size (mm)**	**Coarse Aggregate Percent Passing**	**ASTM C33** (33) **No. 57 Specification**	**Fine Aggregate Percent Passing**	**TDOT 903.01** (34) **Fine Aggregate Specification**
1.5	37.5	100	100	—	—
1	25	100	95-100	—	—
0.5	12.5	55	25-60	—	—
0.375	9.5	—	—	100	100
No. 4	4.75	3	0-10	97	95-100
No. 8	2.36	1	0-5	91	—
No. 16	1.18	—	—	83	50-90
No. 30	0.6	—	—	65	—
No. 50	0.3	—	—	9	5-30
No. 100	0.15	—	—	1	0-10
No. 200	0.075	—	—	0.3	0 - 3

TABLE 3.2: Average Results for Specific Gravity and Absorption

Property	Coarse Aggregate	Fine Aggregate
BSG (dry)	2.682	2.597
BSG (SSD)	2.708	2.623
Absorption	0.96	1.00

Quantities of necessary aggregates were secured and stockpiled so that the same aggregates were used throughout the laboratory evaluation. Similarly, AASHTO M 295 (37) Class F fly ash and Class C fly ash (see Tables 3.3 and 3.4), AASHTO M 302 (38) Grade 120 GGBFS, ASTM C 1240 (39) silica fume, metakaolin, and AASHTO M 194 (40) chemical admixtures were obtained from regional suppliers and stockpiled so that the same materials were used throughout the laboratory evaluation. Type I PC meeting AASHTO M 85 (41) criteria was obtained from a regional supplier. Local tap water was used for all laboratory mixtures.

TABLE 3.3: Class F Fly Ash Chemical Composition

Component	Percent Composition	ASTM C 618-05 (42) Requirements	AASHTO M 295-07 (37) Requirements
SiO_2	47.64	—	—
Al_2O_3	18.83	—	—
Fe_2O_3	17.30	—	—
$SiO_2 + Al_2O_3 + Fe_2O_3$	83.77	70% minimum	70% minimum
CaO	7.92	—	—
MgO	1.01	—	—
SO_3	2.41	5% maximum	5% maximum
Moisture Content	0.11	3% maximum	3% maximum
Na_2O	0.75	—	1.5% maximum
Loss-on-Ignition	0.98	6% maximum	5% maximum

TABLE 3.4: Class C Fly Ash Chemical Composition

Component	**Percent Composition**	**ASTM C 618-05** (42) **Requirements**	**AASHTO M 295-07** (37) **Requirements**
SiO_2	37.45	—	—
Al_2O_3	19.19	—	—
Fe_2O_3	6.10	—	—
$SiO_2 + Al_2O_3 + Fe_2O_3$	62.74	50% minimum	50% minimum
CaO	23.85	—	—
MgO		—	—
SO_3	1.83	5% maximum	5% maximum
Moisture Content	0.08	3% maximum	3% maximum
Na_2O	1.38	—	1.5% maximum
Loss-on-Ignition	0.54	6% maximum	5% maximum

CHAPTER 4 : PROCEDURE

Preliminary Work

In the spring of 2013, the research team generated preliminary curves by substituting literature suggested SCMs for PC in a TDOT Class D mixture containing Class C fly ash. Tables 4.1 and 4.2 show mixture proportions used for preliminary mixtures for silica fume and metakaolin, respectively. The research team also developed two preliminary ternary mixtures. Tables 4.3 and 4.4 show proportions for 50PC/35SL/15F and 62PC/35F/3MK mixtures, respectively. Tables 4.5 and 4.6, respectively, show comparisons of the TDOT 604.03 (43) Class D requirements with the preliminary mixture designs. Tables 4.7 and 4.8 show mean 28-day compressive strengths for the preliminary mixtures. Table 4.9 shows 56-day RCP results for the preliminary mixtures. Figure 4.1 shows the plots for preliminary mixtures containing metakaolin and silica fume. The plot for 50PC/35SL/15F preliminary mixture is shown in Figure 4.2.

TABLE 4.1: Class C Fly Ash and Silica Fume Preliminary Mixture Designs

Component	2%	4%	6%	8%
Type I Portland Cement (lbs/CY)	452.6	440.2	427.8	415.4
Class C Fly Ash (lbs/CY)	155	155	155	155
Silica Fume (lbs/CY)	12.4	24.8	37.2	49.6
No. 57 Limestone SSD (lbs/CY)	1879	1875	1873	1870
River Sand SSD (lbs/CY)	1108	1107	1105	1103
Water (lbs/CY)	229.5	229.5	229.5	229.5
Air-Entrainer (oz/cwt)	0.1	1	1.2	1.2
ASTM C 494 Type A (oz/cwt)	2	2	2	3
ASTM C 494 Type F (oz/cwt)	3	3.5	4.5	5.5

TABLE 4.2: Class C Fly Ash and Metakaolin Preliminary Mixture Designs

Component	2%	4%	6%	8%
Type I Portland Cement (lbs/CY)	452.6	440.2	427.8	415.4
Class C Fly Ash (lbs/CY)	155	155	155	155
Metakaolin (lbs/CY)	12.4	24.8	37.2	49.6
No. 57 Limestone SSD (lbs/CY)	1881	1879	1879	1878
River Sand SSD (lbs/CY)	1109	1109	1108	1107
Water (lbs/CY)	229.5	229.5	229.5	229.5
Air-Entrainer (oz/cwt)	1.25	1.25	2	2.2
ASTM C 494 Type A (oz/cwt)	2	3	3	3
ASTM C 494 Type F (oz/cwt)	3.5	3.5	3.8	5.5

TABLE 4.3: 50PC/35SL/15F Preliminary Mixture Designs

Component	0.40	0.375	0.35	0.325
Type I Portland Cement (lbs/CY)	310	310	310	310
Grade 120 Slag (lbs/CY)	217	217	217	217
Class F Fly Ash (lbs/CY)	93	93	93	93
No. 57 Limestone SSD (lbs/CY)	1810	1836	1860	1887
River Sand SSD (lbs/CY)	1065	1097	1097	1111
Water (lbs/CY)	248	232.5	217	201.5
Air-Entrainer (oz/cwt)	0.9	3.4	2.5	2
ASTM C 494 Type A (oz/cwt)	1	1	2	2.5
ASTM C 494 Type F (oz/cwt)	3	3	3.6	4

TABLE 4.4: Class F Fly Ash and Metakaolin Preliminary Mixture Designs

Component	2%	4%	6%	8%
Type I Portland Cement (lbs/CY)	390.6	378.2	365.8	353.4
Class F Fly Ash (lbs/CY)	217	217	217	217
Metakaolin (lbs/CY)	12.4	24.8	37.2	49.6
No. 57 Limestone SSD (lbs/CY)	1877	1876	1875	1874
River Sand SSD (lbs/CY)	1111	1111	1110	1110
Water (lbs/CY)	229.5	229.5	229.5	229.5
Air-Entrainer (oz/cwt)	1	1	1.5	1.5
ASTM C 494 Type A (oz/cwt)	2	2	2	2
ASTM C 494 Type F (oz/cwt)	3	4	4.5	5

TABLE 4.5: Comparison of Preliminary Mixture Designs with TDOT Class D PCC Requirements

Quantity / Ratio / Percentage	TDOT 604.03 Class D PCC Requirement	All Class C Fly Ash & Metakaolin Mixtures	All Class C Fly Ash & Silica Fume Mixtures	All Class F Fly Ash & Metakaolin Mixtures
Cementing Materials Content (lbs/CY)	620 minimum	620	620	620
Water-Cementing-Materials-Ratio	0.40 maximum	0.37	0.37	0.37
Percent Fine Aggregate by Total Aggregate Volume	44 maximum	38	38	38
Percent SCM Substitution (by weight) for Portland Cement	20 maximum for Class F fly ash or 25 maximum for Class C fly ash	25 Class C fly ash	25 Class C fly ash	35 Class F fly ash
Percent MK or SF SCM Substitution (by weight) for Portland Cement	Currently not allowed	2 to 8	2 to 8	2 to 8

TABLE 4.6: Comparison of 50PC/35SL/15F Preliminary Mixture Design with TDOT Class D PCC Requirements

Quantity / Ratio / Percentage	TDOT 604.03 Class D PCC Requirement	All 50PC/35SL/15F Mixtures
Cementing Materials Content (lbs/CY)	620 minimum	620
Water-Cementing-Materials-Ratio	0.40 maximum	0.325 to 0.40
Percent Fine Aggregate by Total Aggregate Volume	44 maximum	37.5 to 38
Percent SCM Substitution (by weight) for Portland Cement	20 maximum for Class F fly ash or 35 maximum for Grade 120 Slag	15 Class F fly ash and 35 Grade 120 Slag

TABLE 4.7: Mean Compressive Strength Results of Metakaolin and Silica Fume Preliminary Mixtures

Property	2%	4%	6%	8%
Class C Fly Ash and Metakaolin Mixture Mean 28-Day Compressive Strengths (psi)	6760	7300	7720	7780
Class C Fly Ash and Silica Fume Mixture Mean 28-Day Compressive Strengths (psi)	7040	6630	6250	6270
Class F Fly Ash and Metakaolin Mixture Mean 28-Day Compressive Strengths (psi)	5620	5740	5790	6280

TABLE 4.8: Mean Compressive Strength Results of 50PC/35SL/15F Preliminary Mixtures

Property	0.325	0.35	0.375	0.40
50PC/35SL/15F Mixture Mean 28-Day Compressive Strengths (psi)	6140	6070	5430	4910

TABLE 4.9: Rapid Chloride Permeability Results (in coulombs) of Preliminary Mixtures

SCM Dosage	Sample 1	Sample 2	Sample 3	Sample 4	Mean
25C MK 0	2325	2291	2370	2001	2400
25C MK 2	1416	1452	1627	1598	1520
25C MK 4	939	963	876	1079	960
25C MK 6	727	667	671	712	690
25C MK 8	544	561	573	578	560
25C SF 2	Malfunction	1273	1255	1375	1300
25C SF 4	837	903	866	938	890
25C SF 6	Malfunction	716	669	737	710
25C SF 8	596	572	620	625	600
35F MK 2	671	719	Malfunction	766	720
35F MK 4	648	668	623	725	670
35F MK 6	466	584	511	564	530
35F MK 8	481	512	521	514	510
50PC/35SL/15F @ 0.40	813	803	838	879	830
50PC/35SL/15F @ 0.375	805	768	789	757	780
50PC/35SL/15F @ 0.35	605	570	684	678	630
50PC/35SL/15F @ 0.325	589	469	Malfunction	597	550

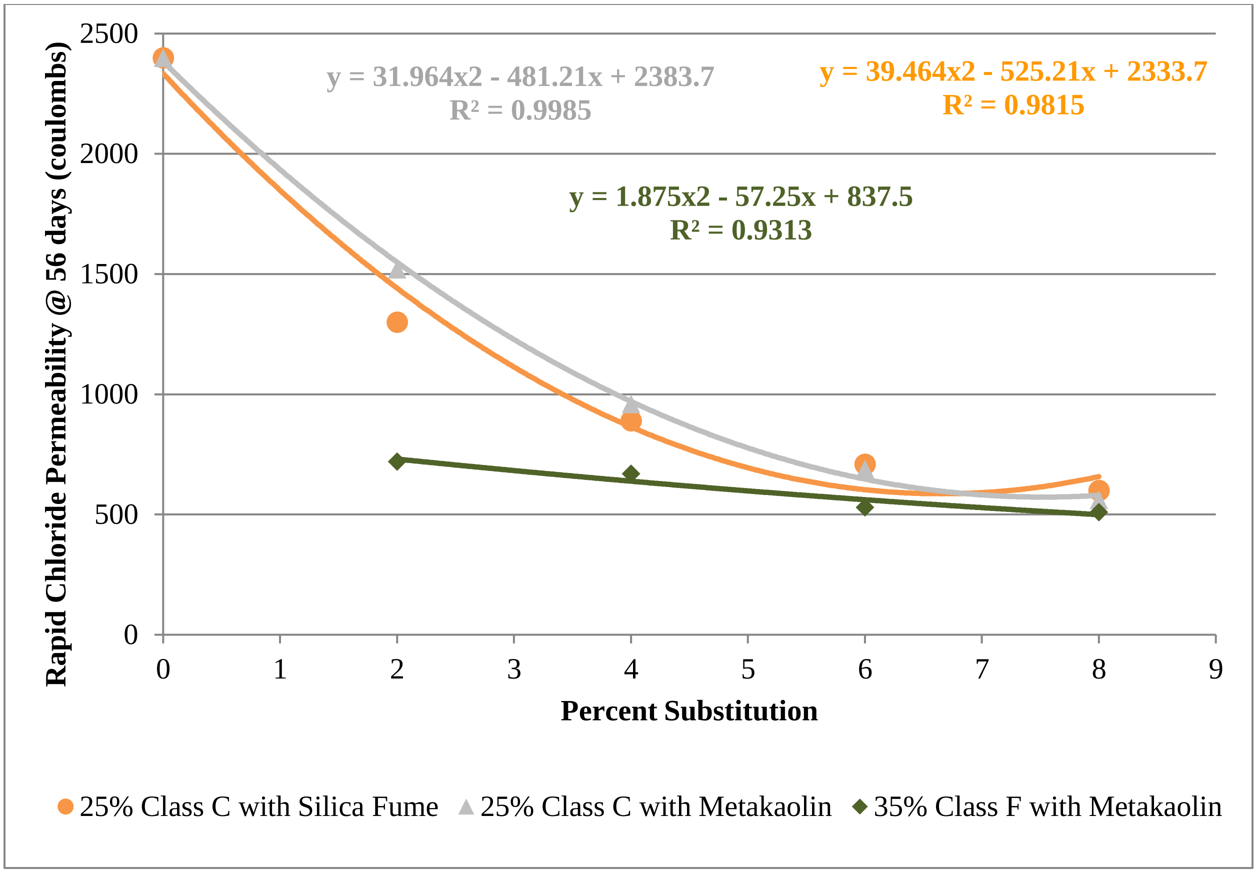

Figure 4.1: Rapid Chloride Permeability of Metakaolin and Silica Fume Preliminary Mixtures

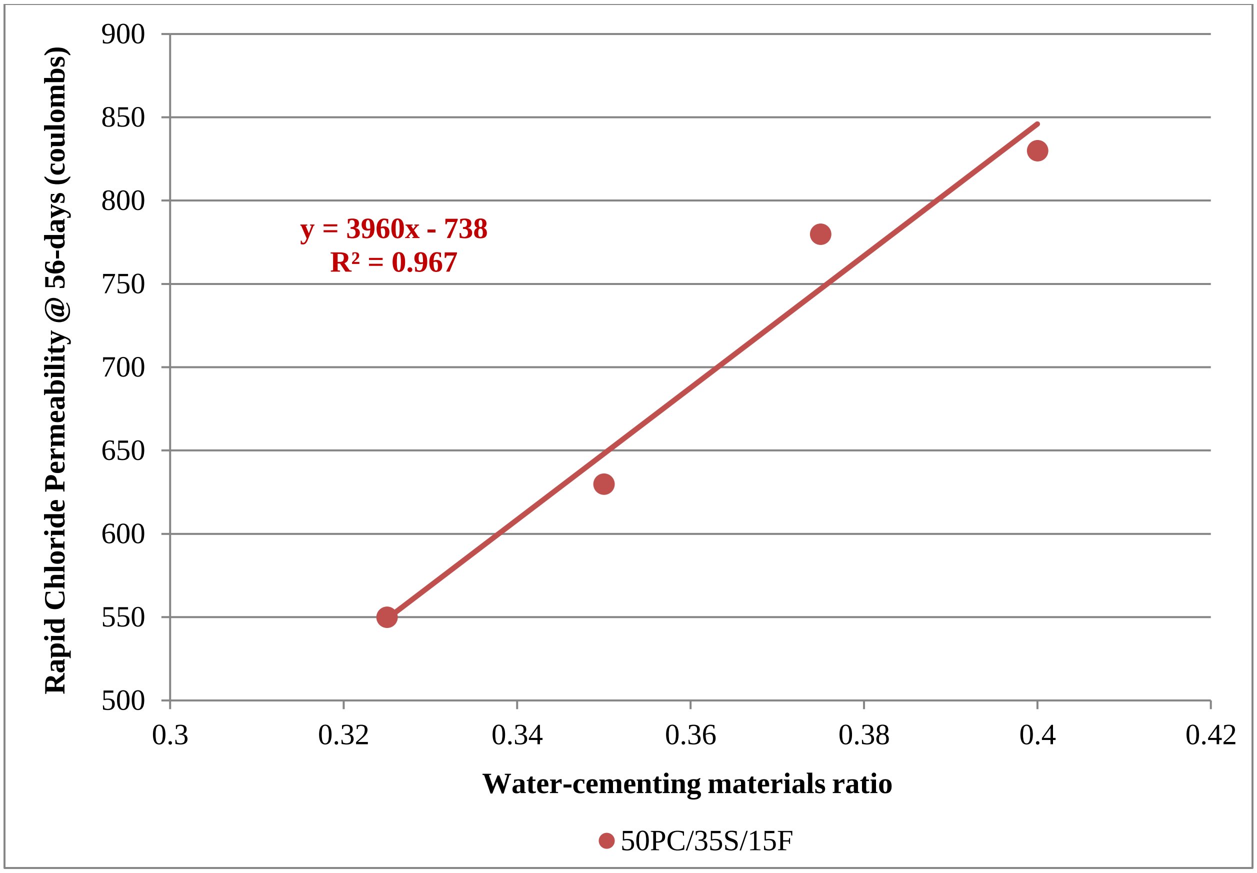

Figure 4.2: Rapid Chloride Permeability of 50PC/35SL/15F Preliminary Mixtures

TDOT M&T Division management requested that the research team assume that a potential new specification would require 1,200 coulombs maximum at 56 days. The goal of the research team was to produce four additional mixtures with a very high probability of meeting the new proposed 1,200 coulomb specification for RCP. The design target value of 779 coulombs for RCPT at 56 days calculated in a previous project was used again.

Validation Mixtures

The catalog validation mixtures were proportioned using guidance from the preliminary mixture curves. The regression equation for each curve was used to determine the practical dosage of 5% (for the 779 coulomb target value) for both silica fume and metakaolin. The preliminary data for the metakaolin and Class F fly ash mixture indicated that 2% metakaolin was adequate. However, due to the shape of the other metakaolin plots, a more conservative dosage of 3% metakaolin was chosen for the 35% Class F fly ash validation mixture. The regression equation for the 50PC/35SL/15F mixture indicated that a w/cm of 0.383 should be chosen (for the 779 coulomb target value). However, since other D-LP and catalog mixtures had all used a w/cm of 0.37, the first author chose to use the common w/cm of 0.37 for the 50PC/35SL/15F validation mixture.

Each catalog validation mixture was designed by trial batching. The trial batches were 1.33 ft^3 and were mixed in a 3.0 ft^3 nominal capacity rotary mixer in accordance with AASHTO R 39 (44). The mixture designs are shown in Table 4.10. Table 4.11 shows comparisons of each catalog validation mixture with TDOT 604.03. Eleven batches of each catalog validation mixture were produced and tested as per Table 4.12. Four 6x12-inch cylinders and three 4x8-inch cylinders were cast from each batch. After approximately 24 hours the cylinders were de-molded and placed in lime-water kept at 73 ± 3°F as per AASHTO R 39 until the specified testing time (44).

Slump was determined in accordance with AASHTO T 119 (45). Unit weight and gravimetric air content were determined in accordance with AASHTO T 121 (46). Air content by pressure method was determined using a pressure meter in accordance with AASHTO T 152 (47). The temperature of concrete was determined in accordance with AASHTO T 309 (48). The 6x12-inch and 4x8-inch cylinders were cast and cured in accordance with AASHTO R 39 (44). The hardened concrete was tested for compressive strength in accordance with AASHTO T 22 (49) using un-bonded caps per ASTM C 1231 (50). Static modulus of elasticity was determined in accordance with ASTM C 469 (51). RCP testing at 56 days was conducted as per AASHTO T 277-07 (52). Absorption of hardened concrete after boiling was determined as per ASTM C 642 (53).

TABLE 4.10: Catalog Validation Mixture Designs

Component	**70PC / 25C / 5SF Class D-LP**	**70PC / 25C / 5MK Class D-LP**	**50PC / 35SL / 15F Class D-LP**	**62PC / 35F / 3MK Class D-LP**
Type 1 Portland Cement (lbs/CY)	435	434	310	384.4
Class F Fly Ash (lbs/CY)	0	0	93	217
Class C Fly Ash (lbs/CY)	155	155	0	0
Grade 120 Slag (lbs/CY)	0	0	217	0
Silica Fume (lbs/CY)	31	0	0	0
Metakaolin (lbs/CY)	0	31	0	18.6
No. 57 Limestone (lbs/CY SSD)	1889	1897	1896	1880
River Sand (lbs/CY SSD)	1121	1124	1125	1118
Water (lbs/CY)	230	229.5	229.5	229.5
Design Percent Air	7	7	7	7
Air Entrainer, oz/cwt (oz/CY)	0.45 (2.8)	1.5 (9.3)	1.5 (9.3)	0.7 (4.3)
ASTM C 494 Type A, oz/cwt (oz/CY)	2.0 (12.4)	3.0 (18.6)	1.0 (6.2)	1.75 (10.9)
ASTM C 494 Type F, oz/cwt (oz/CY)	3.25 (20.2)	3.0 (18.6)	2.1 (13.0)	2.5 (15.5)

TABLE 4.11: Comparison of Catalog Validation Mixture Design Attributes with TDOT Class D PCC Requirements

Quantity / Ratio / Percentage	TDOT 604.03 Class D PCC Requirement [3]	70PC / 25C / 5SF	70PC / 25C / 5MK	50PC / 35SL / 15F	62PC / 35F / 3MK
Cementing Materials Content (lbs/CY)	620 minimum	621	620	620	620
W/CM Ratio	0.40 maximum	0.37	0.37	0.37	0.37
Percent Fine Aggregate by Total Aggregate Volume	44 maximum	38	38	38	38
Percent Fly Ash Substitution (by Weight) for PC	20 (25) maximum for Class F (C)	25C	25C	15F	35F
Percent Slag Substitution (by Weight) for PC	35 maximum	NA	NA	35	NA
Percent Silica Fume Substitution (by Weight) for PC	Not allowed	5	NA	NA	NA
Percent Metakaolin Substitution (by Weight) for PC	Not allowed	NA	5	NA	3

TABLE 4.12: Catalog Validation Mixture Testing Protocol

Test	Frequency
Slump	1 before HRWR per batch 1 after HRWR per batch
Unit Weight and Gravimetric Air Content	1 per batch
Air Content by Pressure Method	1 per batch
Compressive Strength* @ 28 and 56 days	2 6x12 cylinders per date per batch
Static Modulus of Elasticity* @ 28 and 56 days	1 of the 6x12 compressive strength cylinders per date per batch
Rapid Chloride Permeability @ 56 days	2 samples cut from separate 4x8 cylinders per batch
Absorption and Voids in Hardened Concrete @ 56 Days	2 samples cut from the 4x8 cylinders for RCPT testing per batch

* with neoprene pad caps in steel retainers

CHAPTER 5 : RESULTS

Catalog Validation Mixture Results

Plastic properties of the catalog validation mixtures are shown in Tables 5.1, 5.2, 5.3, and 5.4. Mean hardened properties of the catalog validation mixtures are shown in Tables 5.5, 5.6, 5.7, and 5.8. Complete results for 28 and 56-day compressive strengths, 28 and 56-day static modulus of elasticity, 56-day RCP, and 56-day hardened concrete absorption after boiling are shown in Appendices A, B, C, D, E, and F, respectively.

Data Quality

Plastic Properties

The acceptable range of plastic properties was determined by obtaining the single operator standard deviation from AASHTO R 39 Section 9 and multiplying by an ASTM C 670 factor for number of test results. The factor for 10 test results was used even though there were 11 test results since 10 was the largest number of tests shown in ASTM C 670 Table 1. All slump and unit weight test results met the acceptable precision criteria. However, only five of the eight sets of air content test results met the precision criteria. The authors are not concerned since AASHTO R 39 indicates that the precision criteria should be used with caution for air-entrained concrete.

Hardened Properties

The acceptable range of hardened properties was determined by obtaining the standard deviation from appropriate test method and multiplying by an ASTM C 670 factor for number of test results. The factor for 10 test results was used even though there were 11 test results since 10 was the largest number of tests shown in ASTM C 670 Table 1. The multi-laboratory precision was used for 6x12 cylinders since AASHTO T 22 states that preparation of cylinders by different operators would probably increase the variation above multi-laboratory precision criteria. Single operator multi-batch precision was used for static modulus of elasticity since it was the only available precision criteria. All hardened property test results met the acceptable precision.

TABLE 5.1: Plastic Properties for Class C Fly Ash and Silica Fume Validation Mixture

SCM - Batch	Before HRWR Slump (inches)	After HRWR Slump (inches)	Pressure Method Air Content (%)	Gravimetric Air Content (%)	Unit weight (pcf)	Temperature (°F)
CSF - 1	1.75	6.25	7.2	7.27	142.3	74
CSF - 2	1.25	6.00	7.4	6.78	143.0	73
CSF - 3	1.50	6.50	6.4	5.84	144.5	74
CSF - 4	1.25	6.75	7.2	6.62	143.3	72
CSF - 5	1.50	6.25	7.1	6.46	143.5	72
CSF - 6	1.50	6.75	7.4	6.84	142.9	71
CSF - 7	1.75	6.75	7.6	7.31	142.2	72
CSF - 8	2.50	7.75	7.4	6.79	143.0	72
CSF - 9	2.00	7.50	8.0	7.75	141.5	72
CSF - 10	3.00	7.75	7.8	7.54	141.9	74
CSF - 11	2.00	7.00	7.5	7.21	142.4	75
Mean	1.82	6.84	7.36	6.95	142.77	72.8
Range	1.75	1.75	1.4	1.91	2.3	4
Acceptable Range	3.15	3.15	1.35	1.35	4.05	Not available
Meets?	Yes	Yes	No	No	Yes	—

TABLE 5.2: Plastic Properties for Class C Fly Ash and Metakaolin Validation Mixture

SCM - Batch	Before HRWR Slump (inches)	After HRWR Slump (inches)	Pressure Method Air Content (%)	Gravimetric Air Content (%)	Unit weight (pcf)	Temperature (°F)
CMK - 1	1.25	4.75	6.2	6.16	144.6	82
CMK - 2	1.00	5.00	6.4	6.12	144.7	82
CMK - 3	1.50	7.25	7.2	7.25	143.2	76
CMK - 4	1.25	7.00	7.3	7.30	143.1	77
CMK - 5	1.50	5.00	6.8	6.62	143.9	78
CMK - 6	1.75	5.25	6.9	6.71	143.8	78
CMK - 7	1.25	5.25	6.8	6.63	143.9	79
CMK - 8	1.25	5.50	7.0	6.73	143.7	79
CMK - 9	1.00	5.50	6.5	6.51	144.1	78
CMK - 10	1.00	5.75	6.6	6.54	144.0	79
CMK - 11	1.75	5.25	6.6	6.64	143.9	78
Mean	1.32	5.59	6.75	6.66	143.90	78.7
Range	0.75	2.50	1.1	1.13	1.5	6
Acceptable Range	3.15	3.15	1.35	1.35	4.05	Not available
Meets?	Yes	Yes	Yes	Yes	Yes	—

TABLE 5.3: Plastic Properties for 50PC/35SL/15F Validation Mixture

SCM - Batch	Before HRWR Slump (inches)	After HRWR Slump (inches)	Pressure Method Air Content (%)	Gravimetric Air Content (%)	Unit weight (pcf)	Temperature (°F)
50PC/35SL/15F - 1	2.25	8.00	6.6	6.65	143.9	77
50PC/35SL/15F - 2	1.50	8.00	6.1	6.39	144.3	79
50PC/35SL/15F - 3	1.50	7.75	5.6	6.06	144.8	78
50PC/35SL/15F - 4	1.50	7.50	5.8	6.25	144.5	77
50PC/35SL/15F - 5	1.50	8.00	5.7	5.80	145.2	77
50PC/35SL/15F - 6	1.50	7.00	5.8	6.08	144.8	78
50PC/35SL/15F - 7	1.50	7.25	5.8	6.02	144.9	77
50PC/35SL/15F - 8	1.75	7.50	6.4	6.70	143.8	76
50PC/35SL/15F - 9	2.00	7.50	6.6	6.83	143.6	76
50PC/35SL/15F - 10	1.50	7.50	5.6	5.97	144.9	75
50PC/35SL/15F - 11	2.50	7.75	5.7	6.01	144.9	73
Mean	1.73	7.61	5.97	6.25	144.51	76.6
Range	1.0	0.5	0.9	1.03	1.6	6
Acceptable Range	3.15	3.15	1.35	1.35	4.05	Not available
Meets?	Yes	Yes	Yes	Yes	Yes	—

TABLE 5.4: Plastic Properties for 62PC/35F/3MK Validation Mixture

SCM - Batch	Before HRWR Slump (inches)	After HRWR Slump (inches)	Pressure Method Air Content (%)	Gravimetric Air Content (%)	Unit weight (pcf)	Temperature (°F)
62PC/35F/3MK - 1	2.00	7	6.4	6.59	143.1	75
62PC/35F/3MK - 2	2.50	7.5	7.2	7.42	141.8	77
62PC/35F/3MK - 3	2.00	6.25	6.3	6.17	143.8	76
62PC/35F/3MK - 4	2.00	7.5	6.2	6.22	143.7	76
62PC/35F/3MK - 5	2.00	7.75	6.8	6.89	142.7	77
62PC/35F/3MK - 6	2.75	7.5	7.1	7.4	141.9	77
62PC/35F/3MK - 7	3.00	7.25	7.5	7.54	141.7	74
62PC/35F/3MK - 8	3.00	7.75	7.2	7.27	142.1	73
62PC/35F/3MK - 9	2.00	6.5	6.6	6.14	143.8	73
62PC/35F/3MK - 10	1.75	7.75	6.7	6.52	143.2	74
62PC/35F/3MK - 11	1.75	6.5	6	5.9	144.2	72
Mean	2.25	7.20	6.73	6.73	142.91	74.9
Range	1.25	1.5	1.3	1.52	2.5	4
Acceptable Range	3.15	3.15	1.35	1.35	4.05	Not available
Meets?	Yes	Yes	Yes	No	Yes	—

TABLE 5.5: Hardened Properties for Class C Fly Ash and Silica Fume Validation Mixture

SCM-Batch	Mean 28-Day Compressive Strength (psi)	Mean 56-Day Compressive Strength (psi)	Mean 28-Day Static Modulus of Elasticity (psi)	Mean 56-Day Static Modulus of Elasticity (psi)	Mean 56-Day Rapid Chloride Permeability (coulombs)	Mean 56-Day Absorption after Boiling (%)
CSF - 1	6870	7650	4800000	5000000	560	5
CSF - 2	7050	7680	4850000	4950000	450	5
CSF - 3	7370	7860	5250000	5150000	510	4.4
CSF - 4	6820	7150	4900000	5050000	430	4.4
CSF - 5	6660	7060	4750000	5000000	470	5.1
CSF - 6	6950	7540	4900000	4950000	490	5.2
CSF - 7	6690	7370	4800000	4850000	520	5
CSF - 8	6980	7480	5150000	4950000	510	5.2
CSF - 9	5860	6380	4500000	4800000	660	5.4
CSF - 10	6510	6900	4700000	4900000	490	5.1
CSF - 11	6550	7010	4800000	4800000	640	5.4
Mean	6755	7280	4854545	4945455	521	5.02
Range	1510	1480	750000	350000	220	1
Acceptable	Max range of 22.5% of mean = 1519	Max range of 22.5% of mean = 1638	Max range of 19.125% of mean = 928431	Max range of 19.125% of mean = 945818	Max range of 81% of mean = 422	Not available
Meets?	Yes	Yes	Yes	Yes	Yes	—

TABLE 5.6: Hardened Properties for Class C Fly Ash and Metakaolin Validation Mixture

SCM - Batch	Mean 28-Day Compressive Strength (psi)	Mean 56-Day Compressive Strength (psi)	Mean 28-Day Static Modulus of Elasticity (psi)	Mean 56-Day Static Modulus of Elasticity (psi)	Mean 56-Day Rapid Chloride Permeability (coulombs)	Mean 56-Day Absorption after Boiling (%)
CMK - 1	7380	7860	5100000	5150000	740	5.1
CMK - 2	7020	7700	5000000	5200000	760	5.1
CMK - 3	6950	7240	5000000	5000000	790	5.3
CMK - 4	6710	7080	4850000	5000000	750	5.1
CMK - 5	7450	7550	Damaged	5300000	750	4.6
CMK - 6	6930	7290	5300000	5150000	730	4.7
CMK - 7	6870	7390	4850000	4950000	760	5.3
CMK - 8	6710	7190	4900000	5200000	800	5.5
CMK - 9	7640	7850	5300000	5150000	760	5.2
CMK - 10	6800	7450	4800000	5150000	790	5.3
CMK - 11	7270	7180	4950000	5350000	800	4.6
Mean	7066	7435	5005000	5145455	766	5.07
Range	930	780	500000	400000	70	0.9
Acceptable	Max range of 22.5% of mean = 1589	Max range of 22.5% of mean = 1672	Max range of 19.125% of mean = 957206	Max range of 19.125% of mean = 984068	Max range of 81% of mean = 620	Not available
Meets?	Yes	Yes	Yes	Yes	Yes	—

TABLE 5.7: Hardened Properties for 50PC/35SL/15F Validation Mixture

SCM - Batch	Mean 28-Day Compressive Strength (psi)	Mean 56-Day Compressive Strength (psi)	Mean 28-Day Static Modulus of Elasticity (psi)	Mean 56-Day Static Modulus of Elasticity (psi)	Mean 56-Day Rapid Chloride Permeability (Coulombs)	Mean 56-Day Absorption after Boiling (%)
50PC/35SL/15F - 1	6890	7120	4950000	5150000	780	5.2
50PC/35SL/15F - 2	6950	7420	4950000	5150000	760	5.1
50PC/35SL/15F - 3	7290	7860	5100000	4950000	780	5.1
50PC/35SL/15F - 4	7370	7980	5250000	5400000	800	5.3
50PC/35SL/15F - 5	7320	7930	5100000	5350000	840	4.9
50PC/35SL/15F - 6	7280	7950	5250000	5200000	830	5.4
50PC/35SL/15F - 7	7100	7520	5050000	5300000	690	5
50PC/35SL/15F - 8	6900	7660	5050000	5350000	740	5.1
50PC/35SL/15F - 9	7270	7630	5150000	5350000	740	4.9
50PC/35SL/15F - 10	7080	7720	4950000	5150000	810	5
50PC/35SL/15F - 11	7060	7610	5000000	5350000	810	5.1
Mean	7137	7673	5072727	5245455	780	5.1
Range	480	860	300000	450000	150	0.5
Acceptable	Max range of 22.5% of mean = 1605	Max range of 22.5% of mean = 1726	Max range of 19.125% of mean = 970159	Max range of 19.125% of mean = 1003193	Max range of 81% of mean = 631	Not available
Meets?	Yes	Yes	Yes	Yes	Yes	

TABLE 5.8: Hardened Properties for 62PC/35F/3MK Validation Mixture

SCM - Batch	Mean 28-Day Compressive Strength (psi)	Mean 56-Day Compressive Strength (psi)	Mean 28-Day Static Modulus of Elasticity (psi)	Mean 56-Day Static Modulus of Elasticity (psi)	Mean 56-Day Rapid Chloride Permeability (Coulombs)	Mean 56-Day Absorption after Boiling (%)
62PC/35F/3MK - 1	5910	6640	5050000	5000000	880	5.4
62PC/35F/3MK - 2	5600	6330	4600000	4800000	820	5.4
62PC/35F/3MK - 3	6110	6680	4750000	5100000	830	5.4
62PC/35F/3MK – 4	5930	6640	5000000	4950000	840	5.4
62PC/35F/3MK - 5	6030	6460	4550000	5000000	920	5
62PC/35F/3MK – 6	5650	6170	4550000	4750000	960	5.2
62PC/35F/3MK – 7	5520	5980	4400000	5050000	940	5.2
62PC/35F/3MK - 8	5420	6070	4600000	5000000	970	5.3
62PC/35F/3MK – 9	5950	6360	4650000	5000000	870	5.1
62PC/35F/3MK - 10	5830	6280	4750000	4750000	940	5.3
62PC/35F/3MK - 11	6100	6730	4800000	4750000	920	5
Mean	5823	6395	4700000	4922727	899	5.25
Range	690	750	650000	350000	150	0.4
Acceptable	Max range of 22.5% of mean = 1310	Max range of 22.5% of mean = 1438	Max range of 19.125% of mean = 898875	Max range of 19.125% of mean = 941471	Max range of 81% of mean = 728	Not available
Meets?	Yes	Yes	Yes	Yes	Yes	

Material Cost

Table 5.9 shows the estimated material unit costs. Table 5.10 shows the estimated costs per cubic yard. The numbers in Table 5.10 were determined using information from Tables 4.10 and 5.9.

TABLE 5.9: Cost Assumptions

Component	Assumed Cost Delivered to Ready Mix Producer
Type I Portland Cement ($/ton)	110
Class F Fly Ash ($/ton)	30
Class C Fly Ash ($/ton)	50
Grade 120 Slag ($/ton)	85.00*
Silica Fume ($/ton)	1000.00*
Metakaolin ($/ton)	473.00*
No. 57 Limestone ($/ton)	18
River Sand ($/ton)	15
Air Entrainer ($/gallon)	4.5
MRWR ($/gallon)	8.5
HRWR ($/gallon)	12

* plus freight

TABLE 5.10: Estimated Material Costs ($/CY)

Component	20% Class F TDOT Class D	5% SF 25% Class C	5% MK 25% Class C	50PC/35SL/15F	62PC/35F/3MK
Type I Portland Cement	27.28	23.93	23.87	17.05	21.14
Class F Fly Ash	1.86	0.00	0.00	1.40	3.26
Class C Fly Ash	0	3.88	3.88	0.00	0.00
Grade 120 Slag	0	0.00	0.00	9.22	0.00
Silica Fume	0	15.50	0.00	0.00	0.00
Metakaolin	0	0.00	7.33	0.00	4.40
No. 57 Limestone	17.14	17.00	17.07	17.06	16.92
River Sand	8.55	8.41	8.43	8.44	8.39
Air Entrainer	0.08	0.10	0.33	0.33	0.15
MRWR	1.25	0.83	1.25	0.42	0.73
HRWR	1.17	1.90	1.75	1.22	1.46
Total Material Cost (except water)	57.32	71.54	63.90	55.13	56.44

CHAPTER 6 : ANALYSIS OF RESULTS

All catalog plastic properties (see Tables 5.1, 5.2, 5.3, and 5.4) met TDOT Class D PCC requirements. Table 6.1 shows values of hardened properties obtained in previous TDOT projects at TTU that will be used for catalog comparisons in subsequent figures. Figures 6.1, 6.2, 6.3, and 6.4 show comparisons of compressive strength, static modulus of elasticity, RCP, and ASTM C 642 absorption after boiling, respectively. The research team attempted to surgically reduce the RCP and do no harm to other engineering properties. Figures 6.1 through 6.4 seem to indicate that this objective was accomplished with only minor exceptions.

TABLE 6.1: Comparison Values (from previous TDOT projects) for Catalog Hardened Properties

Property	Mean Value	Specimen Size	Batches x Specimens	COV (%)
28-day Compressive Strength (psi)	5473	6 x 12	10 x 2	3.1
	7472	6 x 12	10 x 2	2.7
	5974	6 x 12	10 x 2	3.3
	6177	6 x 12	10 x 2	4.1
56-day Compressive Strength (psi)	6188	6 x 12	10 x 2	2.5
	7913	6 x 12	10 x 2	2.8
	6577	6 x 12	10 x 2	2.1
	6654	6 x 12	10 x 2	3.8
28-day Static Modulus of Elasticity (ksi)	4725	6 x 12	10 x 1*	1.3
	5220	6 x 12	10 x 1*	5.6
	4820	6 x 12	10 x 1*	3.1
	4880	6 x 12	10 x 1*	5.6
56-day Static Modulus of Elasticity (ksi)	5025	6 x 12	10 x 1*	3.2
	5385	6 x 12	10 x 1*	4.6
	5050	6 x 12	10 x 1*	3.1
	4905	6 x 12	10 x 1*	2.7
56-day RCP (coulombs)	1536	4 x 8 Slice	50 x 2	11.0
	813	4 x 8 Slice	10 x 3	8.0
	788	4 x 8 Slice	10 x 3	6.2
	744	4 x 8 Slice	10 x 3	7.5
56-day Absorption after Boiling (%)	4.93	3 x 6	10 x 2	2.9
	4.57	4 x 8 Slice	10 x 3	5.5
	4.96	4 x 8 Slice	10 x 3	5.6
	5.17	4 x 8 Slice	10 x 3	1.8

*** -** average of two runs on a single 6x12 cylinder

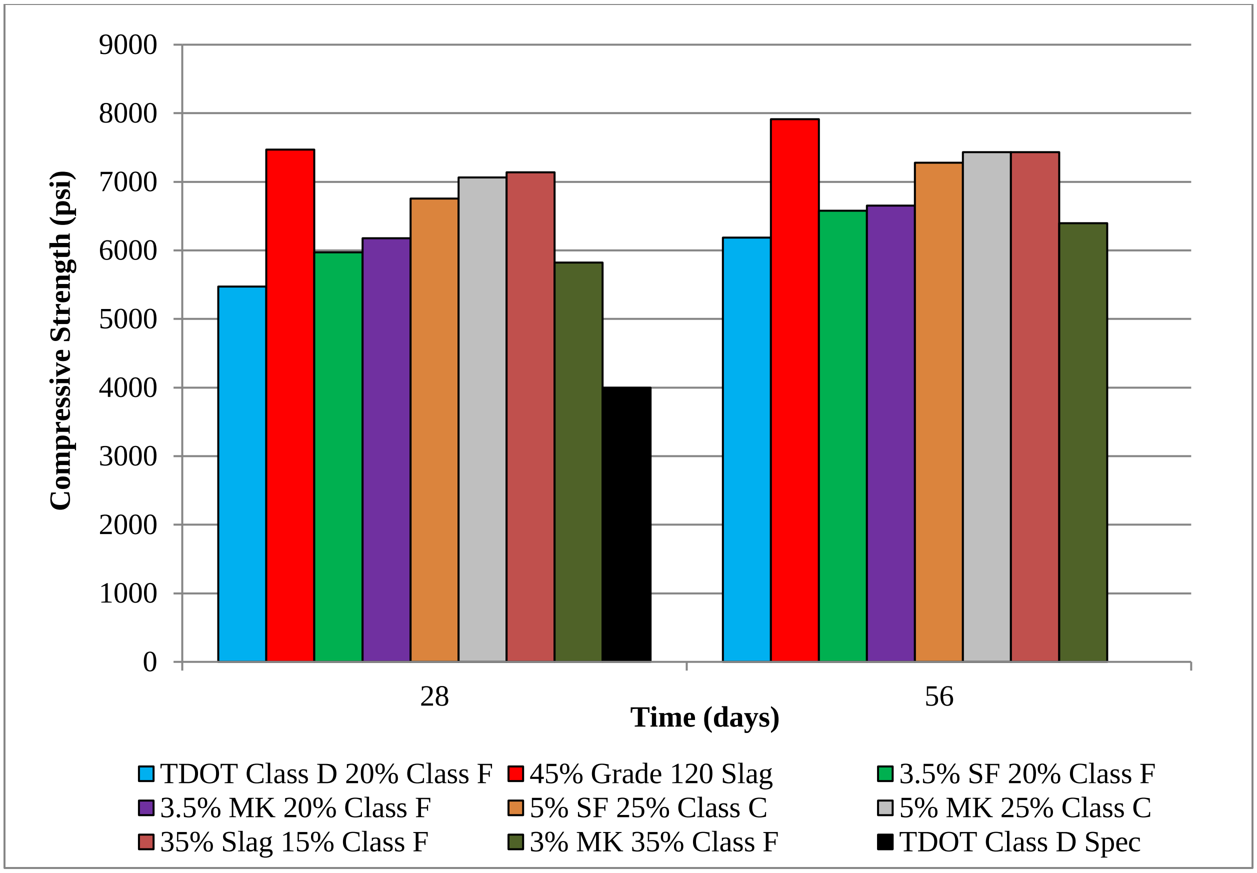

Figure 6.1: Compressive Strength Comparisons

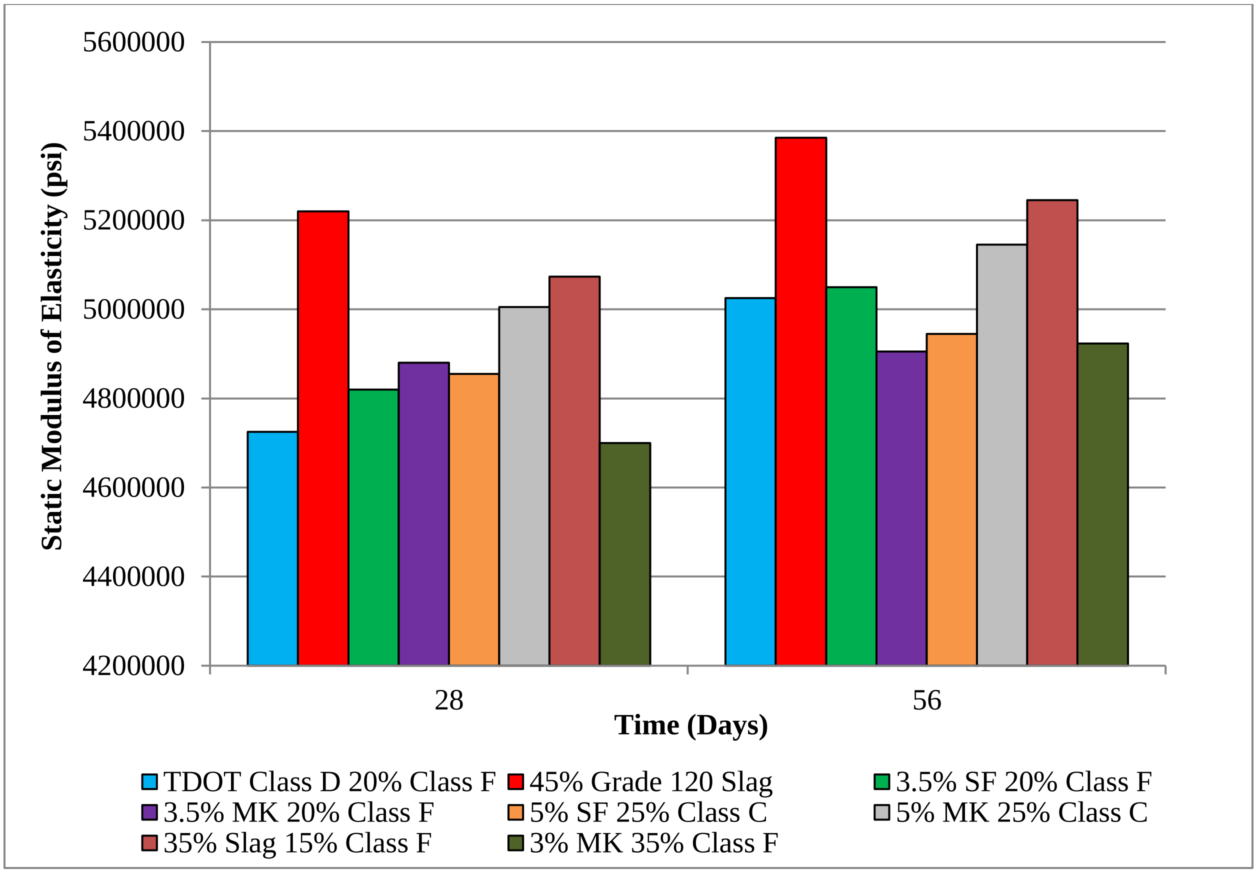

Figure 6.2: Static Modulus of Elasticity Comparisons

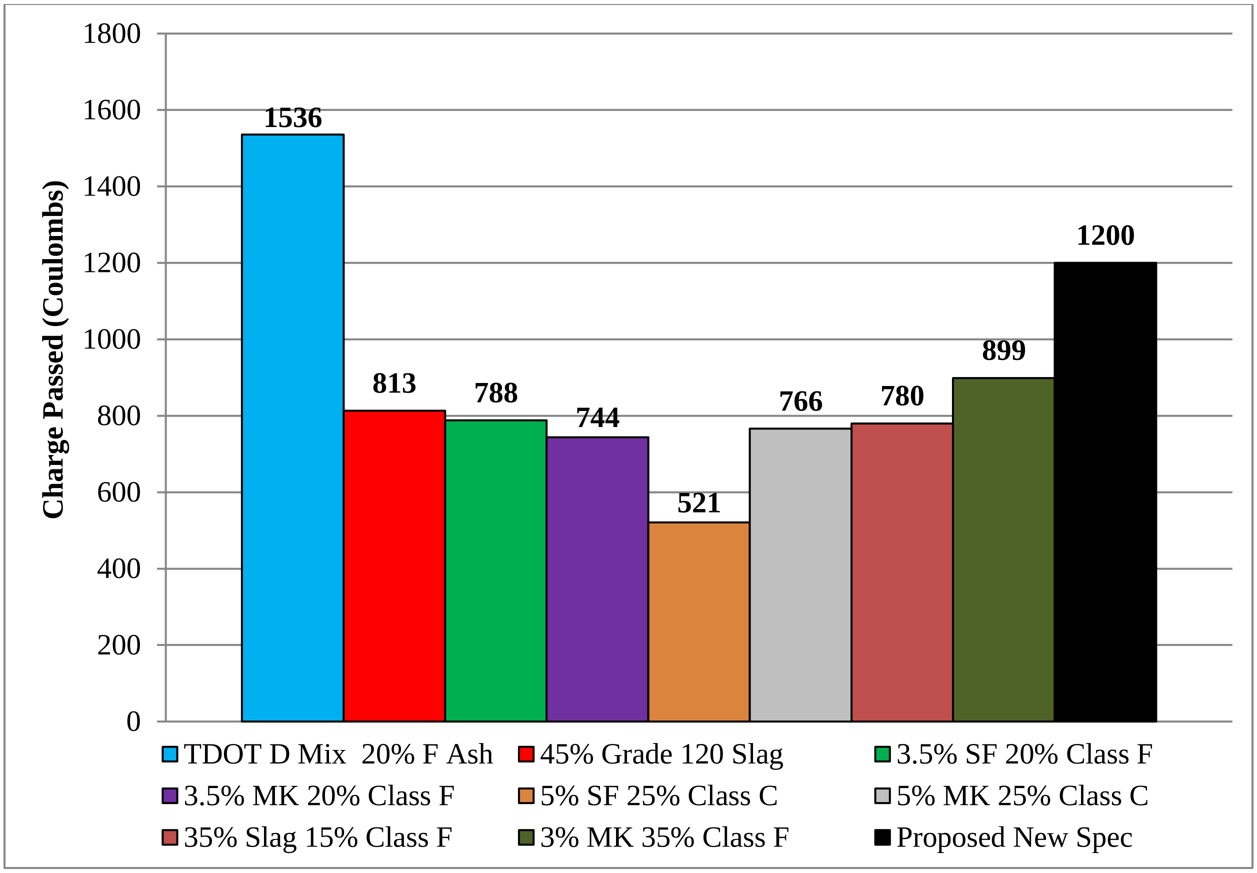

Figure 6.3: 56-Day Rapid Chloride Permeability Comparisons

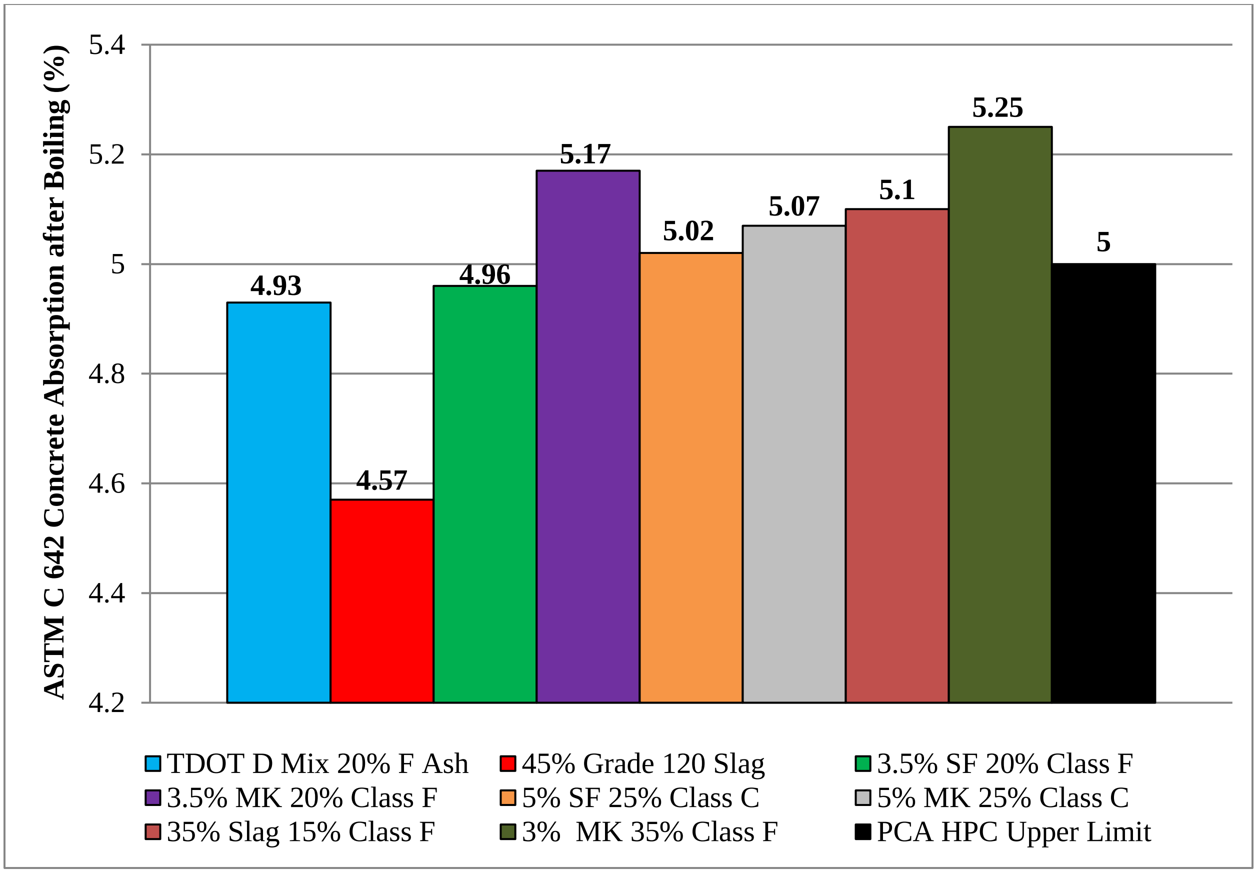

Figure 6.4: 56-Day Hardened Concrete Absorption after Boiling Comparisons

Low Permeability Mixture Comparison

Figure 6.5 shows a comparison of catalog and D-LP maximum, minimum, and mean values of RCP for the seven mixture-types. First, all the RCP results of the seven mixtures met AASHTO T 277-07 requirements for a single operator coefficient of variation (COV) of 12.3%, except for the 5% SF 25% Class C mixture. Second, when a comparison is made of the maximum permeability values obtained for the different mixtures, the 5% SF 25% Class C yields the lowest RCP value. Third, even the maximum RCP value of all seven mixtures was well below (230 coulombs) the proposed new TDOT specification of 1,200 coulombs at 56 days.

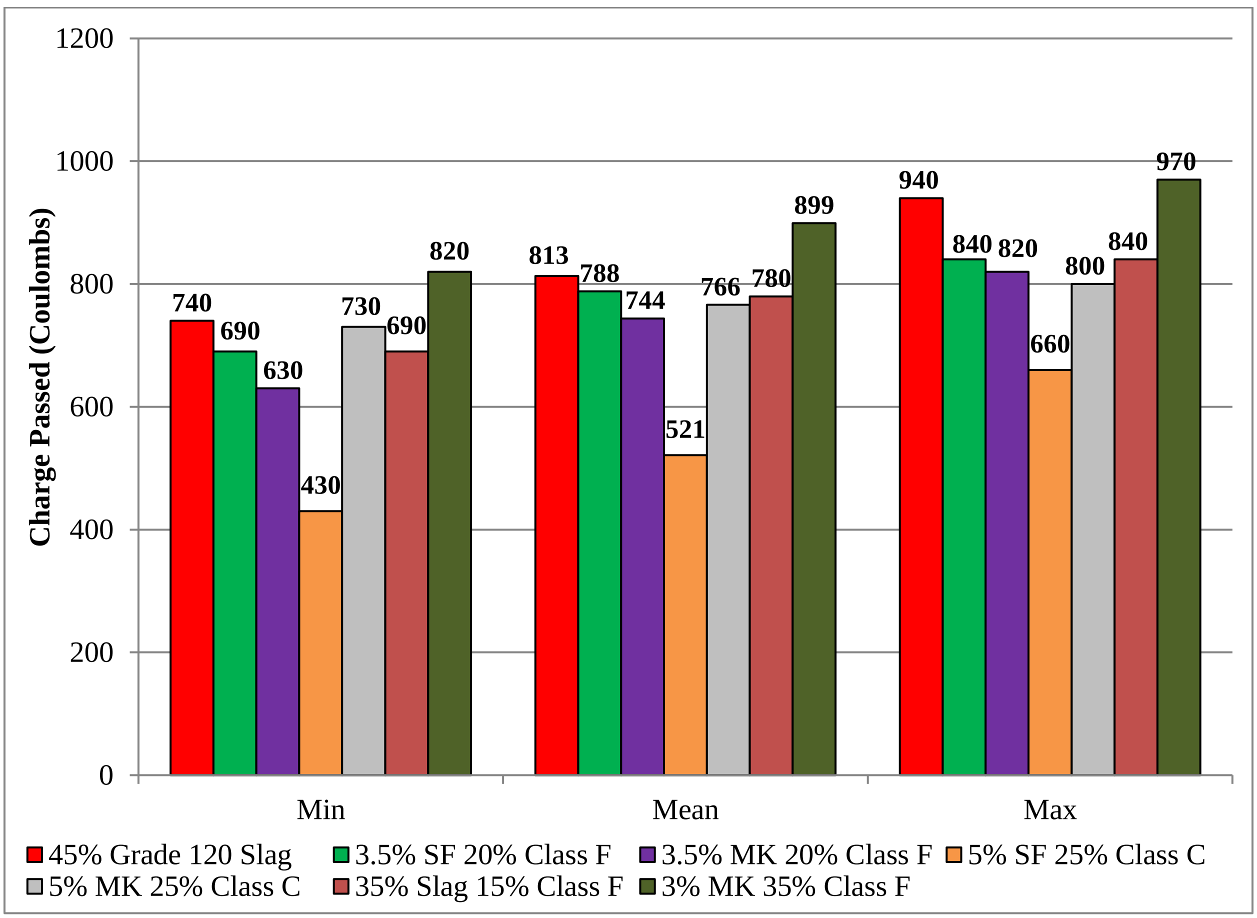

Figure 6.5: Comparison of D-LP 56-day Rapid Chloride Permeability Maximum, Minimum and Mean Values

Statistical Analysis

Comparison of Hardened Properties of Each of the Investigated Mixtures with that of Typical TDOT Class D Mixture

The hardened properties of each of the four investigated mixtures were each in turn compared to those of a typical TDOT Class D mixture from RES 2010-07 to determine whether or not significant differences existed between them. The results of the statistical test of the hypothesis of each mean of a hardened property of a typical TDOT Class D mixture being equal to the corresponding mean of the hardened property of each of the investigated mixtures are reported in Tables 6.2 to 6.5. For each hardened property shown in the first field of each table, the sample mean and sample standard deviation are reported in the second field.

The results show that the mixture with 5% silica fume and 25% Class C fly ash, the mixture with 5% metakaolin and 25% Class C fly ash, and the mixture with 35% slag and 15% Class F fly ash all had 28-day strengths, 56-day strengths, 28-day moduli, and 56-day moduli that significantly exceeded that obtained for the typical TDOT Class D mixture. Each of these three mixtures had a 56-day RCP that was significantly lower than that obtained for the typical TDOT Class D mixture. In addition, each of these three mixtures had a 56-day absorption after boiling that was significantly lower than that obtained for the typical TDOT Class D mixture.

The results also show that the mixture with 3% metakaolin and 35% Class F fly ash had 28-day and 56-day mean strengths that significantly exceeded the corresponding mean strengths obtained for the typical TDOT Class D mixture. However, the 28-day and 56-day mean moduli for these two mixtures were found to be statistically equal. The mean RCP of the mixture with 3% metakaolin and 35% Class F fly ash was significantly lower than that obtained for the typical

TDOT Class D mixture while the mean 56-day absorption after boiling of these two mixtures was found to be equal.

These results show that the hardened properties of concrete made from the four investigated mixtures are either superior to or at worst equivalent to that of a typical TDOT Class D concrete.

TABLE 6.2: Test of Hypotheses of Equality of Means of Hardened Properties of Mixture with 5% Silica Fume and 25% Class C Fly Ash and Typical TDOT Class D Mixture

Hardened Property	Parameter	TDOT Class D	5% Silica Fume and 25% Class C Fly Ash (CSF)	t-Value	Degrees of Freedom	|t-critical|	Result
28-day Strength (psi)	Mean	5030	6755	11.668	24	2.064	CSF significantly greater than Class D
	Standard Deviation	646	386				
56-day Strength (psi)	Mean	5745	7280	9.449	23	2.069	CSF significantly greater than Class D
	Standard Deviation	694	429				
28-day Modulus (ksi)	Mean	4609	4855	3.390	19	2.101	CSF significantly greater than Class D
	Standard Deviation	270	204				
56-day Modulus (ksi)	Mean	4877	4946	1.360	43	2.018	CSF statistically equal to Class D
	Standard Deviation	275	106				
56-day RCP (Coulombs)	Mean	1536	521	-31.239	37	2.026	CSF significantly less than Class D
	Standard Deviation	169	73				
56-day Absorption (%)	Mean	5.30	5.02	-2.676	11	2.228	CSF significantly less than Class D
	Standard Deviation	0.15	0.34				

TABLE 6.3: Test of Hypotheses of Equality of Means of Hardened Properties of Mixture with 5% Metakaolin and 25% Class C Fly Ash and Typical TDOT Class D Mixture

Hardened Property	Parameter	TDOT Class D	5% Metakaolin and 25% Class C Fly Ash (CMK)	t-Value	Degrees of Freedom	|t-critical|	Result
28-day Strength (psi)	Mean	5030	7066	15.365	31	2.040	CMK significantly greater than Class D
	Standard Deviation	646	318				
56-day Strength (psi)	Mean	5745	7435	13.172	41	2.020	CMK significantly greater than Class D
	Standard Deviation	694	274				
28-day Modulus (ksi)	Mean	4609	5005	6.000	21	2.080	CMK significantly greater than Class D
	Standard Deviation	270	179				
56-day Modulus (ksi)	Mean	4877	5145	4.988	35	2.030	CMK significantly greater than Class D
	Standard Deviation	275	123				
56-day RCP (Coulombs)	Mean	1536	766	-30.705	56	2.003	CMK significantly less than Class D
	Standard Deviation	169	25				
56-day Absorption (%)	Mean	5.30	5.07	-2.352	11	2.201	CMK significantly less than Class D
	Standard Deviation	0.15	0.31				

TABLE 6.4: Test of Hypotheses of Equality of Means of Hardened Properties of Mixture with 35% Slag and 15% Class F Fly Ash and Typical TDOT Class D Mixture

Hardened Property	Parameter	TDOT Class D	35% Slag and 15% Class F Fly Ash (FSL)	t-Value	Degrees of Freedom	|t-critical|	Result
28-day Strength (psi)	Mean	5030	7137	19.924	56	2.003	FSL significantly greater than Class D
	Standard Deviation	646	177				
56-day Strength (psi)	Mean	5745	7673	15.351	44	2.015	FSL significantly greater than Class D
	Standard Deviation	694	260				
28-day Modulus (ksi)	Mean	4609	5073	9.162	40	2.023	FSL significantly greater than Class D
	Standard Deviation	270	110				
56-day Modulus (ksi)	Mean	4877	5245	6.498	31	2.042	FSL significantly greater than Class D
	Standard Deviation	275	137				
56-day RCP (Coulombs)	Mean	1536	780	-27.513	57	2.003	FSL significantly less than Class D
	Standard Deviation	169	45				
56-day Absorption (%)	Mean	5.30	5.1	-3.822	14	2.145	FSL significantly less than Class D
	Standard Deviation	0.15	0.15				

TABLE 6.5: Test of Hypotheses of Equality of Means of Hardened Properties for Mixture with 3% Metakaolin and 35% Class F Fly Ash and Typical TDOT Class D Mixture

Hardened Property	Parameter	TDOT Class D	3% Metakaolin and 35% Class F Fly Ash (FMK)	t-Value	Degrees of Freedom	|t-critical|	Result
28-day Strength (psi)	Mean	5030	5823	6.815	45	2.015	FMK significantly greater than Class D
	Standard Deviation	646	239				
56-day Strength (psi)	Mean	5745	6395	5.184	44	2.015	FMK significantly greater than Class D
	Standard Deviation	694	258				
28-day Modulus (ksi)	Mean	4609	4700	1.293	19	2.093	FMK statistically equal to Class D
	Standard Deviation	270	196				
56-day Modulus (ksi)	Mean	4877	4923	0.819	32	2.040	FMK statistically equal to Class D
	Standard Deviation	275	133				
56-day RCP (Coulombs)	Mean	1536	899	-22.054	51	2.008	FMK significantly less than Class D
	Standard Deviation	169	54				
56-day Absorption (%)	Mean	5.30	5.25	-0.973	14	2.145	FMK statistically equal to Class D
	Standard Deviation	0.15	0.16				

Analysis of Rapid Chloride Permeability Test Results

The sample mean and sample standard deviation of the electric charge passed in Rapid Chloride Permeability Tests (RCPT) of the four concrete mixtures investigated in the catalog project are reported in Table 6.6.

TABLE 6.6: Sample Mean and Sample Standard Deviation of the RCP of the Four Class D Low Permeability Mixtures Investigated

Mixture Type	Sample Mean of RCP Values at 56 days (coulombs)	Sample Standard Deviation of RCP Values at 56 days (coulombs)
5% Silica Fume and 25% Class C Fly Ash substitution for PC	521	72.86
5% Metakaolin and 25% Class C Fly Ash substitution for PC	766	24.61
35% Slag and 15% Class F Fly Ash substitution for PC	780	44.72
3% Metakaolin and 35% Class F Fly Ash substitution for PC	899	53.56

These test results show the mixture with 5% Silica Fume and 25% Class C fly ash substitution for PC, with an estimated mean electric charge of 521 coulombs passed, numerically has the lowest RCP of the four mixtures at 56 days. It indicates that this mixture, of the four mixtures investigated, has the lowest chloride permeability. It is followed in permeability performance by the mixture with 5% metakaolin and 25% Class C fly ash substitution for PC, which passed an estimated mean electric charge of 766 coulombs. The concrete mixture with 35% Slag and 15% Class F fly ash substitution for PC with a mean electric charge passed of 780 coulombs follows. The mixture with 3% metakaolin and 35% Class F fly ash substitution for PC numerically has the highest mean electric charge passed (899 coulombs) by any of the mixtures investigated, indicating this mixture to have the highest chloride permeability.

These numerical differences in the mean values of the charge passed by samples made from each of the four concrete mixtures in and of themselves do not necessarily imply that the chloride permeability they each offer are from a statistical viewpoint significantly different since such a comparison of means does not consider the variability in the RCP test results of each mixture. Thus, to reach conclusive statements on whether differences exist in chloride permeability of the four mixtures, a statistical test of the hypothesis that the mean RCPs of different pairs of the four mixtures were equal was undertaken. For the test, a 5% level of significance was used in a two-tailed t-test and the assumption was made that the variances of the RCPs of the mixtures were unknown and unequal. The results of the statistical tests are reported in Table 6.7.

TABLE 6.7: Results of Statistical Test of Equality of the Mean RCP for Pairs of the Four D-LP Mixtures

Mixture Types whose Mean RCPs are Tested for Equality	Results of t-test	Description of Outcome of Statistical Test
Mixture with 5% SF and 25% Class C Fly Ash versus Mixture with 5% MK and 25% Class C Fly Ash	|t-value| = 10.585 |t-critical| = 2.179 Statistically Not Equal	The mean RCP of the mixture with 5% SF and 25% Class C Fly Ash is *significantly less* than the mean RCP of the mixture with 5% MK and 25% Class C Fly Ash
Mixture with 5% SF and 25% Class C Fly Ash versus Mixture with 35% Slag and 15% Class F Fly Ash	|t-value| = 10.051 |t-critical|= 2.120 Statistically Not Equal	The mean RCP of the mixture with 5% SF and 25% Class C Fly Ash is *significantly less* than the mean RCP of the mixture with 35% Slag and 15% Class F Fly Ash
Mixture with 5% SF and 25% Class C Fly Ash versus Mixture with 3% MK and 35% Class F Fly Ash	|t-value| = 13.870 |t-critical|= 2.101 Statistically Not Equal	The mean RCP of the mixture with 5% SF and 25% Class C Fly Ash is *significantly less* than the mean RCP of the mixture with 3% MK and 35% Class F Fly Ash
Mixture with 5% MK and 25% Class C Fly Ash versus Mixture with 35% Slag and 15% Class F Fly Ash	|t-value| = 0.886 |t-critical|= 2.131 Statistically Equal	The mean RCP of the mixture with 5% MK and 25% Class C Fly Ash is *statistically equal* to the mean RCP of the mixture with 35% Slag and 15% Class F Fly Ash
Mixture with 5% MK and 25% Class C Ash versus Mixture with 3% MK and 35% Class F Fly Ash	|t-value| = 7.468 |t-critical|=2.145 Statistically Not Equal	The mean RCP of the mixture with 5% MK and 25% Class C Fly Ash is *significantly less* than the mean RCP of the mixture with 3% MK and 35% Class F Ash
Mixture with 35% Slag and 15% Class F Fly Ash versus Mixture with 3% MK and 35% Class F Fly Ash	|t-value| = 5.660 |t-critical|= 2.093 Statistically Not Equal	The mean RCP of the mixture with 35% Slag and 15% Class F Fly Ash is *significantly less* than the mean RCP of the mixture with 3% MK and 35% Class F Fly Ash

These results show that with the exception of the mixture with 5% metakaolin and 25% Class C fly ash and the mixture with 35% Slag and 15% Class F fly ash, the mean RCP for each mixture is significantly different from the mean RCP of any of the other mixtures. More specifically, they show the mixture with 5% Silica Fume and 25% Class C fly ash to have a chloride permeability that is significantly lower than that of any of the other mixtures investigated. Similarly, the mixture with 5% metakaolin and 25% Class C fly ash has a chloride permeability that is significantly lower than that of the mixture with 3% metakaolin and 35% Class F fly ash. Finally, the mixture with 35% slag and 15% Class F fly ash also has a chloride permeability that is significantly lower than that of the mixture with 3% metakaolin and 35% Class F fly ash. As stated above, the two mixtures, of the four investigated, whose chloride permeability estimates were found to be statistically equal are the mixture with 5% metakaolin and 25% Class C fly ash and the mixture with 35% slag and 15% Class F fly ash.

The proposed RCP specification for D-LP at 56 days maturity is 1200 coulombs. Thus, statistical tests were undertaken of the hypothesis of the mean RCP of each mixture type being equal to the specified value of 1200 coulombs. Again, a 5% level of significance was used in a two-tailed t-test. The results of the t-test are reported in Table 6.8.

TABLE 6.8: Test of Hypothesis of Equality of the Mean RCP of Each D-LP Mixture and the Specified Value of 1200 Coulombs

Mixture Type	Test of Equality of the Mean RCP of a Mixture to 1200 Coulombs	Description of Outcome of Statistical Test
5% Silica Fume and 25% Class C Fly Ash substitution for PC	|t-value| =30.991 |t-critical| =2.228	Mean RCP of mixture with 5% Silica Fume and 25% C Fly Ash is significantly less than 1200 coulombs
5% Metakaolin and 25% Class C Fly Ash substitution for PC	|t-value| = 58.450 |t-critical| =2.228	Mean RCP of mixture with 5% Metakaolin and 25% C Fly Ash is significantly less than 1200 coulombs
35% Slag and 15% Class F Fly Ash substitution for PC	|t-value| =31.148 |t-critical| =2.228	Mean RCP of mixture with 35% Slag and 15% Class F Fly Ash is significantly less than 1200 coulombs
3% Metakaolin and 35% Class F Fly Ash substitution for PC	|t-value| =18.632 |t-critical| =2.228	Mean RCP of mixture with 3% Metakaolin and 35% Class F Fly Ash is significantly less than 1200 coulombs

The absolute value of the computed t-value is reported in the second column of Table 6.8 since for each mixture, the computed t-value had a negative sign because the mean RCP of each mixture was lower than the specified RCP value of 1200 coulombs. For each of the four proposed Class D Low Permeability mixtures, the computed magnitude of the t-statistic far exceeds the magnitude of the critical t-value determined at 10 degrees of freedom, indicating the chloride permeability of each mixture to be significantly lower than the proposed specification of 1200 coulombs and therefore meeting that standard.

Material Cost Comparison

Figure 6.6 shows a comparison of material costs of TDOT Class D, D-LP, and catalog mixtures. Table 6.9 shows a summary comparison of the D-LP and catalog validation mixtures, including some intangible factors. Metakaolin is not a by-product, but rather a purpose produced product. Therefore, metakaolin is not considered a “green” cement replacement. The question of “How different is it from TDOT Class D?” refers to the difficulty that a concrete producer would have changing from a TDOT Class D PCC to a proposed Class D-LP or catalog mixture. Silica fume and metakaolin can be delivered in small bags (25-lbs SF, 55-lbs MK) that do not require equipment for loading into a ready mix truck.

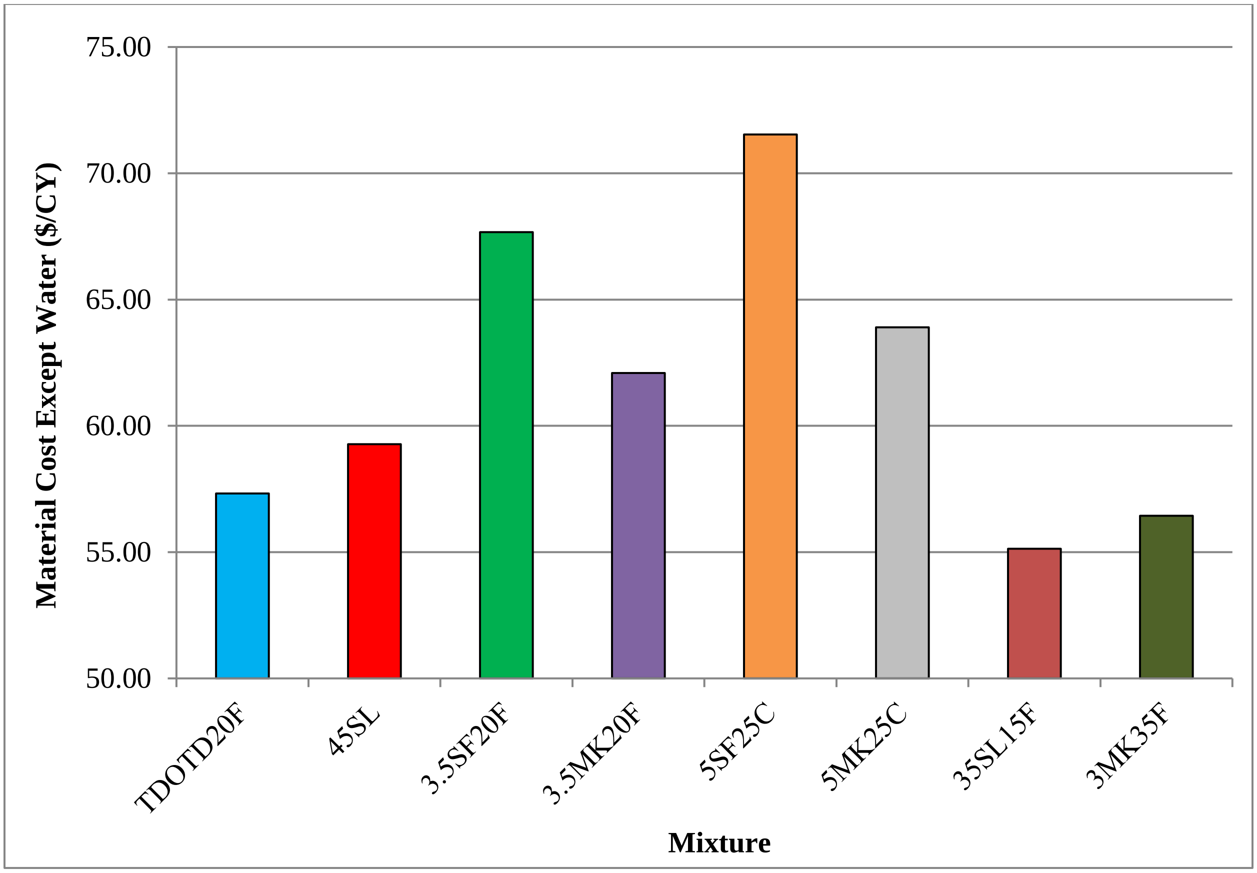

Figure 6.6: Comparison of Material Costs of TDOT Class D, D-LP, and Catalog Mixtures

Table 6.9: Class D-LP and Catalog Summary Comparisons

Mixture	Relative Cost	How "Green" is it?	How different is it from a TDOT Class D Mixture?	Main Advantage	Main Disadvantage
55PC/ 45SL	Third Lowest	Second Most	Very	Green	Need a Slag Silo
76.5PC/ 20F/ 3.5SF	Second Highest	Second Least	Not Much	V. Easy	V. Expensive
76.5PC/ 20F/ 3.5MK	Middle	Least	Not Much	V. Easy	Expensive
70PC/ 25C/ 5SF	Highest	Middle	Not Much	V. Easy	V. Expensive
70PC/ 25C/ 5MK	Third Highest	Third Least	Not Much	V. Easy	Expensive
50PC/ 35SL/ 15F	Lowest	Most	Very	Cheap & Green	Need a Slag Silo
62PC/ 35F/ 3MK	Second Lowest	Third Most	Middle	V. Easy	Slower strength development in cold weather?

CHAPTER 7 : CONCLUSIONS

The following conclusions can be drawn from the results obtained from this study:

1. Concrete mixtures using only materials widely available in Tennessee and meeting TDOT Class D property requirements can be developed whose mean RCPs are significantly lower than the proposed 1,200 coulombs at 56 days. Further, these mixtures can be very similar in composition to a typical current TDOT Class D concrete mixture.

2. The mean RCPs of all four mixtures developed in this study, 5% silica fume with 25% Class C fly ash, 5% metakaolin with 25% Class C fly ash, 35% Grade 120 slag with 15% Class F fly ash, and 3% metakaolin with 35% Class F fly ash were significantly lower than the proposed 1,200 coulombs at 56 days at the 5% significance level.

3. Plastic and hardened properties of all batches of all four mixtures developed in the project met TDOT 604.03 Class D property requirements.

4. Mean hardened properties of all four mixtures developed in the project were either similar to, or superior to, a comparison Class D mixture from RES 2010-07.

CHAPTER 8 : RECOMMENDATIONS

1. The authors recommend that TDOT pursue the development of Class D-LP (Lower Permeability) concrete specification with a maximum allowable RCP of 1,200 coulombs at 56 days. Concrete specimens would be field-cast, lab-cured, and tested as per AASTHO T 277-07.
2. The authors further recommend that TDOT continue the development an informational catalog that provides examples of more concrete mixtures that have a high probability of meeting the proposed new specification. The catalog would not be a recipe book or a complete list of mixtures that could meet the specification, but would rather provide laboratory-tested ideas for experienced mixture designers attempting to produce concrete mixtures that meet the proposed new specification.

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APPENDICES

Appendix A

28-day Compressive Strength

Identification	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Range (psi)	Compressive Strength (psi)
CSF-1	5/23/2013	6830	6909	79	6870
CSF-2	5/28/2013	7111	6988	123	7050
CSF-3	5/28/2013	7486	7243	243	7370
CSF-4	5/30/2013	6850	6797	53	6820
CSF-5	5/30/2013	6642	6680	38	6660
CSF-6	6/4/2013	6926	6975	49	6950
CSF-7	6/4/2013	6803	6585	218	6690
CSF-8	6/11/2013	7017	6933	84	6980
CSF-9	6/11/2013	5869	5841	28	5860
CSF-10	6/13/2013	6443	6579	136	6510
CSF-11	6/13/2013	6427	6662	235	6550
CMK-1	6/18/2013	7482	7278	204	7380
CMK-2	6/18/2013	7085	6952	133	7020
CMK-3	6/20/2013	6721	7186	465	6950
CMK-4	6/20/2013	6658	6753	95	6710
CMK-5	6/25/2013	7153	7747	594	7450
CMK-6	6/25/2013	6914	6943	29	6930
CMK-7	6/27/2013	6928	6812	116	6870
CMK-8	6/27/2013	6855	6564	291	6710
CMK-9	7/2/2013	7660	7614	46	7640
CMK-10	7/2/2013	6813	6786	27	6800
CMK-11	7/4/2013	7349	7199	150	7270

Appendix A (continued)

28-day Compressive Strength

Identification	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Range (psi)	Compressive Strength (psi)
50PC/35SL/15F-1	7/18/2013	7023	6748	275	6890
50PC/35SL/15F-2	7/18/2013	6826	7072	246	6950
50PC/35SL/15F-3	7/23/2013	7241	7346	105	7290
50PC/35SL/15F-4	7/23/2013	7458	7276	182	7370
50PC/35SL/15F-5	7/25/2013	7454	7193	261	7320
50PC/35SL/15F-6	7/25/2013	7295	7259	36	7280
50PC/35SL/15F-7	8/1/2013	7228	6976	252	7100
50PC/35SL/15F-8	8/1/2013	7046	6755	291	6900
50PC/35SL/15F-9	8/6/2013	7180	7352	172	7270
50PC/35SL/15F-10	8/15/2013	7092	7070	22	7080
50PC/35SL/15F-11	8/15/2013	7118	7003	115	7060
62PC/35F/3MK-1	8/22/2013	5827	5990	163	5910
62PC/35F/3MK-2	8/22/2013	5644	5557	87	5600
62PC/35F/3MK-3	9/5/2013	6037	6179	142	6110
62PC/35F/3MK-4	9/5/2013	5805	6060	255	5930
62PC/35F/3MK-5	9/10/2013	5988	6064	76	6030
62PC/35F/3MK-6	9/10/2013	5559	5740	181	5650
62PC/35F/3MK-7	9/17/2013	5499	5535	36	5520
62PC/35F/3MK-8	9/17/2013	5414	5426	12	5420
62PC/35F/3MK-9	9/19/2013	5921	5983	62	5950
62PC/35F/3MK-10	9/19/2013	5841	5817	24	5830
62PC/35F/3MK-11	9/24/2013	6075	6116	41	6100

Appendix B

56-day Compressive Strength

Identification	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Range (psi)	Compressive Strength (psi)
CSF-1	5/23/2013	7428	7869	441	7650
CSF-2	5/28/2013	7870	7488	382	7680
CSF-3	5/28/2013	7993	7724	269	7860
CSF-4	5/30/2013	7267	7036	231	7150
CSF-5	5/30/2013	7118	7000	118	7060
CSF-6	6/4/2013	7335	7746	411	7540
CSF-7	6/4/2013	7425	7311	114	7370
CSF-8	6/11/2013	7315	7640	325	7480
CSF-9	6/11/2013	6466	6293	173	6380
CSF-10	6/13/2013	6966	6829	137	6900
CSF-11	6/13/2013	6985	7028	43	7010
CMK-1	6/18/2013	7885	7832	53	7860
CMK-2	6/18/2013	7737	7670	67	7700
CMK-3	6/20/2013	7093	7386	293	7240
CMK-4	6/20/2013	7059	7094	35	7080
CMK-5	6/25/2013	7408	7687	279	7550
CMK-6	6/25/2013	7036	7535	499	7290
CMK-7	6/27/2013	7328	7442	114	7390
CMK-8	6/27/2013	7179	7207	28	7190
CMK-9	7/2/2013	7966	7732	234	7850
CMK-10	7/2/2013	7167	7737	570	7450
CMK-11	7/4/2013	7188	7173	15	7180

Appendix B (continued)

56-day Compressive Strength

Identification	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Range (psi)	Compressive Strength (psi)
50PC/35SL/15F-1	7/18/2013	6965	7292	327	7120
50PC/35SL/15F-2	7/18/2013	7454	7385	69	7420
50PC/35SL/15F-3	7/23/2013	7711	8014	303	7860
50PC/35SL/15F-4	7/23/2013	8023	7932	91	7980
50PC/35SL/15F-5	7/25/2013	7609	8257	648	7930
50PC/35SL/15F-6	7/25/2013	8122	7775	347	7950
50PC/35SL/15F-7	8/1/2013	7379	7651	272	7520
50PC/35SL/15F-8	8/1/2013	7620	7699	79	7660
50PC/35SL/15F-9	8/6/2013	7540	7724	184	7630
50PC/35SL/15F-10	8/15/2013	7606	7835	229	7720
50PC/35SL/15F-11	8/15/2013	7888	7321	567	7610
62PC/35F/3MK-1	8/22/2013	6509	6764	255	6640
62PC/35F/3MK-2	8/22/2013	6269	6388	119	6330
62PC/35F/3MK-3	9/5/2013	6742	6615	127	6680
62PC/35F/3MK-4	9/5/2013	6646	6634	12	6640
62PC/35F/3MK-5	9/10/2013	6329	6580	251	6460
62PC/35F/3MK-6	9/10/2013	6092	6241	149	6170
62PC/35F/3MK-7	9/17/2013	6036	5930	106	5980
62PC/35F/3MK-8	9/17/2013	6058	6088	30	6070
62PC/35F/3MK-9	9/19/2013	6300	6417	117	6360
62PC/35F/3MK-10	9/19/2013	6253	6304	51	6280
62PC/35F/3MK-11	9/24/2013	6625	6826	201	6730

Appendix C

28-day Static Modulus of Elasticity

Identification	Cast Date	Run 2 Result (psi)	Run 3 Result (psi)	Range (psi)	Static Modulus of Elasticity (psi)
CSF-1	5/23/2013	4770000	4790000	20000	4800000
CSF-2	5/28/2013	4860000	4870000	10000	4850000
CSF-3	5/28/2013	5300000	5220000	80000	5250000
CSF-4	5/30/2013	4890000	4880000	10000	4900000
CSF-5	5/30/2013	4720000	4760000	40000	4750000
CSF-6	6/4/2013	4900000	4910000	10000	4900000
CSF-7	6/4/2013	4830000	4790000	40000	4800000
CSF-8	6/11/2013	5130000	5160000	30000	5150000
CSF-9	6/11/2013	4450000	4500000	50000	4500000
CSF-10	6/13/2013	4680000	4680000	0	4700000
CSF-11	6/13/2013	4800000	4790000	10000	4800000
CMK-1	6/18/2013	5100000	5120000	20000	5100000
CMK-2	6/18/2013	4980000	4980000	0	5000000
CMK-3	6/20/2013	5040000	4990000	50000	5000000
CMK-4	6/20/2013	4840000	4840000	0	4850000
CMK-5	6/25/2013	Damage	Damage	—	—
CMK-6	6/25/2013	5280000	5360000	80000	5300000
CMK-7	6/27/2013	4880000	4850000	30000	4850000
CMK-8	6/27/2013	4930000	4900000	30000	4900000
CMK-9	7/2/2013	5290000	5270000	20000	5300000
CMK-10	7/2/2013	4740000	4820000	80000	4800000
CMK-11	7/4/2013	4930000	4960000	30000	4950000

Appendix C (continued)

28-day Static Modulus of Elasticity

Identification	Cast Date	Run 2 Result (psi)	Run 3 Result (psi)	Range (psi)	Static Modulus of Elasticity (psi)
50PC/35SL/15F-1	7/18/2013	4970000	4930000	40000	4950000
50PC/35SL/15F-2	7/18/2013	4980000	4910000	70000	4950000
50PC/35SL/15F-3	7/23/2013	5100000	5120000	20000	5100000
50PC/35SL/15F-4	7/23/2013	5260000	5260000	0	5250000
50PC/35SL/15F-5	7/25/2013	5100000	5120000	20000	5100000
50PC/35SL/15F-6	7/25/2013	5260000	5260000	0	5250000
50PC/35SL/15F-7	8/1/2013	5060000	5070000	10000	5050000
50PC/35SL/15F-8	8/1/2013	5040000	5040000	0	5050000
50PC/35SL/15F-9	8/6/2013	5170000	5170000	0	5150000
50PC/35SL/15F-10	8/15/2013	4970000	4970000	0	4950000
50PC/35SL/15F-11	8/15/2013	4970000	5060000	90000	5000000
62PC/35F/3MK-1	8/22/2013	5070000	5070000	0	5050000
62PC/35F/3MK-2	8/22/2013	4600000	4640000	40000	4600000
62PC/35F/3MK-3	9/5/2013	4740000	4740000	0	4750000
62PC/35F/3MK-4	9/5/2013	5010000	4990000	20000	5000000
62PC/35F/3MK-5	9/10/2013	4570000	4530000	40000	4550000
62PC/35F/3MK-6	9/10/2013	4550000	4530000	20000	4550000
62PC/35F/3MK-7	9/17/2013	4430000	4410000	20000	4400000
62PC/35F/3MK-8	9/17/2013	4590000	4640000	50000	4600000
62PC/35F/3MK-9	9/19/2013	4650000	4680000	30000	4650000
62PC/35F/3MK-10	9/19/2013	4730000	4790000	60000	4750000
62PC/35F/3MK-11	9/24/2013	4790000	4840000	50000	4800000

Appendix D

56-day Static Modulus of Elasticity

Identification	Cast Date	Run 2 Result (psi)	Run 3 Result (psi)	Range (psi)	Static Modulus of Elasticity (psi)
CSF-1	5/23/2013	4980000	4970000	10000	5000000
CSF-2	5/28/2013	4950000	4950000	0	4950000
CSF-3	5/28/2013	5170000	5160000	10000	5150000
CSF-4	5/30/2013	5060000	5060000	0	5050000
CSF-5	5/30/2013	5040000	4990000	50000	5000000
CSF-6	6/4/2013	4990000	4920000	70000	4950000
CSF-7	6/4/2013	4890000	4850000	40000	4850000
CSF-8	6/11/2013	4960000	4980000	20000	4950000
CSF-9	6/11/2013	4790000	4790000	0	4800000
CSF-10	6/13/2013	4920000	4890000	30000	4900000
CSF-11	6/13/2013	4790000	4820000	30000	4800000
CMK-1	6/18/2013	5130000	5140000	10000	5150000
CMK-2	6/18/2013	5160000	5200000	40000	5200000
CMK-3	6/20/2013	4980000	4980000	0	5000000
CMK-4	6/20/2013	4970000	4980000	10000	5000000
CMK-5	6/25/2013	5310000	5270000	40000	5300000
CMK-6	6/25/2013	5190000	5150000	40000	5150000
CMK-7	6/27/2013	4930000	4990000	60000	4950000
CMK-8	6/27/2013	5160000	5190000	30000	5200000
CMK-9	7/2/2013	5130000	5190000	60000	5150000
CMK-10	7/2/2013	5140000	5200000	60000	5150000
CMK-11	7/4/2013	5370000	5360000	10000	5350000

Appendix D (continued)

56-day Static Modulus of Elasticity

Identification	Cast Date	Run 2 Result (psi)	Run 3 Result (psi)	Range (psi)	Static Modulus of Elasticity (psi)
50PC/35SL/15F-1	7/18/2013	5190000	5130000	60000	5150000
50PC/35SL/15F-2	7/18/2013	5160000	5180000	20000	5150000
50PC/35SL/15F-3	7/23/2013	4940000	4950000	10000	4950000
50PC/35SL/15F-4	7/23/2013	5450000	5350000	100000	5400000
50PC/35SL/15F-5	7/25/2013	5340000	5330000	10000	5350000
50PC/35SL/15F-6	7/25/2013	5240000	5200000	40000	5200000
50PC/35SL/15F-7	8/1/2013	5290000	5290000	0	5300000
50PC/35SL/15F-8	8/1/2013	5350000	5360000	10000	5350000
50PC/35SL/15F-9	8/6/2013	5330000	5330000	0	5350000
50PC/35SL/15F-10	8/15/2013	5170000	5170000	0	5150000
50PC/35SL/15F-11	8/15/2013	5360000	5370000	10000	5350000
62PC/35F/3MK-1	8/22/2013	4970000	4980000	10000	5000000
62PC/35F/3MK-2	8/22/2013	4820000	4820000	0	4800000
62PC/35F/3MK-3	9/5/2013	5080000	5080000	0	5100000
62PC/35F/3MK-4	9/5/2013	4950000	4920000	30000	4950000
62PC/35F/3MK-5	9/10/2013	5000000	5010000	10000	5000000
62PC/35F/3MK-6	9/10/2013	4740000	4740000	0	4750000
62PC/35F/3MK-7	9/17/2013	5010000	5050000	40000	5050000
62PC/35F/3MK-8	9/17/2013	5060000	4980000	80000	5000000
62PC/35F/3MK-9	9/19/2013	4980000	4980000	0	5000000
62PC/35F/3MK-10	9/19/2013	4760000	4740000	20000	4750000
62PC/35F/3MK-11	9/24/2013	4760000	4760000	0	4750000

Appendix E

56-day Rapid Chloride Permeability

Identification	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
CSF-1	539	567	559	28	560
CSF-2	425	486	426	61	450
CSF-3	509	520	501	19	510
CSF-4	348	439	496	148	430
CSF-5	463	480	477	17	470
CSF-6	507	510	449	61	490
CSF-7	Malfunction	488	560	72	520
CSF-8	438	590	500	152	510
CSF-9	681	658	638	43	660
CSF-10	477	548	458	90	490
CSF-11	627	628	678	51	640
CMK-1	745	723	763	40	740
CMK-2	782	749	737	45	760
CMK-3	803	781	787	22	790
CMK-4	698	781	764	83	750
CMK-5	749	770	730	40	750
CMK-6	693	739	744	51	730
CMK-7	800	767	702	98	760
CMK-8	788	777	825	48	800
CMK-9	762	761	759	3	760
CMK-10	788	809	784	25	790
CMK-11	810	790	Malfunction	20	800

Appendix E (continued)

56-day Rapid Chloride Permeability

Identification	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
50PC/35SL/15F-1	802	761	778	41	780
50PC/35SL/15F-2	759	757	755	4	760
50PC/35SL/15F-3	772	764	814	50	780
50PC/35SL/15F-4	780	811	813	33	800
50PC/35SL/15F-5	875	799	837	76	840
50PC/35SL/15F-6	798	863	839	65	830
50PC/35SL/15F-7	662	Malfunction	712	50	690
50PC/35SL/15F-8	699	749	775	76	740
50PC/35SL/15F-9	725	746	761	36	740
50PC/35SL/15F-10	804	806	810	6	810
50PC/35SL/15F-11	763	817	852	89	810
62PC/35F/3MK-1	893	883	874	19	880
62PC/35F/3MK-2	808	807	829	22	820
62PC/35F/3MK-3	839	856	793	63	830
62PC/35F/3MK-4	830	861	835	31	840
62PC/35F/3MK-5	967	922	879	88	920
62PC/35F/3MK-6	973	970	947	26	960
62PC/35F/3MK-7	944	982	888	94	940
62PC/35F/3MK-8	979	904	1027	123	970
62PC/35F/3MK-9	875	837	902	65	870
62PC/35F/3MK-10	919	962	943	43	940
62PC/35F/3MK-11	934	895	944	49	920

Appendix F

56-day Concrete Absorption after Boiling

Identification	Slice 1 Result (%)	Slice 2 Result (%)	Slice 3 Result (%)	Range (%)	Absorption after Boiling (%)
CSF-1	5.02	5.04	4.98	0.06	5
CSF-2	4.99	5.12	4.96	0.16	5
CSF-3	4.34	4.38	4.35	0.04	4.4
CSF-4	4.39	4.38	4.41	0.03	4.4
CSF-5	5.09	5.11	5.07	0.04	5.1
CSF-6	5.17	5.25	5.3	0.13	5.2
CSF-7	5.04	4.96	5.04	0.08	5
CSF-8	5.13	5.29	5.14	0.16	5.2
CSF-9	5.4	5.32	5.58	0.26	5.4
CSF-10	5.02	5.11	5.1	0.09	5.1
CSF-11	5.36	5.4	5.43	0.07	5.4
CMK-1	5.13	5.03	5.27	0.24	5.1
CMK-2	5.13	5.1	5.12	0.03	5.1
CMK-3	5.34	5.28	5.32	0.06	5.3
CMK-4	4.99	5.1	5.05	0.11	5.1
CMK-5	4.57	4.61	4.66	0.09	4.6
CMK-6	4.67	4.63	4.86	0.23	4.7
CMK-7	5.39	5.19	5.39	0.2	5.3
CMK-8	5.37	5.36	5.62	0.26	5.5
CMK-9	5.2	5.21	5.21	0.01	5.2
CMK-10	5.38	5.25	5.18	0.2	5.3
CMK-11	4.57	4.62	4.69	0.12	4.6

Appendix F (continued)

56-day Concrete Absorption after Boiling

Identification	Slice 1 Result (%)	Slice 2 Result (%)	Slice 3 Result (%)	Range (%)	Absorption after Boiling (%)
50PC/35SL/15F-1	5.21	5.12	5.12	0.09	5.2
50PC/35SL/15F-2	5	5.01	5.16	0.16	5.1
50PC/35SL/15F-3	5.36	4.86	4.95	0.5	5.1
50PC/35SL/15F-4	5.31	5.33	Damaged	0.02	5.3
50PC/35SL/15F-5	4.95	4.74	5.01	0.27	4.9
50PC/35SL/15F-6	5.37	5.57	5.15	0.42	5.4
50PC/35SL/15F-7	4.99	5.14	4.94	0.2	5
50PC/35SL/15F-8	4.98	5.37	4.93	0.44	5.1
50PC/35SL/15F-9	4.84	4.98	4.87	0.11	4.9
50PC/35SL/15F-10	5.02	4.96	4.86	0.16	5
50PC/35SL/15F-11	5.05	5.15	5.23	0.18	5.1
62PC/35F/3MK-1	5.57	5.3	5.27	0.3	5.4
62PC/35F/3MK-2	5.43	5.47	5.37	0.1	5.4
62PC/35F/3MK-3	5.35	5.4	5.43	0.08	5.4
62PC/35F/3MK-4	5.51	5.49	5.31	0.2	5.4
62PC/35F/3MK-5	4.93	4.95	5.14	0.21	5
62PC/35F/3MK-6	5.07	5.18	5.19	0.12	5.2
62PC/35F/3MK-7	5.23	5.23	5.2	0.03	5.2
62PC/35F/3MK-8	5.35	5.29	5.23	0.12	5.3
62PC/35F/3MK-9	5.14	5.12	5.01	0.13	5.1
62PC/35F/3MK-10	5.39	5.23	5.32	0.16	5.3
62PC/35F/3MK-11	4.91	4.96	5.05	0.14	5