Development of Performance Properties of Ternary Mixtures and Concrete Pavement Mixture Design and Analysis (MDA):

Effect of Paste Quality on Fresh and Hardened Properties of Ternary Mixtures

National Concrete Pavement Technology Center

Technical Report
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16. Abstract

The purpose of this study was to investigate the effect of cement paste quality on the concrete performance, particularly fresh properties, by changing the water-to-cementitious materials ratio (w/cm), type and dosage of supplementary cementitious materials (SCM), and air-void system in binary and ternary mixtures.

In this experimental program, a total matrix of 54 mixtures with w/cm of 0.40 and 0.45; target air content of 2%, 4%, and 8%; a fixed cementitious content of 600 pounds per cubic yard (pcy), and the incorporation of three types of SCMs at different dosages was prepared. The fine aggregate-to- total aggregate ratio was fixed at 0.42. Workability, rheology, air-void system, setting time, strength, Wenner Probe surface resistivity, and shrinkage were determined.

The effects of paste variables on workability are more marked at the higher w/cm. The compressive strength is strongly influenced by the paste quality, dominated by w/cm and air content. Surface resistivity is improved by inclusion of Class F fly ash and slag cement, especially at later ages. Ternary mixtures performed in accordance with their ingredients. The data collected will be used to develop models that will be part of an innovative mix proportioning procedure.

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DEVELOPMENT OF PERFORMANCE PROPERTIES OF TERNARY MIXTURES AND CONCRETE PAVEMENT MIXTURE DESIGN AND ANALYSIS (MDA): EFFECT OF PASTE QUALITY ON THE FRESH AND HARDENED PROPERTIES OF TERNARY MIXTURES

Technical Report
July 2012

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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- California
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INTRODUCTION

The aim of the work described in this report was to investigate how changes in the amount and type of cementitious materials would affect mixture performance, particularly the fresh properties. Cementitious systems included ordinary portland cement, binary mixtures with slag cement, Type F and C fly ash, and ternary mixtures containing a combination of slag cement and one type of fly ash. It is intended that these data will contribute to the body of knowledge about ternary mixtures, as well as provide input data for other work investigating an innovative approach to mixture proportioning.

LITERATURE REVIEW

This section presents a brief review of literature focusing on effects of cementitious systems on three concrete properties:

- Workability
- Strength
- Durability

Concrete properties are affected by the concrete mixture components. Therefore, the effect of the following mixture characteristics on workability, strength, and durability are discussed:

- Water-to-cementitious materials ratio (w/cm)
- Supplementary cementitious materials (SCM)
- Air-void system

A detailed literature review regarding the effect of mix characteristics (w/cm, SCM, cement content, aggregates, and chemical admixtures) on a wider range of concrete properties can be accessed in the technical report of "Optimizing Cementitious Content in Concrete Mixtures for Required Performance (2012) [1]".

Workability

The American Concrete Institute (ACI) Committee 116R (2000) [2] defines workability as "that property of freshly mixed concrete or mortar that determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished to a homogenous condition."

Workability affects concrete mixture performance, as low workability is difficult to place and finish, resulting in quality problems such as honeycomb, bleeding, segregation; strength loss, and also durability problems associated with improper consolidation [3, 4]. Deficiencies in freshly made concrete such as loss of workability, segregation, and bleeding during the consolidation can reduce the service life [5]. Segregation is harmful especially while placing concrete for pavement because it causes strength loss, edge slump, spalling and scaling, thereby reducing the pavement lifetime [5]. Therefore, for an adequate pavement lifetime, a workable concrete mixture should be produced that is flowable under vibration and stable after finishing and consolidating.

Workability is commonly assessed using the slump test even though the test is of limited value because it does not fully characterize concrete flow [6]. The slump test, however, is a useful indicator of uniformity between batches [7].

The effect of w/cm, SCM, and air-void system on workability of a mixture is discussed below.

w/cm

For a given cement content, increasing the water content in concrete will increase the flow and compactability of the mix, thus enhancing the workability [5, 7, 8]. However, excessive water content should be avoided to reduce the risk of segregation and bleeding [5, 8, 9] as well as to avoid the detrimental effects on associated performance of the hardened mixture due to increased w/cm.

SCM

Supplementary cementitious materials generally improve the workability of concrete and decrease the tendency to bleed and segregate by enhancing the packing density. This is due to their lower specific gravity and smaller particle size compared to ordinary portland cement [5, 7-14].

The particle size distribution, morphology, and surface characteristics of SCM play an important role on workability [4]. For example, mixtures containing fly ash tend to improve workability due to the spherical morphology that leads the reduction of the inter-particle friction. On the other hand, silica fume increases the water requirement and stickiness of a concrete mixture because of its high surface area [4, 5, 7, 12, 15, 16].

Air-void system

For a given w/cm, entrained air improves the workability and consistency of concrete mixtures by increasing the paste volume, especially those containing low cement and water content, rough-textured aggregates, or lightweight aggregates [4, 5].

Strength

Strength is a property used as a primary design input in all pavement design procedures because it defines the ability of concrete to resist stress without failure [4, 5].

The response of concrete to applied stress depends on the stress type and how the porosity of overall concrete is affected by the following factors [4]:

- w/cm
- compaction
- curing conditions
- degree of hydration
- aggregate size and mineralogy
- admixture types
- SCM
- air-void system

The effect of w/cm, SCM, and air-void system on strength is discussed below.

w/cm

Abrams [17] established the relationship that increasing w/cm decreases strength.

Strength at any age is a function of w/cm and the degree to which the cementitious materials have hydrated, because they affect the porosity of both cement paste and the interfacial transition zone (ITZ) between the coarse aggregate and cement paste [4, 5, 7-9, 18].

According to Kennedy [19], the strength of concrete is determined by the amount of mixing water, as long as the volume of cement paste is sufficient to fill the voids between aggregate particles and coat the aggregate particles. Strength decreases with increasing w/cm (Figure 1) because the capillary porosity increases as presented in Figure 2 [5, 7-9, 18, 20, 21].

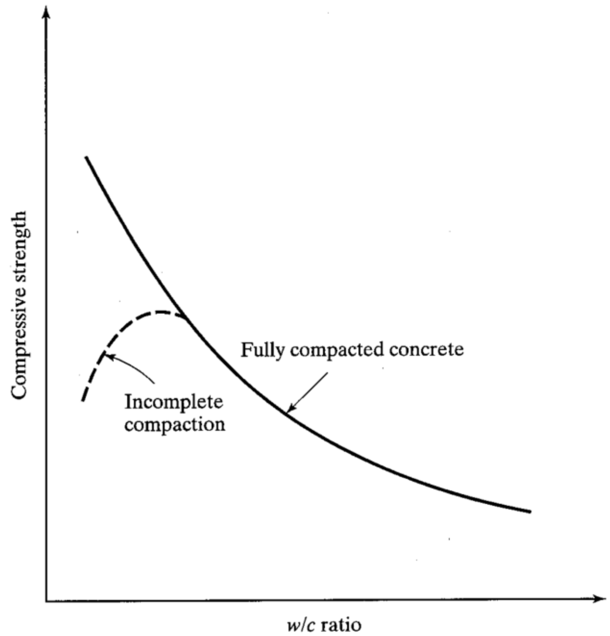


Figure 1. Relationship between compressive strength and water-to-cement (w/c) ratio [8]

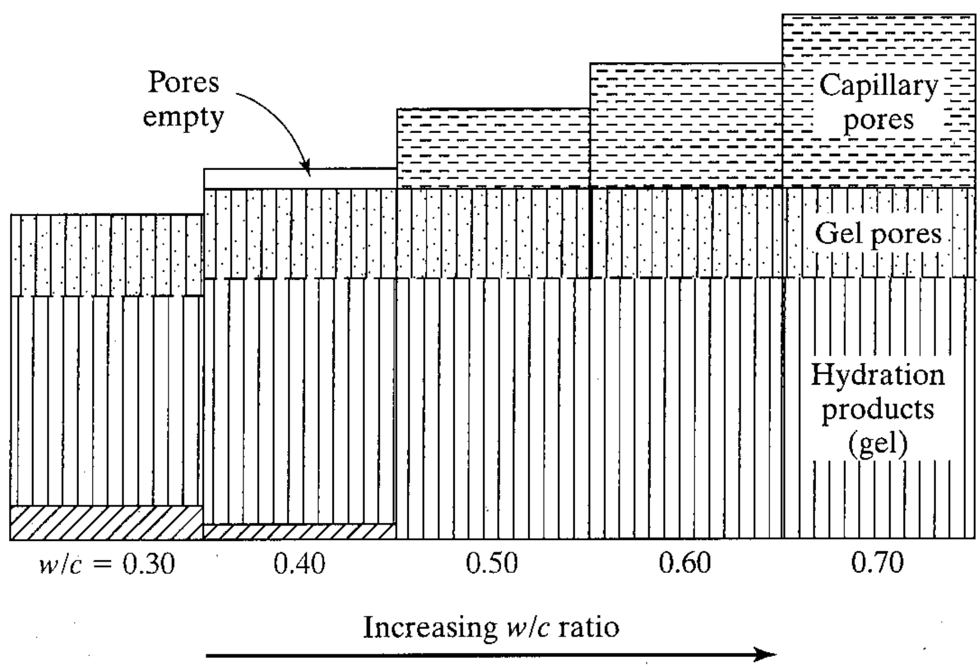
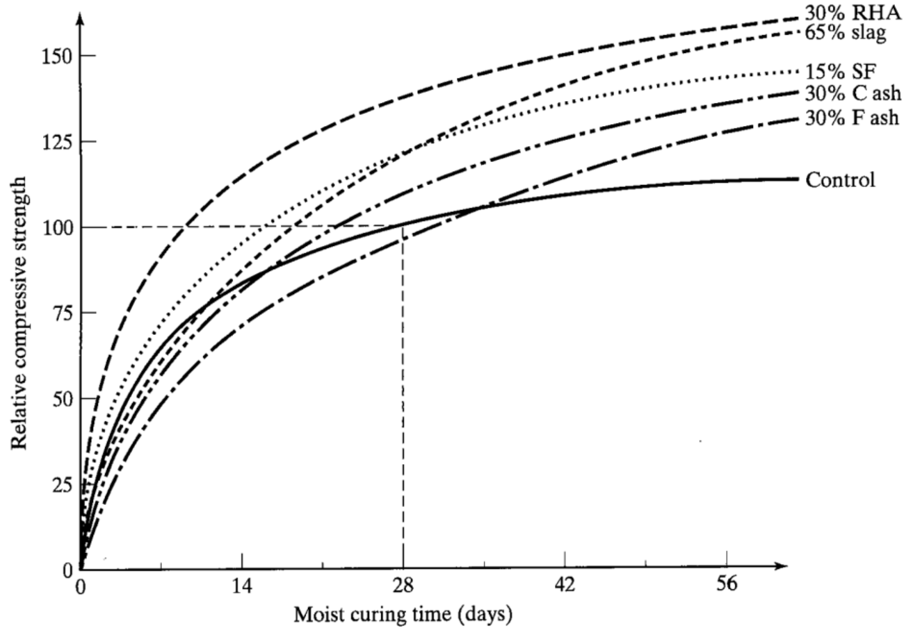


Figure 2. Relationship between porosity and w/c [8]

SCM

The addition of SCMs such as silica fume, slag cement, and fly ash reduce pore size and the porosity of both cement matrix and the ITZ, thereby increasing strength [4, 5, 7-9, 12, 16, 22]. However, the chemistry, fineness, and dosage of the SCM affect the strength development of concrete as presented in Figure 3 [5, 8, 13, 14, 23, 24]. For example, silica fume is very reactive and therefore increases both the early- and later-age strength by affecting cement hydration immediately [5, 8, 9]. On the other hand, class F fly ash and slag cement increase the ultimate strength, but they decrease the early strength [5, 9, 16].



RHA = rice husk ash
SF = silica fume

Figure 3. Relationship between relative compressive strength and supplementary cementitious materials [8]

Air-void system

When incorporated into the system, air voids generally increase the porosity, thus decreasing the strength as a result of insufficient compaction or through the inclusion of air-entraining admixture [4].

For a given w/cm, the effect of increasing the entrained air volume on compressive strength is depicted in Figure 4. For a given w/cm, entrained air decreases the concrete strength due to the increased porosity (Figure 4). A common rule of thumb is that for each 1% of air by volume, strength decreases approximately 5% [25]. In those mixtures with low w/cm and cement content, entrained air is believed to improve the strength by improving the ITZ [4].

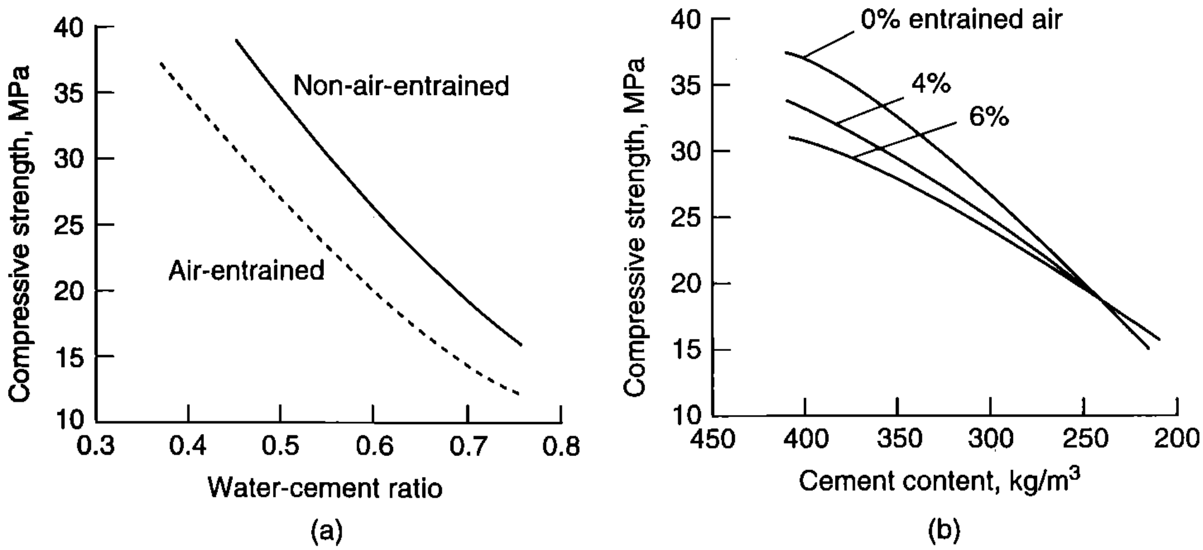


Figure 4. Influence of entrained air on compressive strength [4]

Durability

Concrete durability is a critical factor affecting the long-term pavement performance [14]. ACI Committee 201 [2] defines durability of concrete as "the ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration and retain its original form, quality, and serviceability when exposed to its environment."

Deterioration mechanisms, which progress over time, are mostly caused by external factors such as freeze-thaw damage, sulfate attack, chloride ingress, and carbonation [25, 26]. These mechanisms involve the presence or penetration of fluids and aggressive ions such as chlorides, hence, limiting the penetration of water and aggressive ions is fundamental to ensure durability [27].

Concrete is a porous material with various types of pores [9, 25]:

- Pores in the hydrated cement paste (gel pores, capillary pores, hollow-shell pores, air voids)
- Pores in the aggregates
- Pores associated with the ITZ
- Voids due to construction deficiencies, e.g., honeycombing due to poor compaction

These pores have a harmful effect on the durability of concrete since they become the penetration paths for fluids and ions [26]. The potential durability of concrete is directly affected by the permeability of a mixture [4]. Therefore, the effect of w/cm, SCM, and air-void system on permeability as a durability indicator will be discussed below.

w/cm

As w/c decreases, the porosity of the paste decreases and concrete becomes less permeable, thus reducing passage of water and aggressive compounds such as chlorides and sulfates [5, 7-9, 20, 28-30]. Reduction in porosity achieved by decreasing w/cm results in reduction in concrete permeability, and therefore enhances durability [29]. This trend is illustrated in Figure 5.

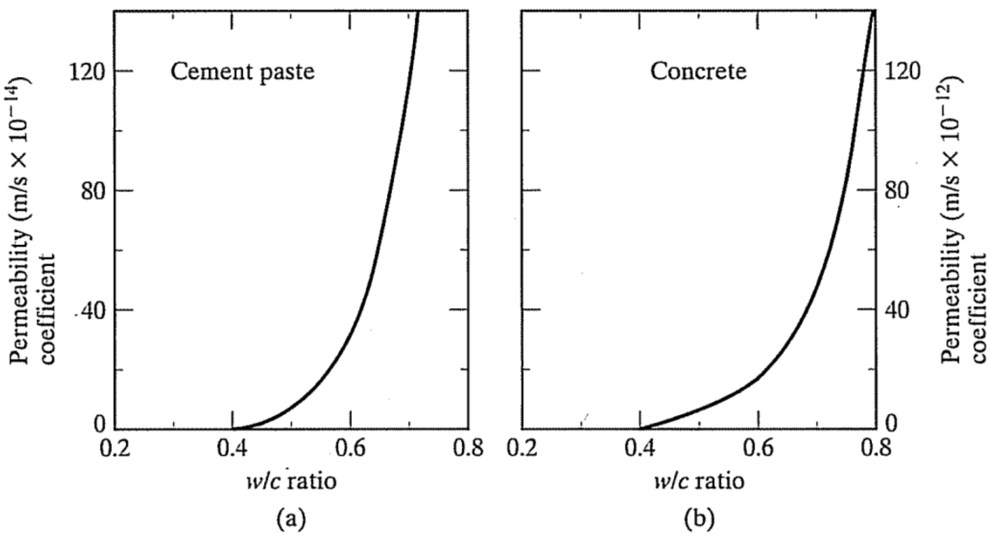


Figure 5. Influence of w/c on the permeability of (a) cement paste and (b) concrete [9]

The effect of w/c on the capillary volume is presented in Figure 6. Permeability increases for concrete with w/c greater than 0.42 as a result of the increased capillary volume [8].

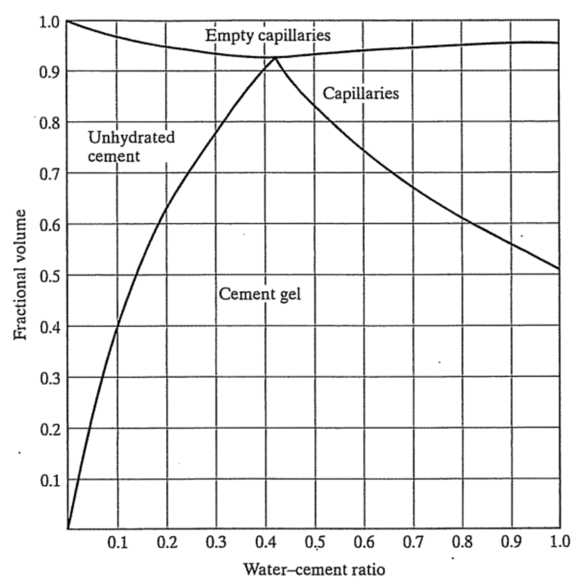


Figure 6. Composition of sealed and fully hydrated portland cement paste [31]

Due to the facts discussed above, ACI 302 [32] recommends a w/cm of no greater than 0.50 for concrete floors and slabs subjected to moderate and severe exposures to freezing and thawing, and a w/cm of no greater than 0.45 for concrete subjected to deicing chemicals.

SCM

The addition of SCM in concrete mixes will generally increase concrete durability in terms of improving impermeability, resistance to thermal cracking, and alkali-aggregate expansion [4, 5, 7-9, 16, 30]. In addition, the inclusion of SCM in concrete usually improves the resistance to sulfates, seawater, and acids by reducing pore size, permeability, and calcium hydroxide content of the hydrated product; and improves the ITZ between the cement paste and aggregates [8, 9, 24, 25]. The permeability resistance depends on the fineness, dosage, and chemistry of SCM, and the reaction rate between SCM and calcium hydroxide that forms calcium silicate hydrate gel [5, 8, 13, 14, 23, 24].

Furthermore, concretes containing SCM may have lower durability at early ages, but higher ultimate durability compared to plain concrete because increasing the testing age of the mixes incorporating SCM reduces the porosity of concrete, size of pores, and the interconnection between them as a result of the continued pozzolanic reaction [33, 34].

On the other hand, the addition of SCM may increase the carbonation rate (thus decreasing durability) by reducing the calcium hydroxide amount [25, 30, 35].

Air-void system

Depending on its form, air can adversely affect the durability by increasing permeability [30]. Air voids, particularly the large voids, increase corrosion, leading to physical damage and decreased durability of reinforced structures by increasing the chloride threshold for the corrosion initiation of steel reinforcement [30].

On the other hand, having a good air-void system increases durability when concrete is subjected to the freeze-thaw (F-T) conditions [5, 7-9, 30]. Therefore, the use of air entraining admixture (AEA) is recommended in concrete subjected to F-T in a moist condition or to deicing chemicals because the presence of AEA provides a more uniform distribution of small, stable air voids and empty capillaries that allow a relief of hydraulic pressure (caused by the formation of ice) by the flow of water into these spaces [36].

Summary

The effect of w/cm, air-void system, and different types of SCM on workability, strength, and durability is presented in Table 1.

Table 1. Effects of w/cm, air-void system, and SCMs on concrete properties

Property	w/cm	air	F fly ash	C fly ash	Slag cement	Silica fume
Workability ↑	↑	↑	↑	↑	↑	↓
Ultimate strength ↑	↓	↓	↑	↑	↑	↑
Permeability ↓	↓	↓	↓	↓	↓	↓
Chloride ingress ↓	↓	↓	↓	↓	↓	↓
Sulfate resistance ↑	↓	↓	↑	↕	↑	↑
F-T resistance ↑	↓	↑	↔	↔	↔	↔
Durability ↑	↓	↓	↑	↑	↑	↑

MATERIALS AND METHODS

This section reviews the materials and methods used in this study. The first subsection describes the overall research design, followed by materials, test variables, specimen preparation, and finally, the experimental work.

Research Design

The purpose of this experimental project is to quantify variation in workability of ternary concrete mixtures with a fixed aggregate system and varying paste quality. Although the main focus was to evaluate the effect of paste quality on workability, various fresh and hardened properties were also analyzed.

Variables

To determine the effect of paste quality on overall concrete behavior, cementitious combination, air content, and water-to-cementitious materials ratio (w/cm) were selected as variables as follows:

- w/cm: 0.40 and 0.45
- Air content: 2%, 4% and 8%
- Cementitious combination:
  - Plain concrete with only portland cement (P)
  - 15% class F fly ash (F) and 85% P
  - 15% class C fly ash (C) and 85% P
  - 20% slag cement (SL) and 80% P
  - 30% F and 70% P
  - 30% C and 70% P
  - 40% SL and 60% P
  - 20% F, 20% SL and 60%
  - 20% C, 20% SL and 60% P

In this experimental program, a total matrix of 54 mixtures was prepared. The mix identification is based on the three variables. For example, 45_15F_4 refers to a mix with w/cm of 0.45, 15% of class F fly ash replacement level, and 4% of designed air content.

A high-range water-reducing admixture was used in the drier mixtures to improve workability. Slump values were recorded. To achieve the target air content, a synthetic-based air entraining admixture was used.

Fixed Parameters

The fine aggregate-to-total aggregate ratio was fixed as 0.42 based on data from the combined aggregate gradation charts. Test methods and selection of the fine aggregate-to-total aggregate ratio is discussed in detail in the aggregates section. This was done to remove aggregate grading as a variable from the experimental matrix.

The air entraining admixture type was fixed as tall-oil-based throughout the experimental work.

A fixed cementitious content of 600 lb/yd^3 (pcy) was used for all mixtures.

Materials

Cementitious Materials

A single batch was obtained of each of Type I portland cement, Class F fly ash, Class C fly ash, and Grade 120 slag cement.

The chemical composition of the cementitious materials is presented in Table 2.

Table 2. Chemical composition of the cementitious materials, % by mass

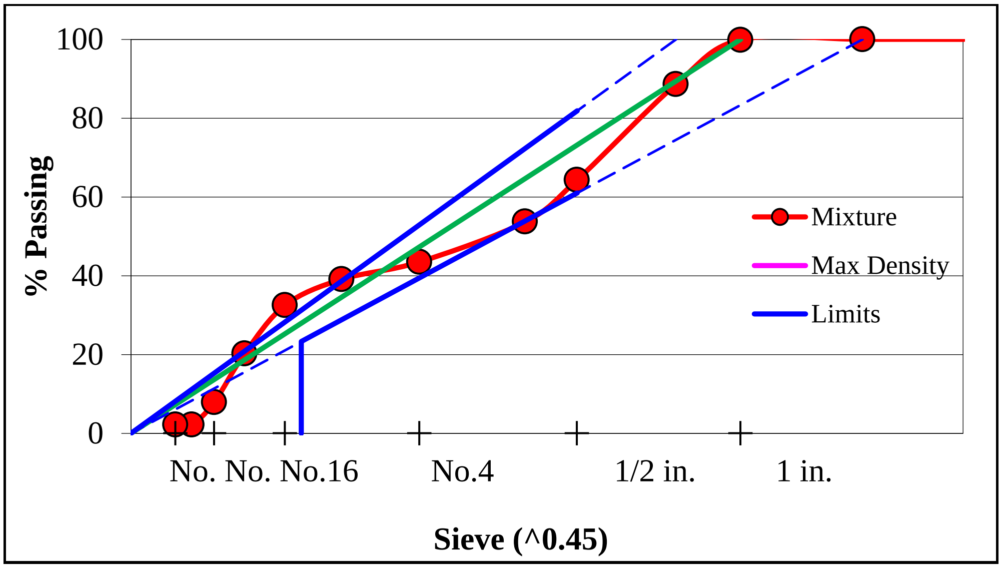
Oxides	Portland cement	F fly ash	C fly ash	Slag cement
Silicon dioxide (SiO_2)	20.13	52.10	36.70	37.60
Aluminum oxide (Al_2O_3)	4.39	16.00	20.10	9.53
Ferric oxide (Fe_2O_3)	3.09	6.41	6.82	0.44
Calcium oxide (CaO)	62.82	14.10	23.30	40.20
Magnesium oxide (MgO)	2.88	4.75	4.92	11.00
Sulfur trioxide (SO_3)	3.20	0.59	1.88	1.14
Potassium oxide (K_2O)	0.57	2.36	0.48	0.44
Sodium oxide (Na_2O)	0.10	1.72	1.62	0.45
Loss on ignition	2.55	0.09	0.25	0.00

Aggregates

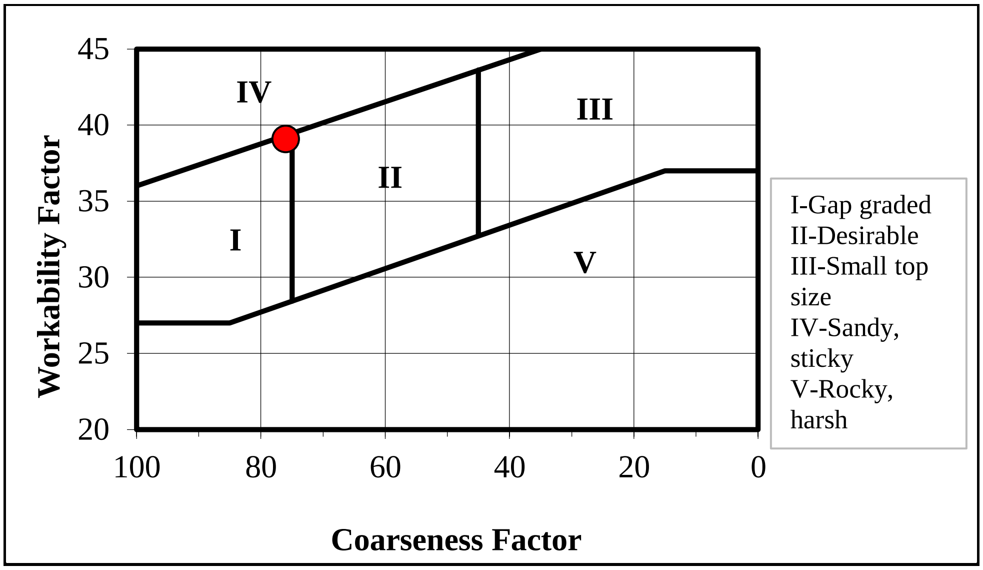
No.4 (4.75 mm) nominal maximum size concrete sand and 1 in. nominal maximum size crushed limestone were used in the study.

The void percentage of the combined aggregates was kept constant as19.8% for all the mixtures to remove the aggregate grading as a variable from the experimental matrix. This was selected by assessing the 0.45 power chart (Figure 7a) and Shilstone workability factor chart (Figure 7b) [1, 37].

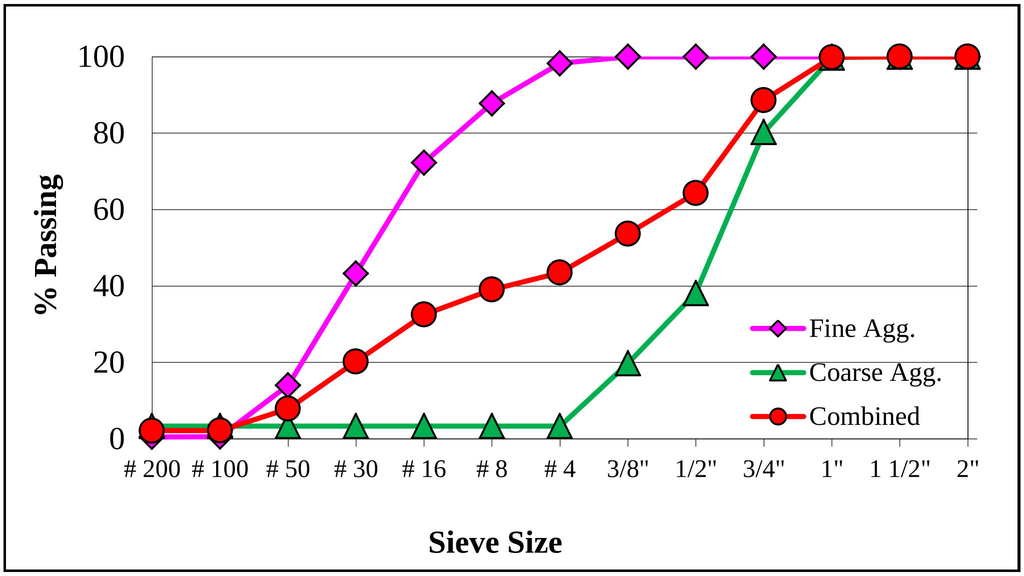
The appropriateness of the selected sand / total aggregate ratio of 0.42 was checked by plotting the data in an ASTM C33 plot (Figure 7c) and a "Haystack" plot (Figure 7d). The Haystack plot did not present an ideal combination, but was the best combination that could be achieved with the materials available. While not ideal, this type of gradation is common in many construction sites, and is therefore an appropriate combination for this research study.



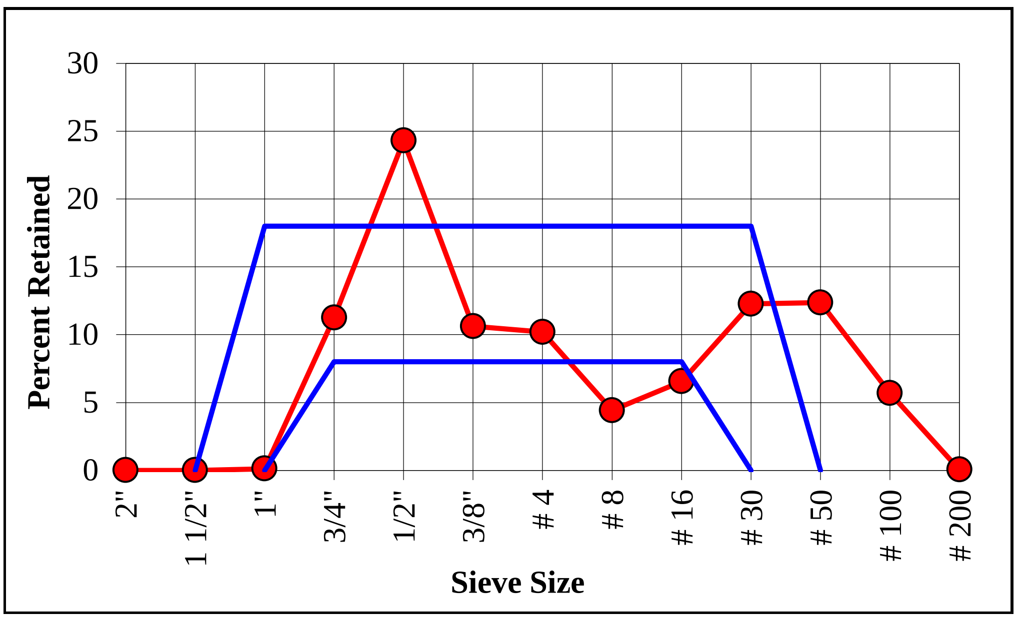
a) Power 45 gradation curve



b) Shilstone workability factor chart



c) ASTM C33 gradation graph



d) Haystack plot

Figure 7. Combined aggregate gradation curves

The bulk density (unit weight) and volume of voids in the combined aggregate were measured in accordance with ASTM C29. The overall unit weight of the combined aggregates was 131 lb/ft^3 (pcf) and the void percentage was 19.8%.

The specific gravity and absorption of the coarse and fine aggregates were determined using ASTM C127 and ASTM C128, respectively. The saturated surface dry (SSD) specific gravity and the absorption values of the coarse aggregate were 2.67% and 0.93%, respectively. The SSD specific gravity and absorption values of the fine aggregate were 2.62% and 1.07%, respectively.

Mix Proportions

The mix proportions for the 54 mixtures are given in Table 3.

Table 3. Mix proportions

No	Mix ID	P (pcy)	F (pcy)	C (pcy)	SL (pcy)	Binder (pcy)	Water (pcy)	w/cm	Sand (pcy)	Stone (pcy)	Theory Vp/Vv	Actual Vp/Vv
1	40_P_0	600				600	240	0.40	1358	1875	192.2	197.0
2	40_P_4	600				600	240	0.40	1320	1823	212.0	223.3
3	40_P_8	600				600	240	0.40	1246	1720	255.1	249.5
4	45_P_0	600				600	270	0.45	1324	1829	209.7	217.4
5	45_P_4	600				600	270	0.45	1287	1777	230.6	241.4
6	45_P_8	600				600	270	0.45	1212	1674	276.1	282.2
7	40_15F_0	510	90			600	240	0.40	1350	1864	196.2	191.3
8	40_15F_4	510	90			600	240	0.40	1313	1813	216.2	226.7
9	40_15F_8	510	90			600	240	0.40	1238	1709	259.9	271.7
10	45_15F_0	510	90			600	270	0.45	1316	1818	214.0	211.9
11	45_15F_4	510	90			600	270	0.45	1280	1767	235.0	237.8
12	45_15F_8	510	90			600	270	0.45	1204	1663	281.1	281.1
13	40_30F_0	420	180			600	240	0.40	1343	1854	200.2	198.3
14	40_30F_4	420	180			600	240	0.40	1305	1802	220.5	233.2
15	40_30F_8	420	180			600	240	0.40	1230	1698	264.8	270.7
16	45_30F_0	420	180			600	270	0.45	1309	1808	218.2	213.1
17	45_30F_4	420	180			600	270	0.45	1272	1756	239.6	245.1
18	45_30F_8	420	180			600	270	0.45	1196	1652	286.2	271.6
19	40_15C_0	510		90		600	240	0.40	1351	1866	195.5	205.4
20	40_15C_4	510		90		600	240	0.40	1314	1814	215.5	228.1
21	40_15C_8	510		90		600	240	0.40	1239	1711	259.2	265.0
22	45_15C_0	510		90		600	270	0.45	1318	1820	213.3	208.2
23	45_15C_4	510		90		600	270	0.45	1280	1768	234.3	248.1
24	45_15C_8	510		90		600	270	0.45	1206	1665	280.3	265.9
25	40_30C_0	420		180		600	240	0.40	1345	1857	199.0	201.4
26	40_30C_4	420		180		600	240	0.40	1307	1805	219.2	229.7
27	40_30C_8	420		180		600	240	0.40	1232	1702	263.2	275.1

Table 3. Mix proportions (cont.)

No	Mix ID	P (pcy)	F (pcy)	C (pcy)	SL (pcy)	Binder (pcy)	Water (pcy)	w/cm	Sand (pcy)	Stone (pcy)	Theory Vp/Vv	Actual Vp/Vv
28	45_30C_0	420		180		600	270	0.45	1311	1811	216.9	211.8
29	45_30C_4	420		180		600	270	0.45	1274	1759	238.2	252.6
30	45_30C_8	420		180		600	270	0.45	1199	1656	284.6	284.6
31	40_20SL_0	480			120	600	240	0.40	1354	1870	194.0	196.5
32	40_20SL_4	480			120	600	240	0.40	1316	1818	213.9	224.3
33	40_20SL_8	480			120	600	240	0.40	1242	1715	257.4	269.1
34	45_20SL_0	480			120	600	270	0.45	1321	1824	211.7	214.3
35	45_20SL_4	480			120	600	270	0.45	1283	1772	232.6	244.7
36	45_20SL_8	480			120	600	270	0.45	1209	1669	278.4	269.4
37	40_40SL_0	360			240	600	240	0.40	1351	1865	195.9	200.8
38	40_40SL_4	360			240	600	240	0.40	1313	1813	215.9	226.4
39	40_40SL_8	360			240	600	240	0.40	1238	1710	259.6	248.2
40	45_40SL_0	360			240	600	270	0.45	1317	1819	213.7	216.8
41	45_40SL_4	360			240	600	270	0.45	1280	1767	234.8	246.9
42	45_40SL_8	360			240	600	270	0.45	1205	1664	280.8	278.4
43	40_T1_0	360	120		120	600	240	0.40	1344	1856	199.4	192.1
44	40_T1_4	360	120		120	600	240	0.40	1306	1804	219.7	230.2
45	40_T1_8	360	120		120	600	240	0.40	1232	1701	263.8	252.3
46	45_T1_0	360	120		120	600	270	0.45	1311	1810	217.4	217.4
47	45_T1_4	360	120		120	600	270	0.45	1273	1758	238.7	233.2
48	45_T1_8	360	120		120	600	270	0.45	1198	1654	285.2	282.8
49	40_T2_0	360		120	120	600	240	0.40	1345	1858	198.6	193.7
50	40_T2_4	360		120	120	600	240	0.40	1308	1806	218.8	218.8
51	40_T2_8	360		120	120	600	240	0.40	1233	1703	262.8	251.3
52	45_T2_0	360		120	120	600	270	0.45	1312	1812	216.5	211.4
53	45_T2_4	360		120	120	600	270	0.45	1274	1760	237.7	246.6
54	45_T2_8	360		120	120	600	270	0.45	1200	1657	284.2	275.0

Experimental Work

For each mixture, nine cylinders (4*8 in.) and three beams (3*3*11 in.) were prepared. The tests conducted are given in Table 4. Mixtures were prepared in accordance with ASTM C 192. Specimens were prepared in accordance with ASTM C31 and stored under plastic sheeting until the samples were demolded after 24 hours, and cured in a fog room in accordance with ASTM C192. Samples were kept in the fog room until tested.

Table 4. Test matrix

Fresh Property	Method	# of Specimens	Age (days)
Slump	ASTM C143	1	-
Air content	ASTM C231	1	-
Paste rheometer*	Brookfield R/S SST 2000	2	-
Air void analysis (AVA)	ASTM C457	2	-
Setting time	ASTM C403	1	-
Hardened Property	**Method**	**# of Specimens**	**Age (days)**
Compressive strength	ASTM C39	2 per age	7, 28, 56
Surface resistivity	Wenner Probe	3 per age	7, 28, 56
Shrinkage	ASTM C157	3 per age	3, 7, 14, 28, 42, 56

* The rheology test was conducted on a limited set of the paste matrix

RESULTS

Test results are presented and discussed under the following categories:

- Workability
- Air-void system
- Setting time
- Compressive strength
- Surface resistivity
- Shrinkage

A good portion of the data are presented in the figures in which the horizontal axis is the volume of paste divided by the volume of voids in the aggregate system (Vp/Vvoid). The paste content volume was calculated by adding up the volume of water, the cementitious materials, and the measured air in the system. The cementitious materials volume was determined by dividing the cementitious materials content by the corresponding specific gravity for each type of cementitious material. The volume of the air used in the calculation was obtained from the air content test performed in accordance with the ASTM C231.

The effect of Vp/Vvoid on the test results was used as a means of illustrating the effects of changes in the paste system on concrete fresh and hardened properties. If there is insufficient paste to fill all of the voids between the aggregate particles, performance is likely to be compromised [37]. Once sufficient paste is provided to fill the voids and coat the aggregate particles and separate them to provide adequate workability and finishability, the quality of the paste should dominate the trends.

In figures shown below, the colors represent the target air contents in mixtures:

- 2% is represented using blue symbols
- 4% is represented using red symbols
- 8% is represented using green symbols

The shapes represent the binder types in mixtures:

- Control mixture is designated as a square
- Mixes containing 15% of F fly ash are designated as diamonds
- Mixes containing 30% of F fly ash are designated as triangles
- Mixes containing 15% of C fly ash are designated as crosses
- Mixes containing 30% of C fly ash are designated as asterisks
- Mixes containing 20% of slag are designated as circles
- Mixes containing 40% of slag are designated as plus symbols
- Ternary type 1 (60% OPC+20% F + 20% slag cement) is designated as a long dash
- Ternary type 2 (60% OPC+20% C + 20% slag cement) is designated as a small dash

The fresh and hardened concrete properties are presented in Tables 5 and 6, respectively.

Table 5. Fresh concrete properties

No	Mix ID	OPC (pcy)	F Ash (pcy)	C Ash (pcy)	Slag (pcy)	Water (pcy)	w/cm	Fine Agg. (pcy)	Coarse Agg. (pcy)	Vp/ Vvoids (%)	Slump (in.)	Air Content (%)	Spacing Factor (mm.)	Initial Setting (min.)	Final Setting (min.)
1	40_P_2	600				240	0.40	1358	1875	197	1.8	2.5	1.266	265	350
2	40_P_4	600				240	0.40	1320	1823	223	2.6	5.1	0.424	217	279
3	40_P_8	600				240	0.40	1246	1720	249	1.5	7.5	-	250	331
4	45_P_2	600				270	0.45	1324	1829	217	4.5	2.8	1.676	255	368
5	45_P_4	600				270	0.45	1287	1777	241	4.3	5.0	0.353	250	310
6	45_P_8	600				270	0.45	1212	1674	282	4.5	8.5	0.205	291	375
7	40_15F_2	510	90			240	0.40	1350	1864	191	1.8	1.5	1.398	340	442
8	40_15F_4	510	90			240	0.40	1313	1813	227	2.3	5.0	0.228	430	530
9	40_15F_8	510	90			240	0.40	1238	1709	272	3.5	9.0	0.145	360	475
10	45_15F_2	510	90			270	0.45	1316	1818	212	8.8	1.8	-	300	400
11	45_15F_4	510	90			270	0.45	1280	1767	238	8.8	4.3	0.348	418	550
12	45_15F_8	510	90			270	0.45	1204	1663	281	11.0	8.0	0.265	460	590
13	40_30F_2	420	180			240	0.40	1343	1854	198	2.0	1.8	1.161	360	500
14	40_30F_4	420	180			240	0.40	1305	1802	233	3.0	5.2	0.287	430	520
15	40_30F_8	420	180			240	0.40	1230	1698	271	4.8	8.5	0.200	390	480
16	45_30F_2	420	180			270	0.45	1309	1808	213	9.8	1.5	0.908	460	590
17	45_30F_4	420	180			270	0.45	1272	1756	245	9.8	4.5	0.297	445	570
18	45_30F_8	420	180			270	0.45	1196	1652	272	11.0	6.8	0.457	550	665
19	40_15C_2	510		90		240	0.40	1351	1866	205	2.3	3.0	1.293	365	460
20	40_15C_4	510		90		240	0.40	1314	1814	228	3.2	5.2	0.162	440	610
21	40_15C_8	510		90		240	0.40	1239	1711	265	2.0	8.5	0.190	440	570
22	45_15C_2	510		90		270	0.45	1318	1820	208	4.3	1.5	2.101	490	630
23	45_15C_4	510		90		270	0.45	1280	1768	248	4.0	5.3	0.352	460	610
24	45_15C_8	510		90		270	0.45	1206	1665	266	5.5	6.8	0.155	490	660

No	Mix ID	OPC (pcy)	F Ash (pcy)	C Ash (pcy)	Slag (pcy)	Water (pcy)	w/cm	Fine Agg. (pcy)	Coarse Agg. (pcy)	Vp/ Vvoids (%)	Slump (in.)	Air Content (%)	Spacing Factor (mm.)	Initial Setting (min.)	Final Setting (min.)
25	40_30C_2	420		180		240	0.40	1345	1857	201	1.8	2.3	1.611	500	630
26	40_30C_4	420		180		240	0.40	1307	1805	230	2.3	5.0	0.194	470	630
27	40_30C_8	420		180		240	0.40	1232	1702	275	2.5	9.0	0.151	580	790
28	45_30C_2	420		180		270	0.45	1311	1811	212	4.5	1.5	1.481	540	725
29	45_30C_4	420		180		270	0.45	1274	1759	253	4.5	5.3	0.271	570	760
30	45_30C_8	420		180		270	0.45	1199	1656	285	11.0	8.0	0.218	600	-
31	40_20SL_2	480			120	240	0.40	1354	1870	196	2.0	2.3	1.578	260	335
32	40_20SL_4	480			120	240	0.40	1316	1818	224	2.5	5.0	0.373	272	350
33	40_20SL_8	480			120	240	0.40	1242	1715	269	2.5	9.0	0.122	360	485
34	45_20SL_2	480			120	270	0.45	1321	1824	214	4.3	2.3	1.362	297	375
35	45_20SL_4	480			120	270	0.45	1283	1772	245	4.8	5.1	0.317	270	350
36	45_20SL_8	480			120	270	0.45	1209	1669	269	4.2	7.3	0.224	350	490
37	40_40SL_2	360			240	240	0.40	1351	1865	201	1.5	2.5	1.131	270	350
38	40_40SL_4	360			240	240	0.40	1313	1813	226	1.5	5.0	0.226	250	345
39	40_40SL_8	360			240	240	0.40	1238	1710	248	2.5	7.0	0.180	305	400
40	45_40SL_2	360			240	270	0.45	1317	1819	217	2.5	2.3	1.479	305	400
41	45_40SL_4	360			240	270	0.45	1280	1767	247	3.5	5.1	0.376	190	292
42	45_40SL_8	360			240	270	0.45	1205	1664	278	3.8	7.8	0.178	338	428
43	40_T1_2	360	120		120	240	0.40	1344	1856	192	2.8	1.3	1.985	335	413
44	40_T1_4	360	120		120	240	0.40	1306	1804	230	3.2	5.0	0.290	360	450
45	40_T1_8	360	120		120	240	0.40	1232	1701	252	5.8	7.0	0.317	360	450
46	45_T1_2	360	120		120	270	0.45	1311	1810	217	6.8	2.0	-	350	470
47	45_T1_4	360	120		120	270	0.45	1273	1758	233	8.0	3.5	0.496	440	525
48	45_T1_8	360	120		120	270	0.45	1198	1654	283	6.5	7.8	0.285	395	480

No	Mix ID	OPC (pcy)	F Ash (pcy)	C Ash (pcy)	Slag (pcy)	Water (pcy)	w/cm	Fine Agg. (pcy)	Coarse Agg. (pcy)	Vp/ Vvoids (%)	Slump (in.)	Air Content (%)	Spacing Factor (mm.)	Initial Setting (min.)	Final Setting (min.)
49	40_T2_2	360		120	120	240	0.40	1345	1858	194	2.0	1.5	1.689	420	525
50	40_T2_4	360		120	120	240	0.40	1308	1806	219	2.5	4.0	0.338	460	580
51	40_T2_8	360		120	120	240	0.40	1233	1703	251	2.8	7.0	0.265	-	-
52	45_T2_2	360		120	120	270	0.45	1312	1812	211	6.0	1.5	2.114	440	600
53	45_T2_4	360		120	120	270	0.45	1274	1760	247	6.0	4.8	0.323	540	650
54	45_T2_8	360		120	120	270	0.45	1200	1657	275	4.0	7.3	0.201	-	-

Table 6. Hardened concrete properties

No	Mix ID	Vp/ Vvoids (%)	Strength (psi)			Surf. Resistivity (kΩcm)			Shrinkage, %					
			7	28	56	7	28	56	3	7	14	28	42	56
1	40_P_2	197	5537	6799	7367	6.9	9.4	10.3	-0.006	-0.010	-0.018	-0.029	-0.036	-0.036
2	40_P_4	223	4445	4886	5944	7.8	8.4	12.2	-0.011	-0.020	-0.026	-0.036	-0.041	-0.041
3	40_P_8	249	4473	5347	6210	8.5	10.5	11.7	-0.011	-0.017	-0.029	-0.035	-0.040	-0.041
4	45_P_2	217	4668	5787	6503	6.5	8.6	9.7	-0.007	-0.011	-0.017	-0.027	-0.035	-0.036
5	45_P_4	241	3961	5258	5603	6.5	10.1	9.2	-0.011	-0.018	-0.025	-0.034	-0.039	-0.040
6	45_P_8	282	3351	4328	4691	6.4	8.1	9.1	-0.013	-0.018	-0.038	-0.038	-0.039	-0.041
7	40_15F_2	191	5576	6901	7713	7.8	11.9	17.0	-0.009	-0.015	-0.021	-0.035	-0.033	-0.036
8	40_15F_4	227	3963	4922	5390	8.7	13.3	18.6	-0.007	-0.014	-0.022	-0.037	-0.034	-0.039
9	40_15F_8	272	3151	4227	5276	7.2	12.3	18.7	-0.014	-0.018	-0.025	-0.028	-0.033	-0.036
10	45_15F_2	212	4527	6007	6815	6.2	10.1	14.4	-0.014	-0.020	-0.026	-0.031	-0.039	-0.040
11	45_15F_4	238	3910	4847	5796	-	11.1	15.8	0.000	-0.014	-0.024	-0.029	-0.033	-0.035
12	45_15F_8	281	-	4263	5288	-	9.3	13.2	-0.001	-0.004	-0.008	-0.024	-0.028	-0.029
13	40_30F_2	198	4469	6187	7355	7.2	16.9	27.7	-0.008	-0.018	-0.025	-0.029	-0.035	-0.037
14	40_30F_4	233	3187	4489	6216	7.3	16.5	29.1	-0.013	-0.016	-0.023	-0.029	-0.035	-0.036
15	40_30F_8	271	3174	4676	6263	6.6	15.6	28.6	-0.015	-0.017	-0.028	-0.031	-0.035	-0.038
16	45_30F_2	213	3577	5472	6774	6.0	13.5	22.7	-0.011	-0.018	-0.023	-0.025	-0.036	-0.038
17	45_30F_4	245	2940	4416	5408	-	13.7	22.3	-0.007	-0.013	-0.022	-0.027	-0.030	-0.032
18	45_30F_8	272	-	4144	4737	-	12.0	21.0	-0.001	-0.003	-0.016	-0.028	-0.033	-0.035
19	40_15C_2	205	5944	7551	8256	6.5	9.8	12.3	-0.007	-0.019	-0.023	-0.030	-0.031	-0.035
20	40_15C_4	228	3635	4292	5336	7.0	11.0	13.2	-0.012	-0.022	-0.027	-0.038	-0.039	-0.042
21	40_15C_8	265	4047	5168	6036	7.9	11.8	14.0	-0.006	-0.018	-0.023	-0.033	-0.037	-0.037
22	45_15C_2	208	5395	6949	7705	6.2	8.6	10.3	-0.013	-0.021	-0.025	-0.032	-0.035	-0.038
23	45_15C_4	248	4250	5580	6298	6.6	9.3	11.8	-0.009	-0.015	-0.020	-0.029	-0.030	-0.034
24	45_15C_8	266	3721	4532	5884	5.7	8.2	9.9	-0.013	-0.024	-0.029	-0.037	-0.041	-0.045

No	Mix ID	Vp/ Vvoids (%)	Strength (psi)			Surf. Resistivity (kΩcm)			Shrinkage, %					
			7	28	56	7	28	56	3	7	14	28	42	56
25	40_30C_2	201	5974	7802	8652	7.1	11.2	16.5	-0.009	-0.018	-0.022	-0.029	-0.029	-0.033
26	40_30C_4	230	3422	4781	5319	6.8	13.3	19.0	-0.014	-0.022	-0.027	-0.037	-0.035	-0.039
27	40_30C_8	275	3345	4579	5040	6.5	12.5	17.5	-0.009	-0.021	-0.027	-0.038	-0.043	-0.043
28	45_30C_2	212	5220	7030	7618	5.1	9.0	12.8	-0.014	-0.021	-0.025	-0.031	-0.032	-0.035
29	45_30C_4	253	4096	5691	6160	5.7	10.4	15.5	-0.013	-0.022	-0.027	-0.032	-0.035	-0.039
30	45_30C_8	285	4430	5531	6248	6.1	8.5	12.6	-0.010	-0.022	-0.029	-0.038	-0.037	-0.041
31	40_20SL_2	196	5629	7508	8105	8.6	14.7	16.1	-0.007	-0.015	-0.021	-0.038	-0.048	-0.048
32	40_20SL_4	224	4926	6531	7191	8.5	12.2	15.9	-0.008	-0.014	-0.025	-0.031	-0.036	-0.038
33	40_20SL_8	269	3456	5220	5504	12.4	23.7	30.9	-0.006	-0.013	-0.021	-0.027	-0.027	-0.033
34	45_20SL_2	214	4938	6934	7399	7.3	12.6	13.9	-0.010	-0.018	-0.025	-0.042	-0.043	-0.043
35	45_20SL_4	245	4172	5516	6284	7.5	12.4	13.6	-0.010	-0.015	-0.026	-0.034	-0.038	-0.040
36	45_20SL_8	269	3681	5805	6907	9.9	19.6	26.6	-0.006	-0.014	-0.022	-0.028	-0.033	-0.036
37	40_40SL_2	201	5482	8379	9026	9.0	20.0	30.3	-0.010	-0.014	-0.018	-0.028	-0.032	-0.031
38	40_40SL_4	226	4944	7514	8177	10.0	24.0	30.0	-0.010	-0.016	-0.021	-0.027	-0.031	-0.032
39	40_40SL_8	248	4103	6001	6605	11.4	27.4	31.6	-0.016	-0.022	-0.031	-0.035	-0.038	-0.038
40	45_40SL_2	217	4623	8100	8517	8.0	22.1	26.3	-0.008	-0.013	-0.018	-0.027	-0.030	-0.030
41	45_40SL_4	247	4080	6965	7384	8.2	20.8	26.6	-0.013	-0.018	-0.023	-0.029	-0.032	-0.032
42	45_40SL_8	278	3711	5718	5974	9.0	22.4	29.0	-0.014	-0.019	-0.029	-0.034	-0.037	-0.038
43	40_T1_2	192	4939	7347	8247	8.6	22.3	33.2	-0.005	-0.018	-0.024	-0.031	-0.036	-0.036
44	40_T1_4	230	3336	5653	6620	11.2	21.4	32.1	-0.013	-0.018	-0.026	-0.029	-0.030	-0.031
45	40_T1_8	252	3326	5817	6865	8.7	17.0	24.8	-0.015	-0.019	-0.027	-0.034	-0.036	-0.036
46	45_T1_2	217	3923	6345	9386	7.3	17.0	25.5	-0.005	-0.019	-0.026	-0.030	-0.034	-0.034
47	45_T1_4	233	3439	5897	6165	6.3	15.7	25.2	-0.006	-0.020	-0.026	-0.035	-0.042	-0.044
48	45_T1_8	283	2888	5483	6433	8.1	16.6	24.9	-0.017	-0.021	-0.029	-0.031	-0.033	-0.034

No	Mix ID	Vp/ Vvoids (%)	Strength (psi)			Surf. Resistivity (kΩcm)			Shrinkage, %					
			7	28	56	7	28	56	3	7	14	28	42	56
49	40_T2_2	194	5051	8064	9313	6.4	14.8	23.2	-0.008	-0.020	-0.025	-0.031	-0.035	-0.036
50	40_T2_4	219	3385	6625	7335	5.0	13.0	18.7	-0.019	-0.025	-0.028	-0.033	-0.035	-0.036
51	40_T2_8	251	3510	5860	6464	7.4	13.9	20.1	-0.014	-0.029	-0.031	-0.033	-0.034	-0.035
52	45_T2_2	211	5562	8031	9387	6.1	14.5	20.8	-0.010	-0.023	-0.033	-0.035	-0.038	-0.039
53	45_T2_4	247	3183	5735	6867	4.4	11.5	16.6	-0.022	-0.028	-0.033	-0.040	-0.042	-0.043
54	45_T2_8	275	2743	4780	5500	6.4	12.6	21.2	-0.015	-0.030	-0.031	-0.034	-0.037	-0.037

DISCUSSION

Workability

The effect of the paste quality on workability was investigated using the slump test. The data from rheometer tests [38] was also used for comparison. The slump test results are depicted in Figures 8 and 9, and the rheometer data are plotted in Figure 10.

Figure 8 shows that compared to the control mixture, the addition of SCMs have a minor effect on improving the workability for mixtures having Vp/Voids ranging between 190 and 240%, for a w/cm of 0.40. The effect of SCMs was more marked in mixtures with higher paste contents. Class F fly ash exhibited a slightly higher workability compared to the other binder types. This result is not surprising because Class F fly ash particles would be expected to reduce the inter-particle friction in the mixtures, and improve workability [7]. Increasing the paste content slightly increased the workability since more paste was provided to lubricate the aggregates. The difference between binary and ternary mixtures was not significant.

To confound these observations, it should be borne in mind that as the target air content was increased, the paste content also increased. Also, the increased amount of air likely played a role in increasing workability [8].

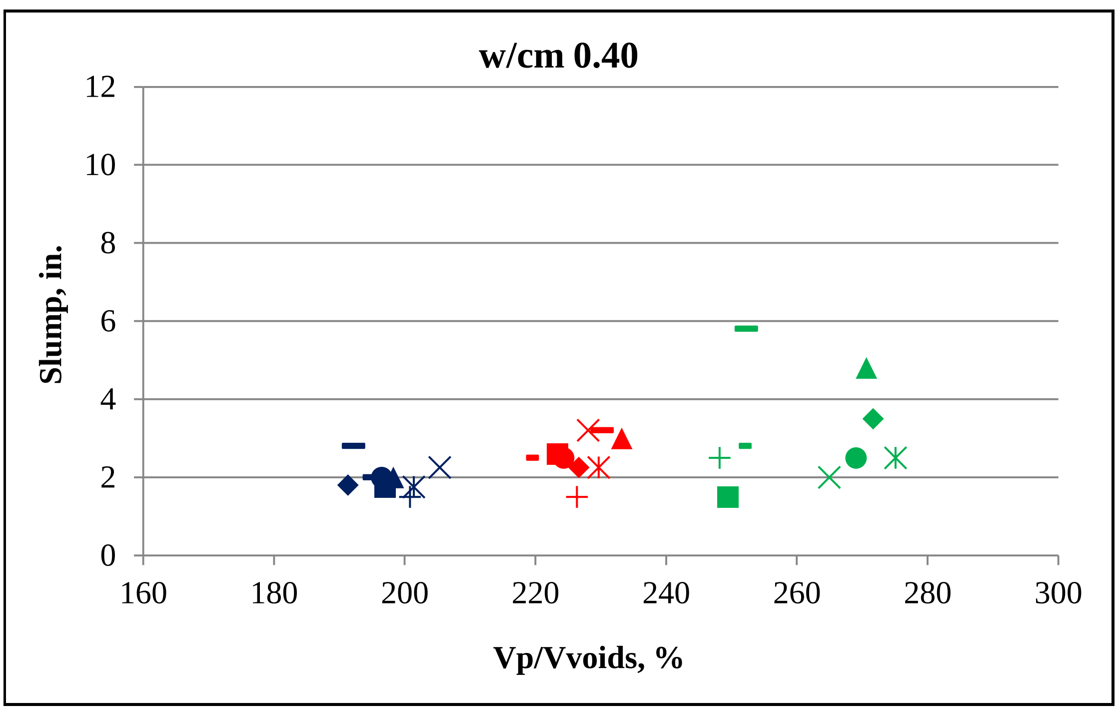


Figure 8. The effect of Vp/Vvoids on workability for a w/cm of 0.40

Comparison of Figures 8 and 9 shows that increasing w/cm from 0.40 to 0.45 significantly increased the workability in some cases.

It is notable that the slag mixtures were slightly less workable at the higher w/cm, while the Class F fly ash was significantly better. The Class C fly ash mixtures were somewhat improved, while the ternary mixtures followed the trends of their constituent materials. These trends are all consistent with the observation in the rheology tests on paste, and as reported in the literature [39]. This means that paste rheology tests therefore have potential to provide input to the mix proportioning process.

Considering the scope of this study focuses on the concrete for pavements, the required slump value would range between 1 and 3 in. [40]. This means that paste content, SCM type and dosage, and to some extent air content, are parameters that can be varied to control workability.

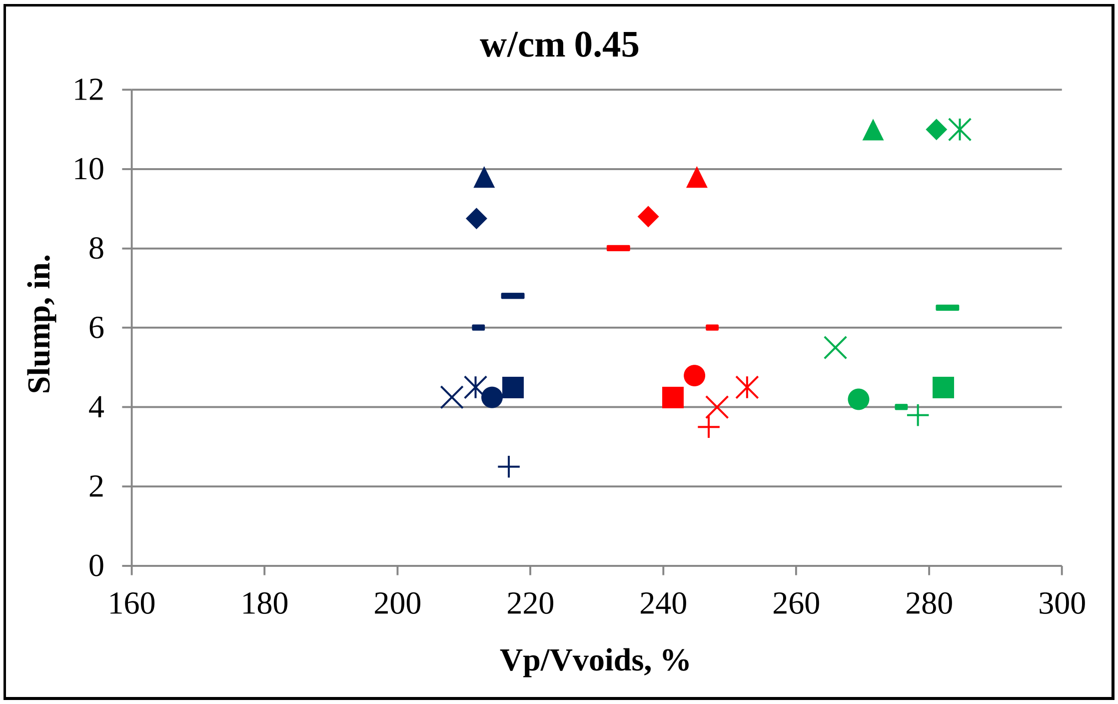


Figure 9. The effect of Vp/Vvoids on workability for a w/cm of 0.45

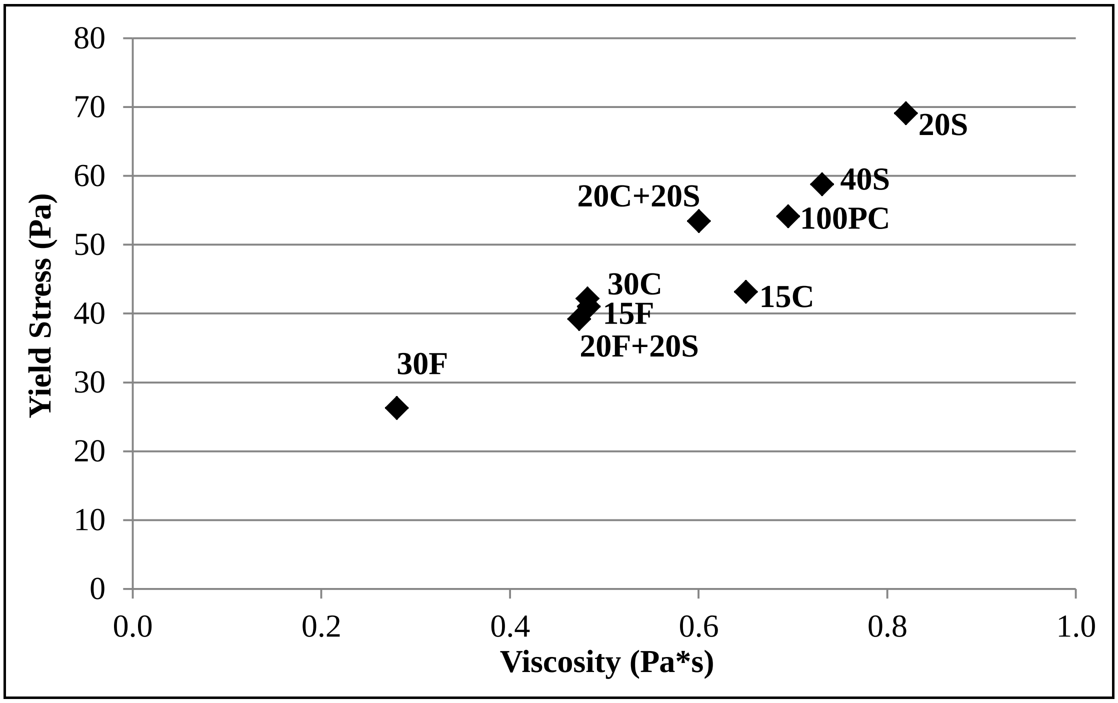


Figure 10. Data from rheology tests for paste mixtures with a w/cm of 0.40

Air-void system

The air-void analyzer (AVA) test was conducted to determine the air-void system of the fresh concrete mixes. The effect of the Vp/Vvoids on the air-void system is presented in Figures 11 and 12.

The commonly accepted rule of thumb for a good air-void system requires a spacing factor less than 0.008 in. (200 μm) measured using ASTM C457. Recent studies [41, 42] have shown that concrete with a spacing factor of less than 0.3 mm when measured by AVA would be equivalent and acceptable for F-T durability. Therefore, the AVA test results were evaluated according to the acceptance criterion of the spacing factor of <0.3 mm.

Not surprisingly Figures 11 and 12 show that based on this criterion, mixes designed to have a 2% of air content (designated in blue) do not meet the requirement of having a spacing factor less than 0.30 mm. In addition, some of the mixes having a target air content of 4% had a spacing factor less than 0.3 mm. This is not surprising because 4% total air traditionally exhibits marginal performance in the field. Furthermore, the mixes having a target air content of 8% (designated as green color) had a spacing factor less than 0.3 mm, as desired.

Little difference is seen in respect to the effect of w/cm on relationship between spacing factor and air content, except perhaps more scatter is seen in the higher w/cm system.

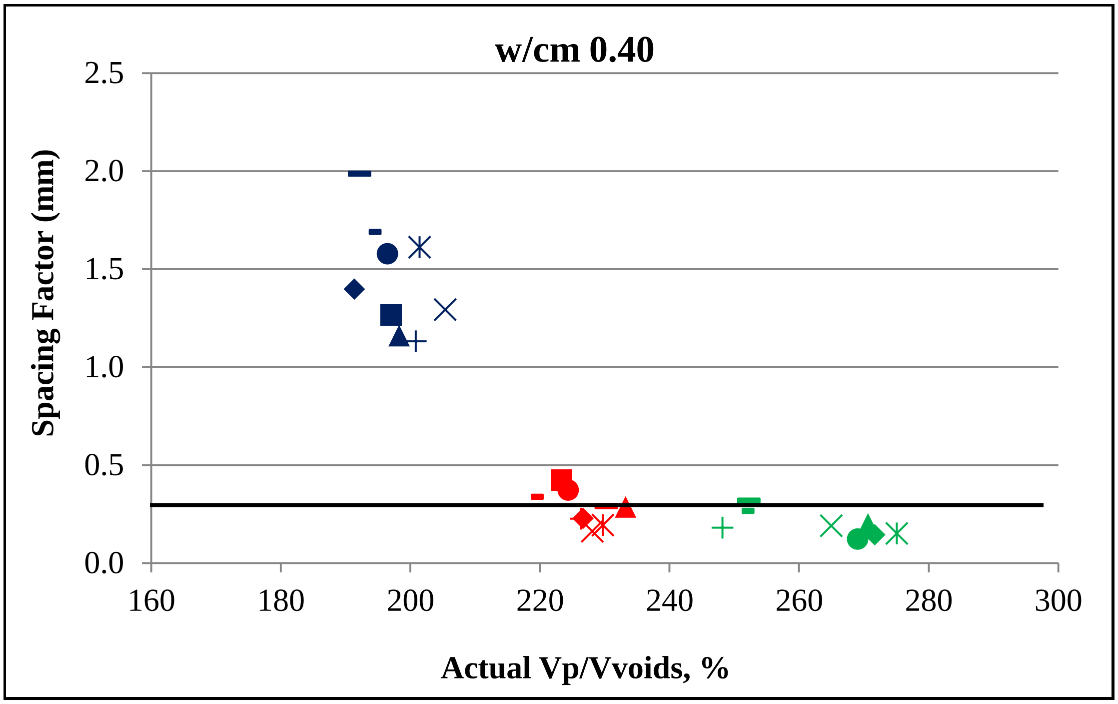


Figure 11. The relationship between Vp/Vvoids and air-void system for a w/cm of 0.40

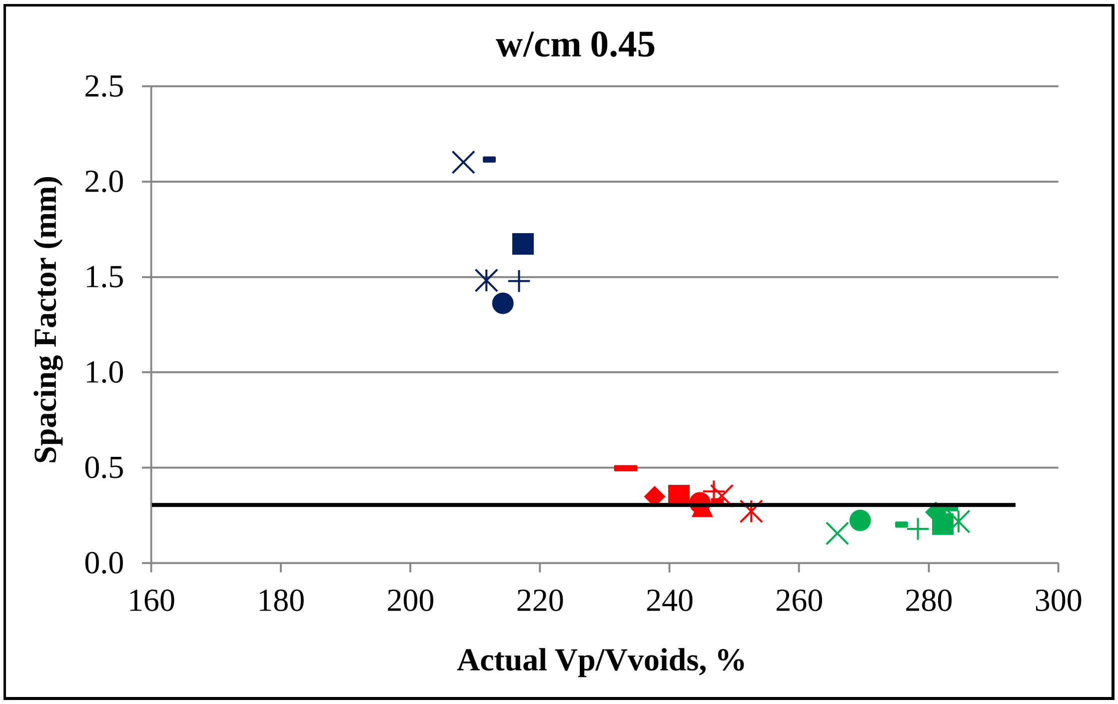


Figure 12. The relationship between Vp/Vvoids and air-void system for a w/cm of 0.45

The effects of the inclusion of SCMs on the air-void system cannot be established as there is no obvious trend.

Setting time

The initial and final setting times were recorded and presented in Table 1. The relationship between Vp/Vvoids and final setting times are presented in Figures 13 and 14.

Increasing the Vp/Vvoids did not play a significant role affecting the setting time as would be expected.

The addition of fly ash increased the setting time compared to the control mixture. However, the addition of slag cement resulted in similar setting times as plain concrete. This result is consistent with the literature [43].

The ternary mixtures also slightly retarded the setting time consistent with the effects of their ingredients.

The ratio of initial to final setting times was found to vary between 0.65 to 0.84, and was independent of w/cm. The ratio of initial to final setting times of plain concrete and mixes containing slag cement were similar and ranged from 0.65 to 0.80. The ratio of initial to final setting times of the mixes containing fly ash and ternary mixes were similar and ranged from 0.72 to 0.84.

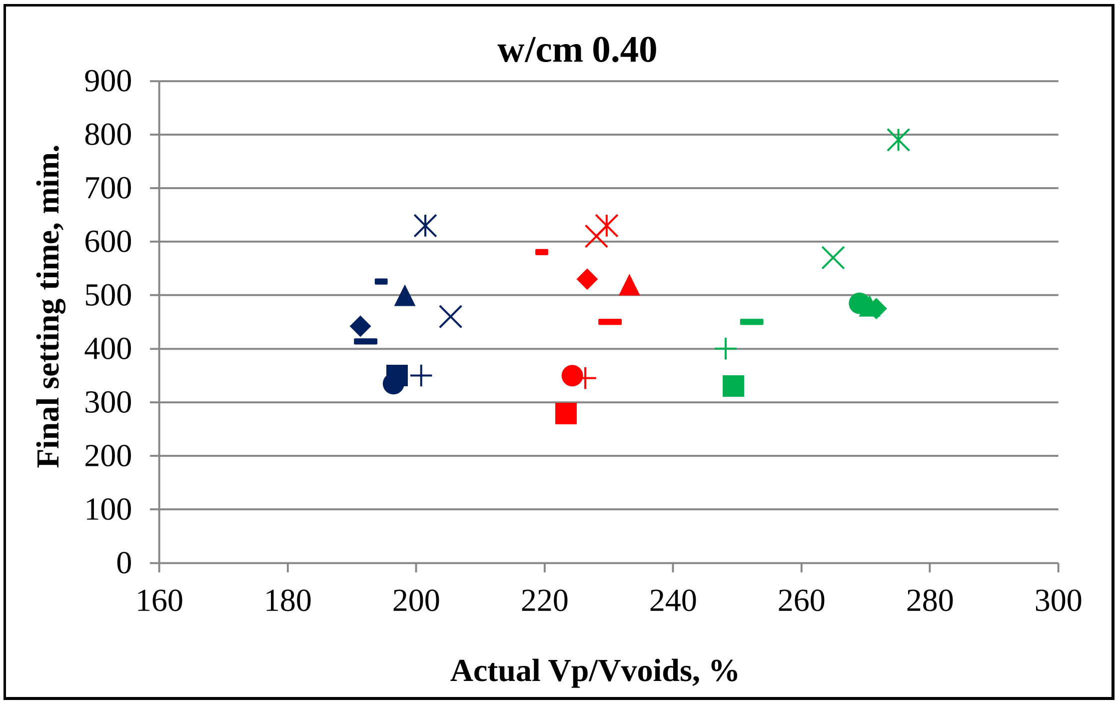


Figure 13. The relationship between Vp/Vvoids and final setting time for a w/cm of 0.40

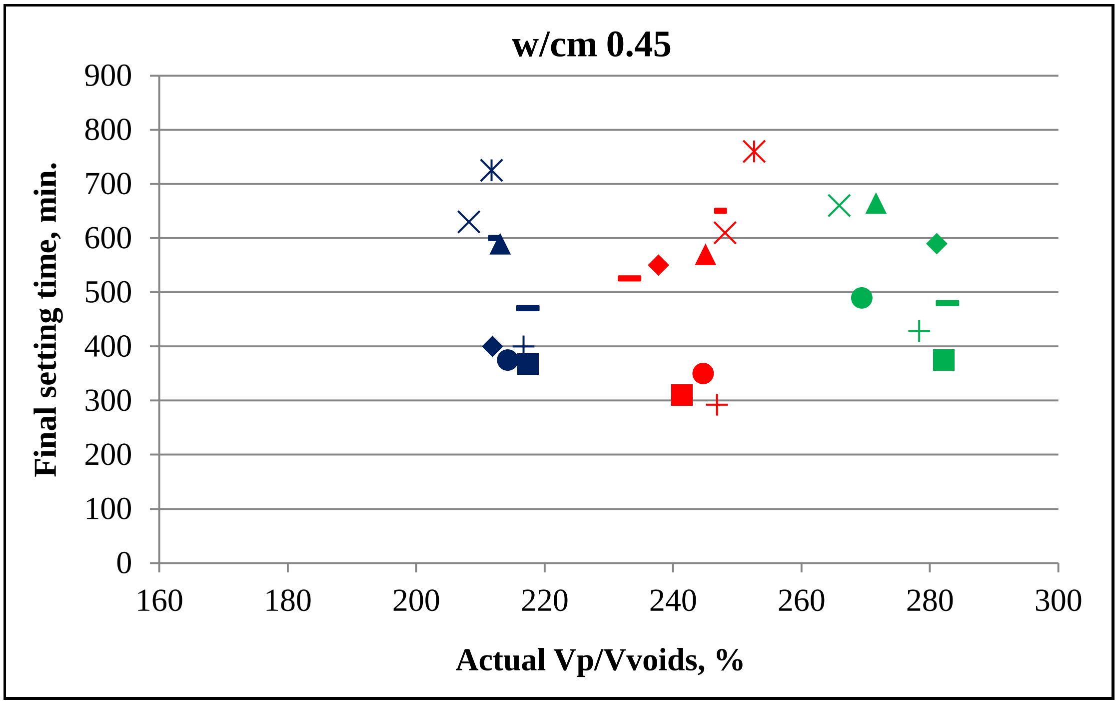


Figure 14. The relationship between Vp/Vvoids and final setting time for a w/cm of 0.45

Compressive Strength

The relationship between Vp/Vvoids and 7-, 28-, and 56-day compressive strengths are presented in Figures 15 through 20.

According to Figures 15 and 16, as Vp/Vvoids ratio increased, the 7-day compressive strength decreased slightly, likely due to the increased air content. The binary mixes containing slag cement exhibited similar strength results with plain mixture at 7-day. However, the addition of both types of fly ash decreased the 7-day compressive strength. This result is consistent with the literature [39].

As expected, increasing w/cm from 0.40 to 0.45 decreased compressive strength for similar systems due to the increased water content increasing the capillary porosity.

The ternary mixtures exhibited slightly lower compressive strengths at 7 days.

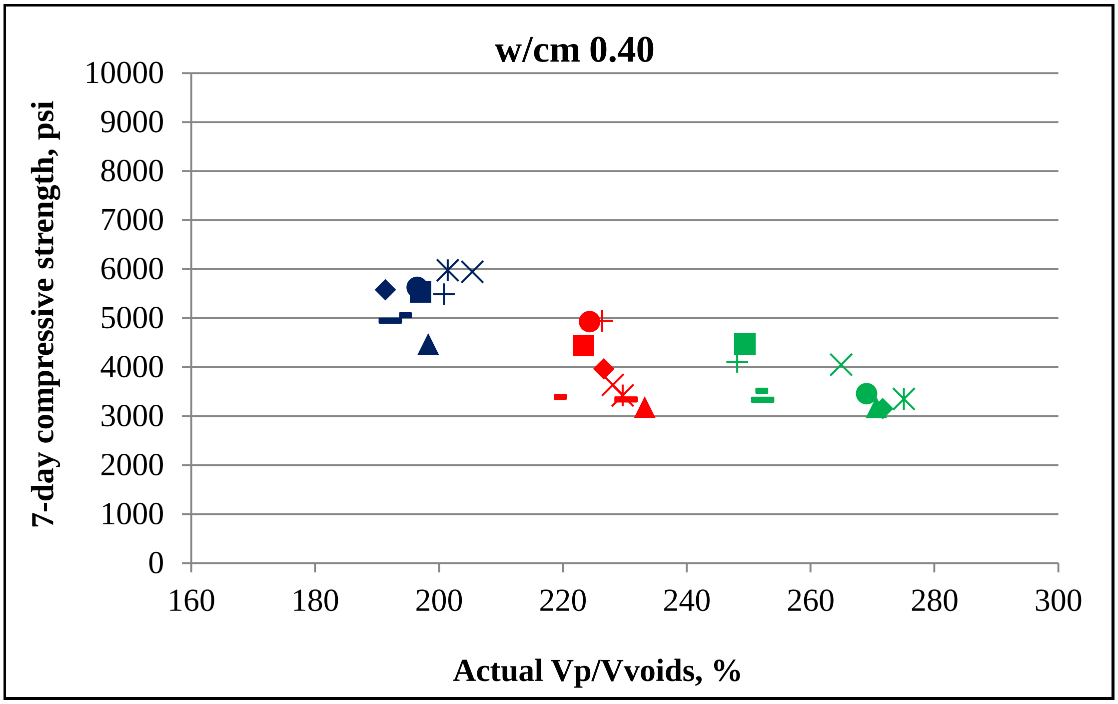


Figure 15. The relationship between Vp/Vvoids and 7-day compressive strength for a w/cm of 0.40

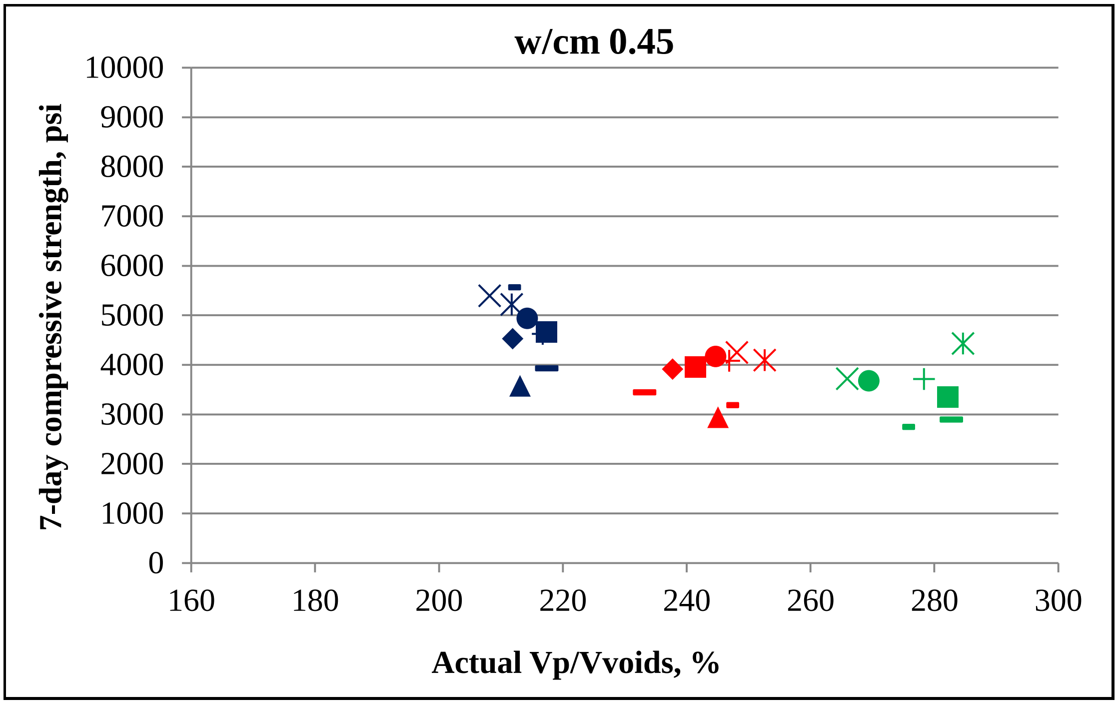


Figure 16. The relationship between Vp/Vvoids and 7-day compressive strength for a w/cm of 0.45

Similarly to the 7-day results, increasing the Vp/Vvoids ratio decreased 28-day compressive strength due to the increased air content (Figures 17 and 18). However, at 28 days, the pozzolanic reactivity of SCM (especially for slag cement) increased and yielded higher compressive strengths than the plain mixtures.

The binary mixes containing class C fly ash exhibited similar strengths to the plain mixtures at 28 days. However, due to the slow pozzolanic reactivity of class F fly ash, the binary mixes containing class F fly ash exhibited lower 28-day compressive strength compared to the plain mix. This result is consistent with the findings in the literature [44].

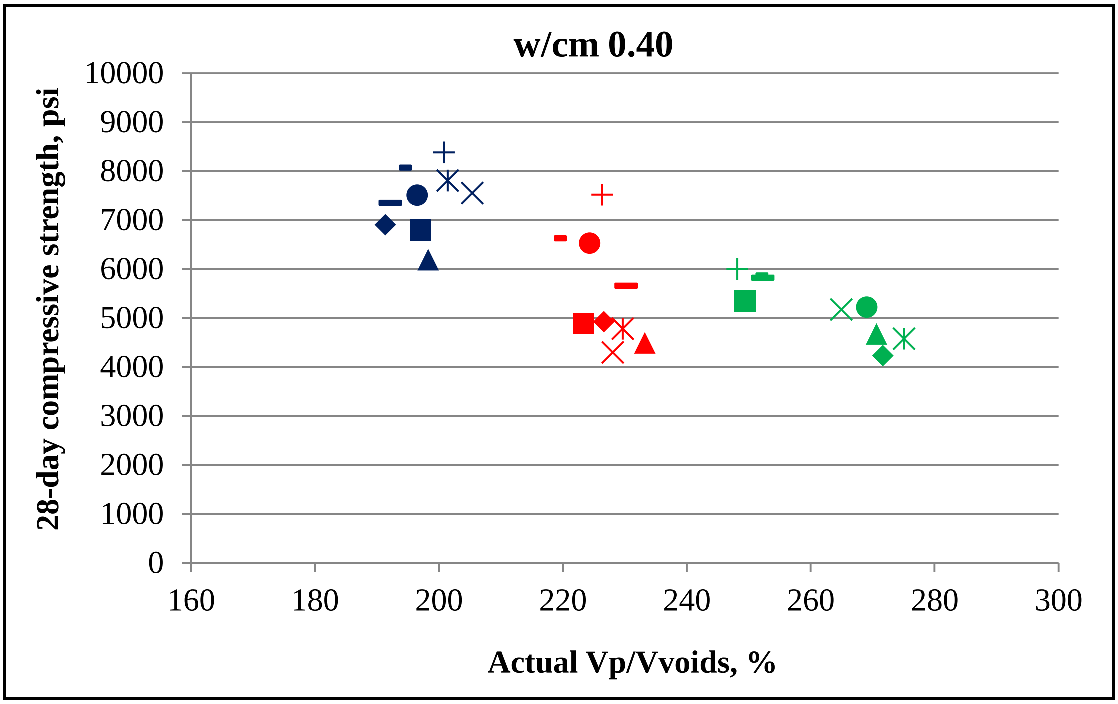


Figure 17. The relationship between Vp/Vvoids and 28-day compressive strength for a w/cm of 0.40

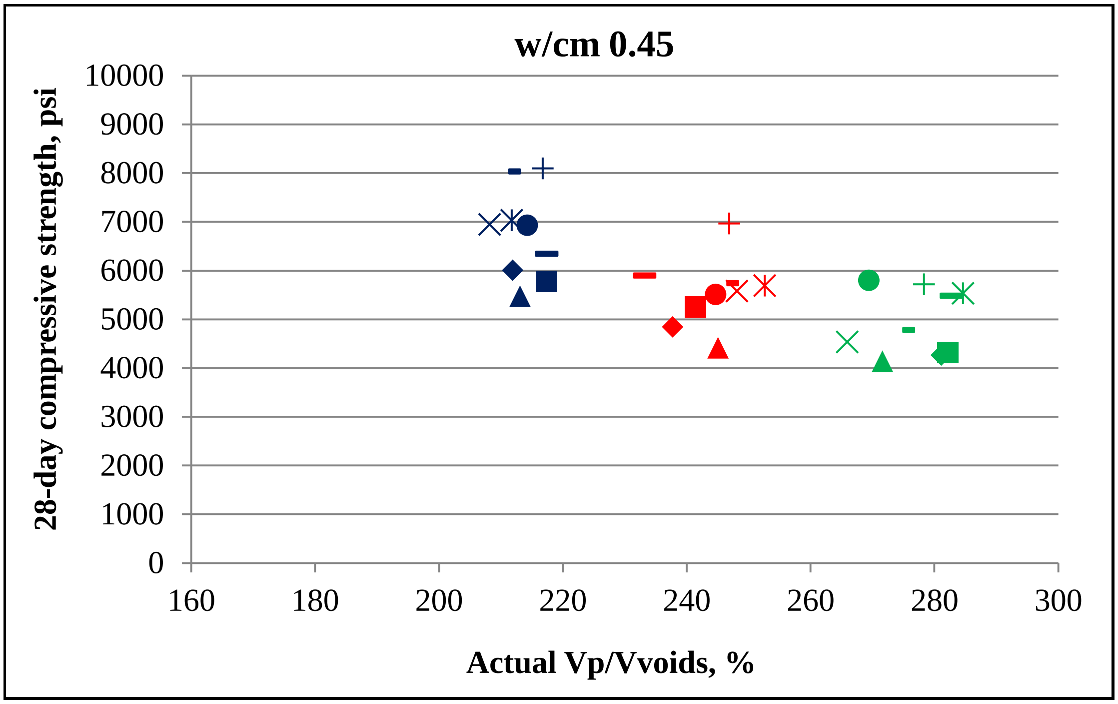


Figure 18. The relationship between Vp/Vvoids and 28-day compressive strength for a w/cm of 0.45

Once again, increasing the Vp/Vvoids ratio was associated with a decreased 56-day compressive strength (Figures 19 and 20). The addition of slag cement and class C fly ash tended to enhance the 56-day compressive strength; however, the binary mixes containing class F fly ash did not significantly improve the 56-day compressive strength.

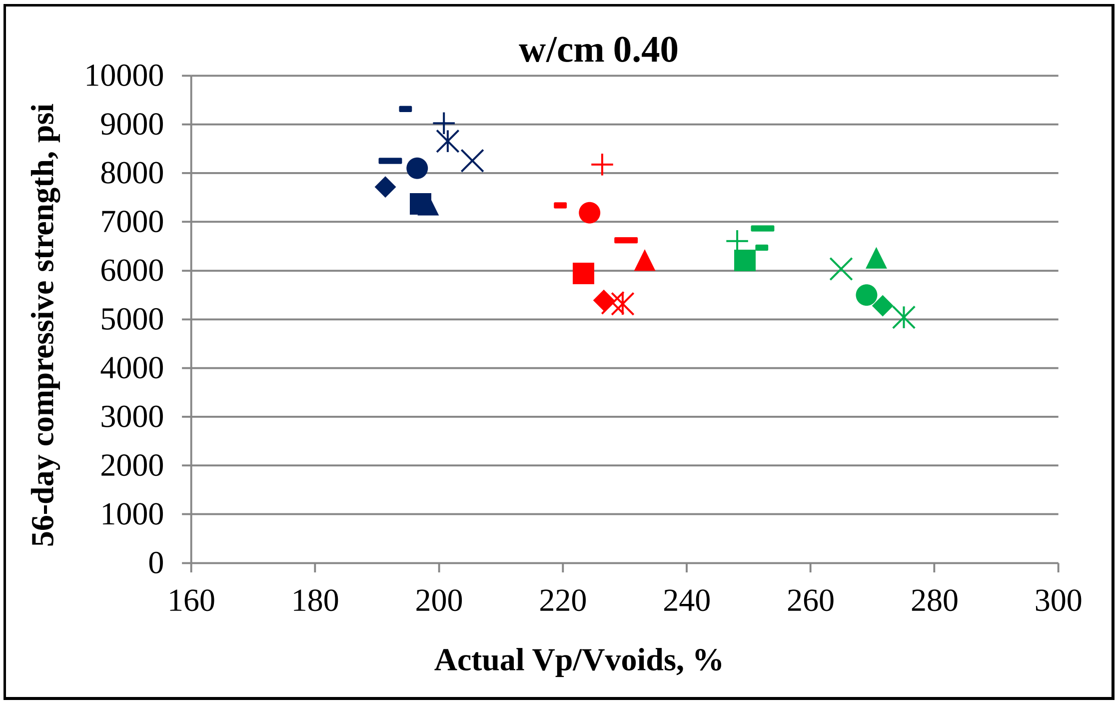


Figure 19. The relationship between Vp/Vvoids and 56-day compressive strength for a w/cm of 0.40

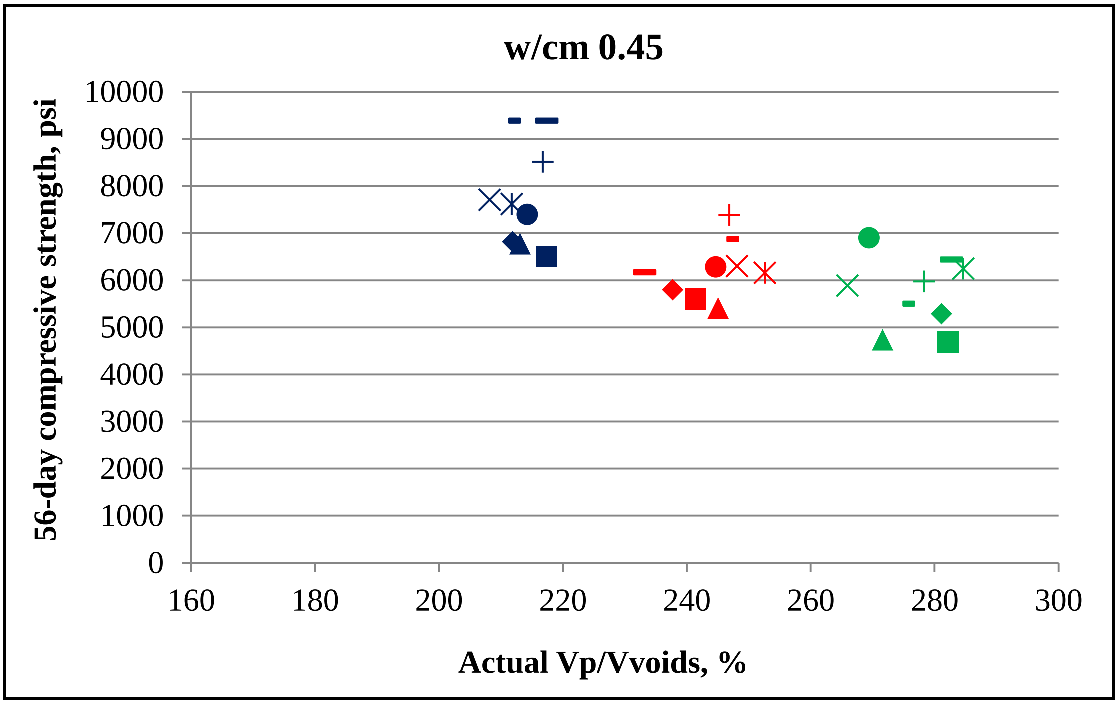


Figure 20. The relationship between Vp/Vvoids and 56-day compressive strength for a w/cm of 0.45

Figure 21 presents the effect of air content on 56-day compressive strength. Increasing the air content decreased the compressive strength, as expected. The slope of the best-fit line indicates a strength loss of about 3.5% per unit air increase across the full spectrum of materials tested. This is consistent with the literature [45] that air content affects strength approximately 5% for each percentage change in air content for a given w/cm.

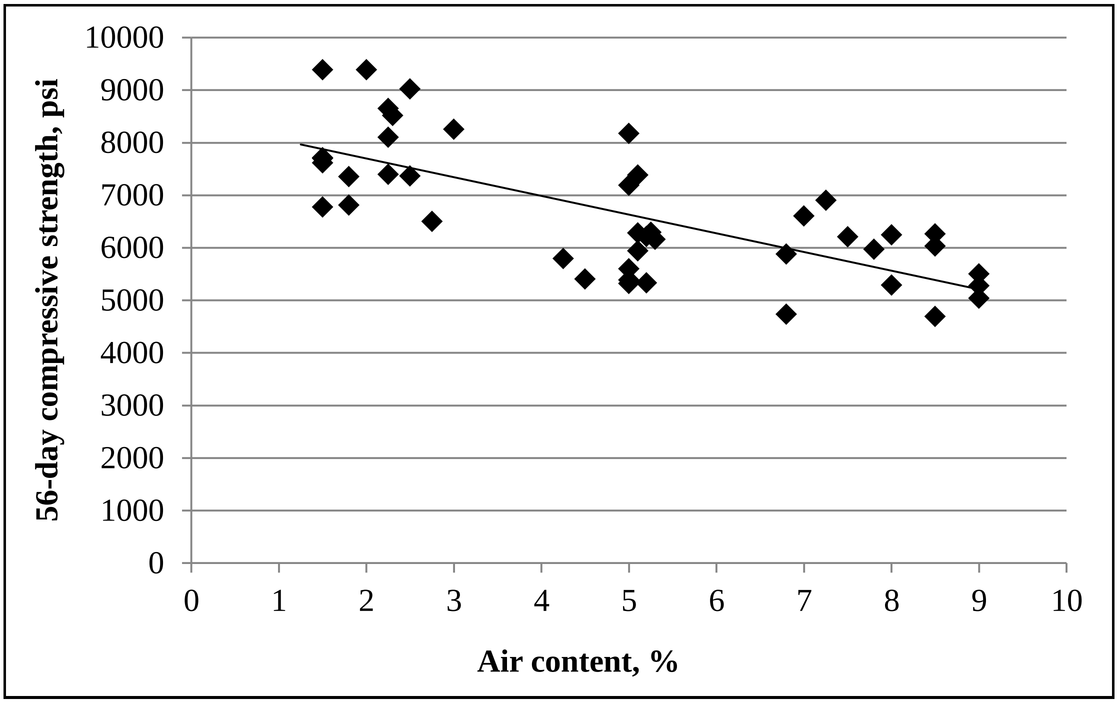


Figure 21. The effect of air content on 56-day compressive strength

In summary, the effects of the SCM's were mostly as expected, except perhaps that the F ash system was slower than expected at the greater ages. Also, as expected, the effect of increasing paste content was marginal, and masked by the effect of the increasing air content.

Surface Resistivity

The relationship between Vp/Vvoids and 7-, 28- and 56-day surface resistivity are presented in Figures 22 through 27.

It can be seen in Figures 22 and 23 that increasing the Vp/Vvoids ratio does not significantly affect the 7-day surface resistivity. This result is expected because at 7 days a limited degree of hydration has occurred in both the plain and SCM mixtures.

As expected, increasing the w/cm from 0.40 to 0.45 decreased the surface resistivity slightly.

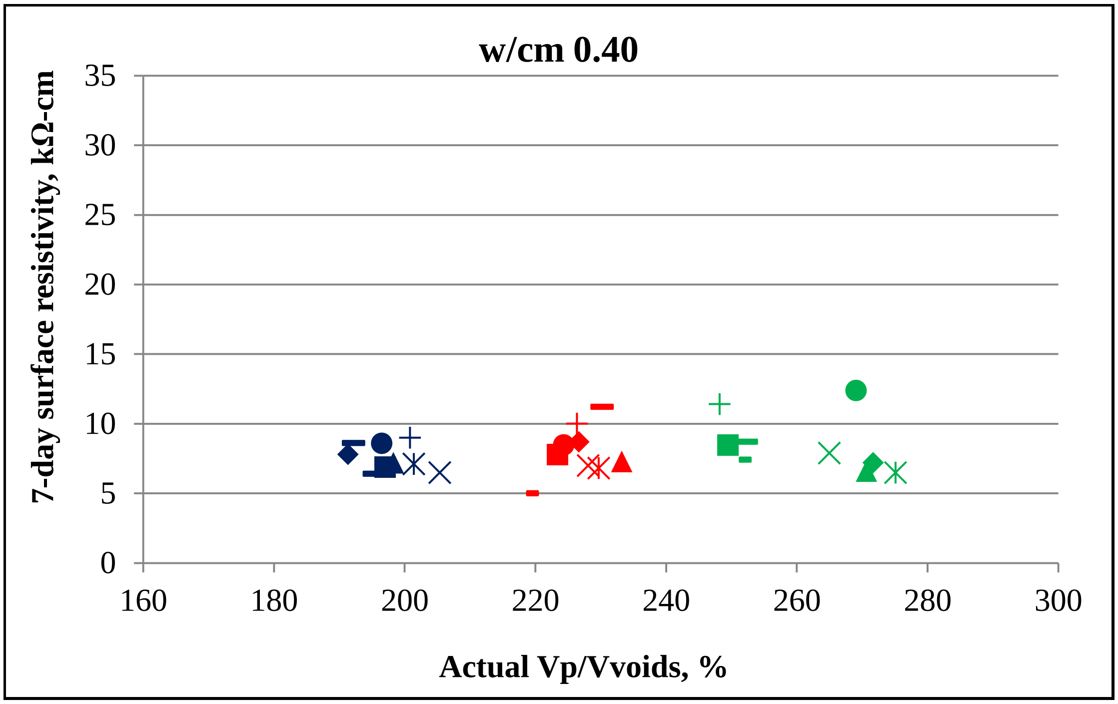


Figure 22. The relationship between Vp/Vvoids and 7-day surface resistivity for a w/cm of 0.40

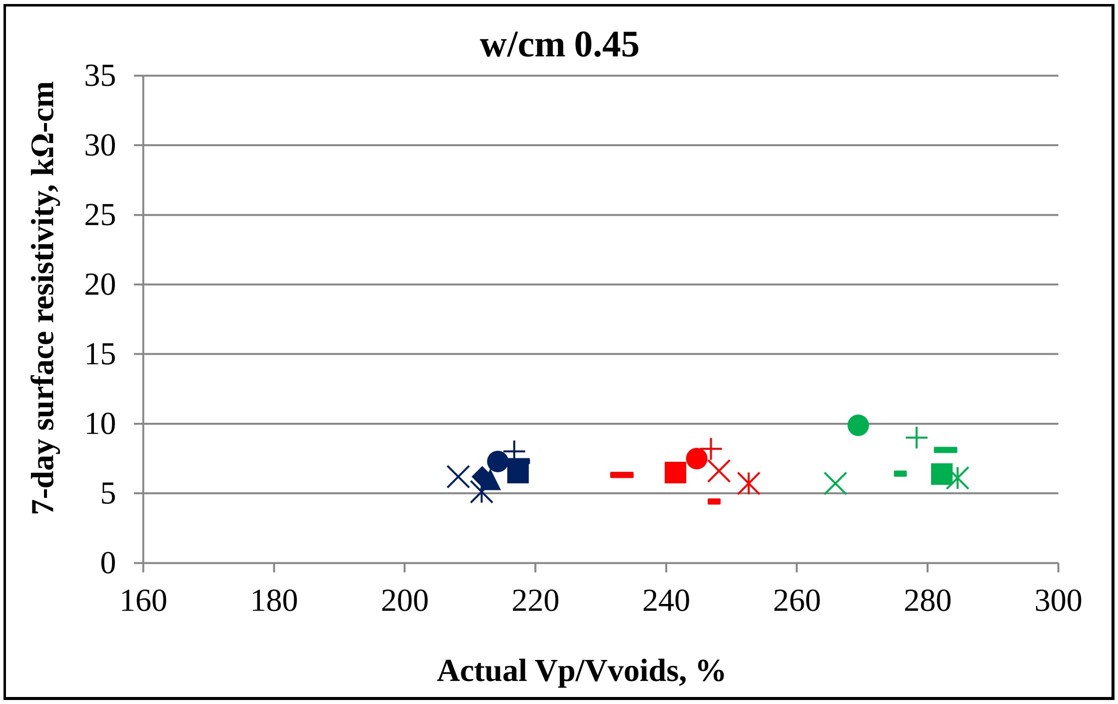


Figure 23. The relationship between Vp/Vvoids and 7-day surface resistivity for a w/cm of 0.45

As shown in Figures 24 and 25, little change in 28-day strength was seen with increasing the Vp/Vvoids ratio. However, it should be noted that in this study the binder content was kept constant. Therefore, for a given w/cm, changes in paste volume were due to increased air content. Thus, the obtained result is expected because the increased air content caused longer duration for the currents to travel from one surface to another, thereby exhibiting a higher surface resistivity.

Figures 24 through 27 show that concrete mixtures benefited from the addition of SCM because their 28- and 56-day surface resistivity results were equal or higher than the plain mixture, depending on the type and amount of the SCM used. The addition of slag cement (especially at 40% of replacement level) and ternary mixtures containing 20% of F fly ash and 20% of slag cement significantly improved the 28- and 56-day surface resistivity.

This result is consistent with the literature [44] that fly ash and slag cement increase the resistance against penetration. The addition of class F fly ash slightly improved the 28-day resistivity, whereas the effect of class C fly ash was not as significant.

Figures 24 and 25 show that increasing w/cm from 0.40 to 0.45 decreased the surface resistivity as a result of the increased capillary porosity.

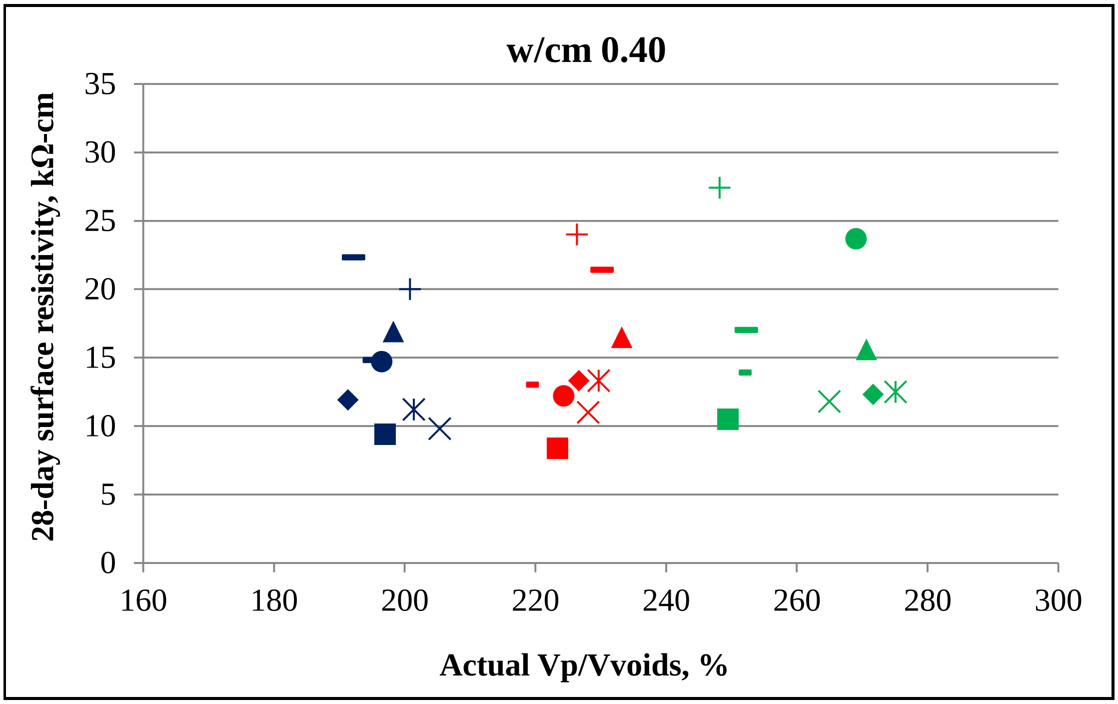


Figure 24. The relationship between Vp/Vvoids and 28-day surface resistivity for a w/cm of 0.40

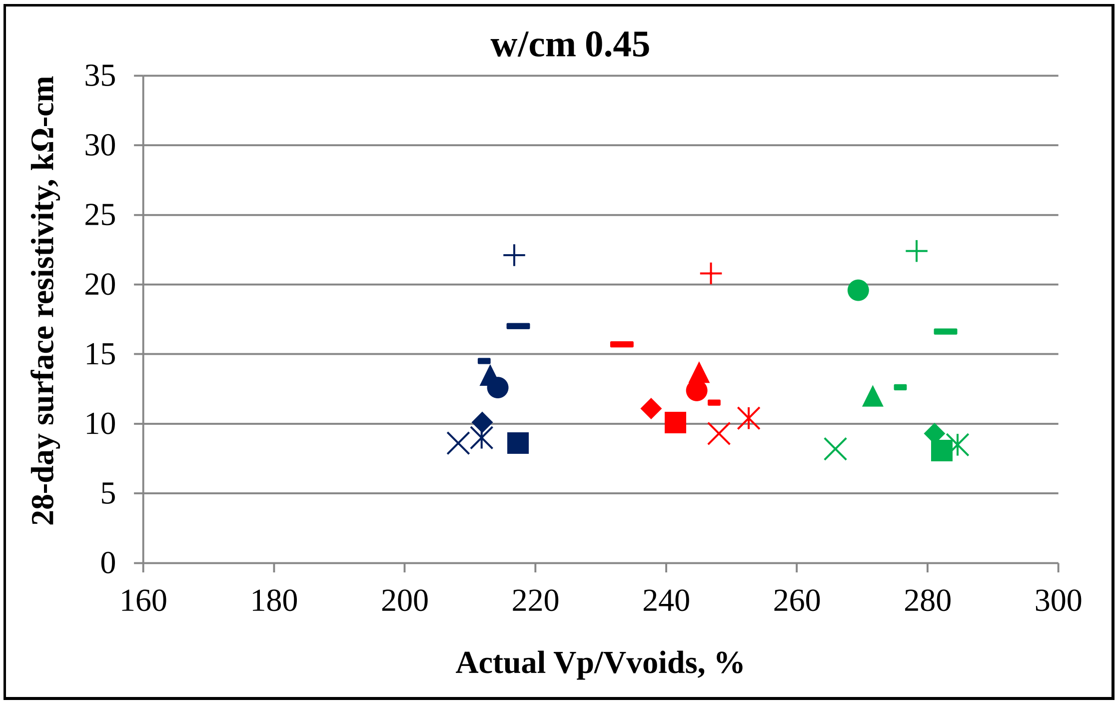


Figure 25. The relationship between Vp/Vvoids and 28-day surface resistivity for a w/cm of 0.45

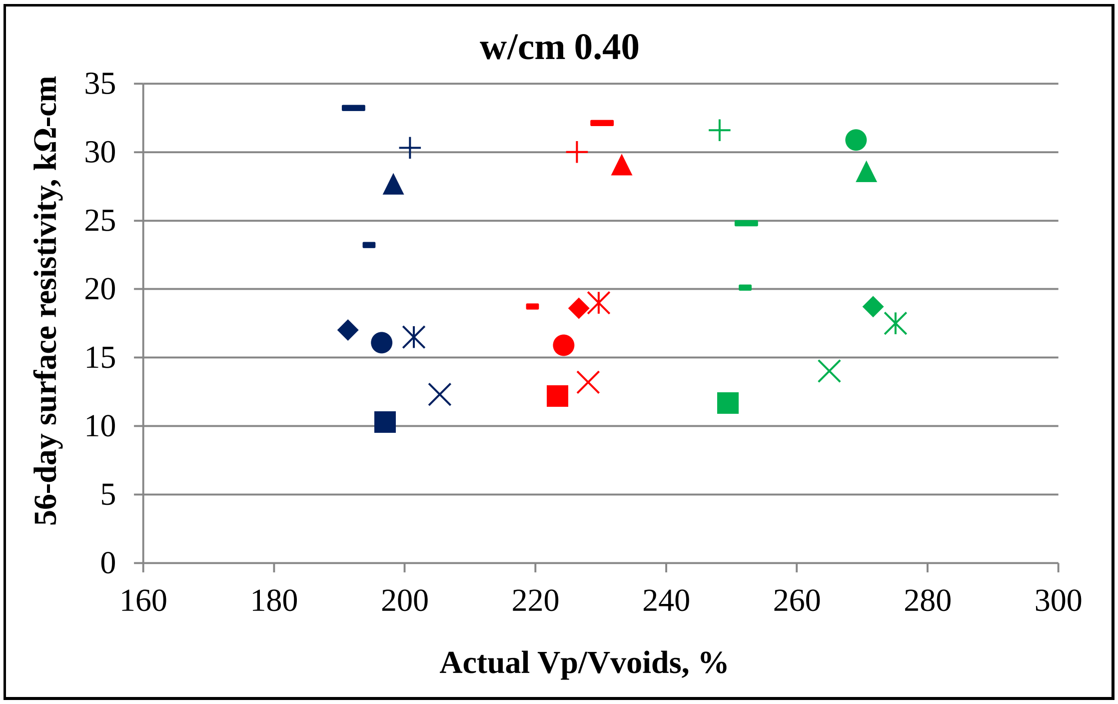


Figure 26. The relationship between Vp/Vvoids and 56-day surface resistivity for a w/cm of 0.40

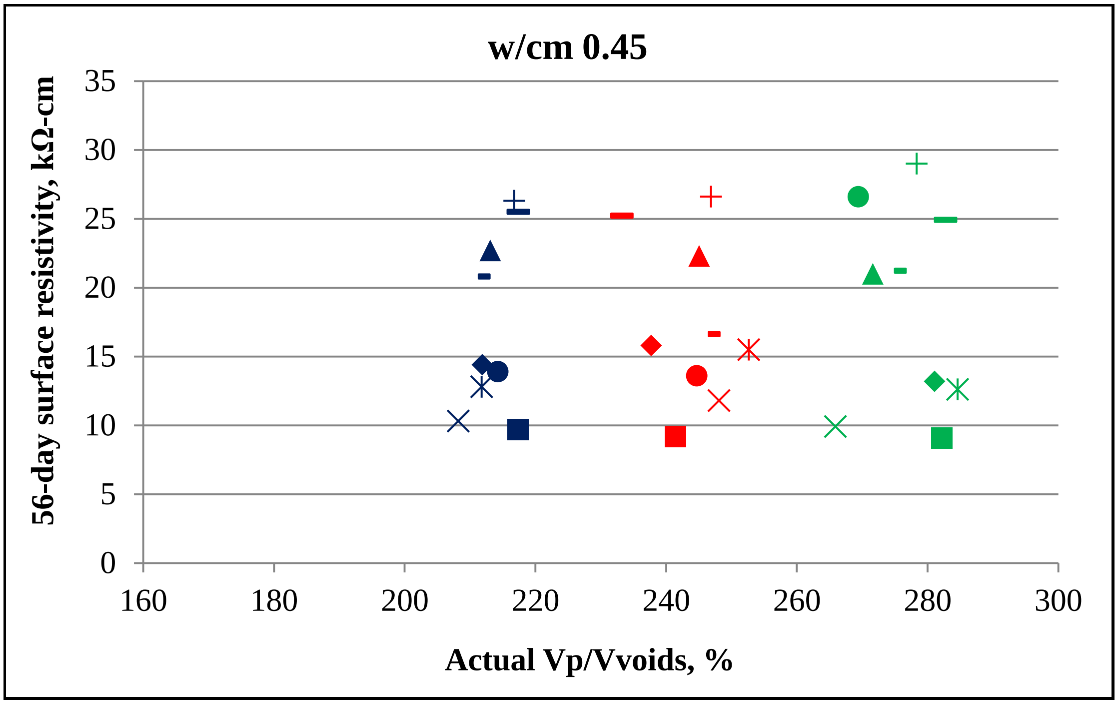


Figure 27. The relationship between Vp/Vvoids and 56-day surface resistivity for a w/cm of 0.45

The relationship between 56-day surface resistivity and 56-day compressive strength result is presented in Figure 28. Based on the plot, there is no relationship between strength and surface resistivity. For example, concrete mixture having approximately 6000 psi of 56-day compressive strength could provide a low surface resistivity of 10 kΩcm to 33 kΩcm [46].

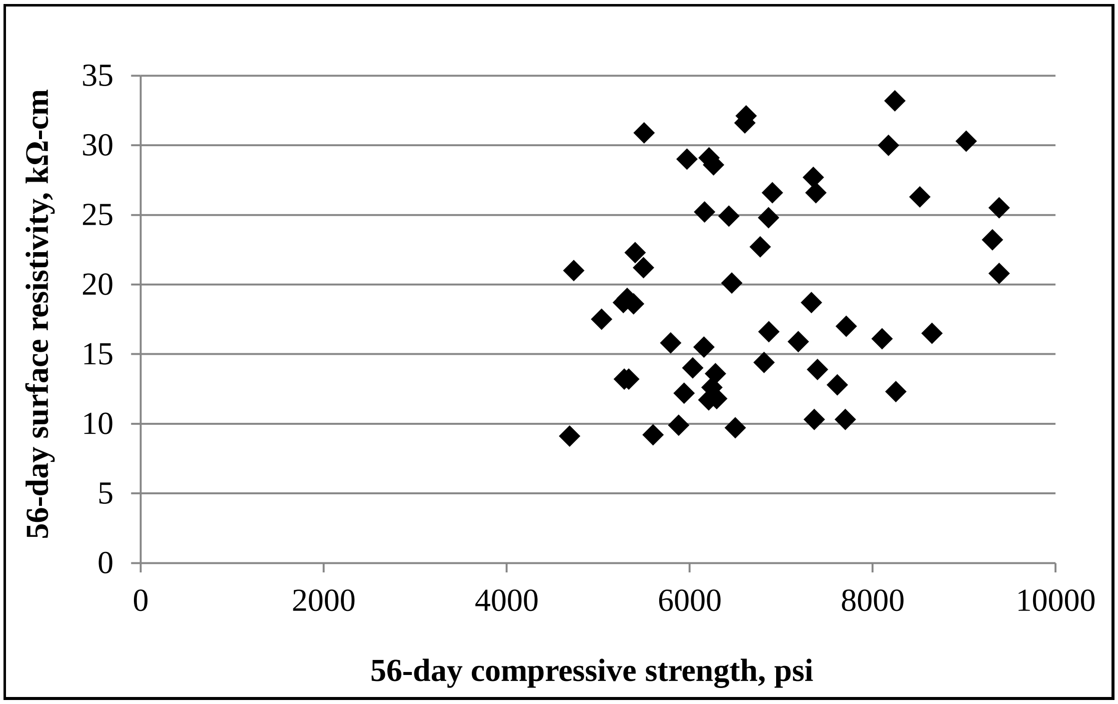


Figure 28. The relationship between 56-day surface resistivity and 56-day compressive strength

Shrinkage

For a given w/cm of 0.40 and 0.45, the changes in 56-day drying shrinkage with changing Vp/Vvoids are presented in Figures 29 and 30.

As seen in the figures, increasing Vp/Vvoids ratio does not significantly affect the 56-day shrinkage. Likewise, little change in shrinkage was seen with varying SCMs. This is consistent with the literature [39].

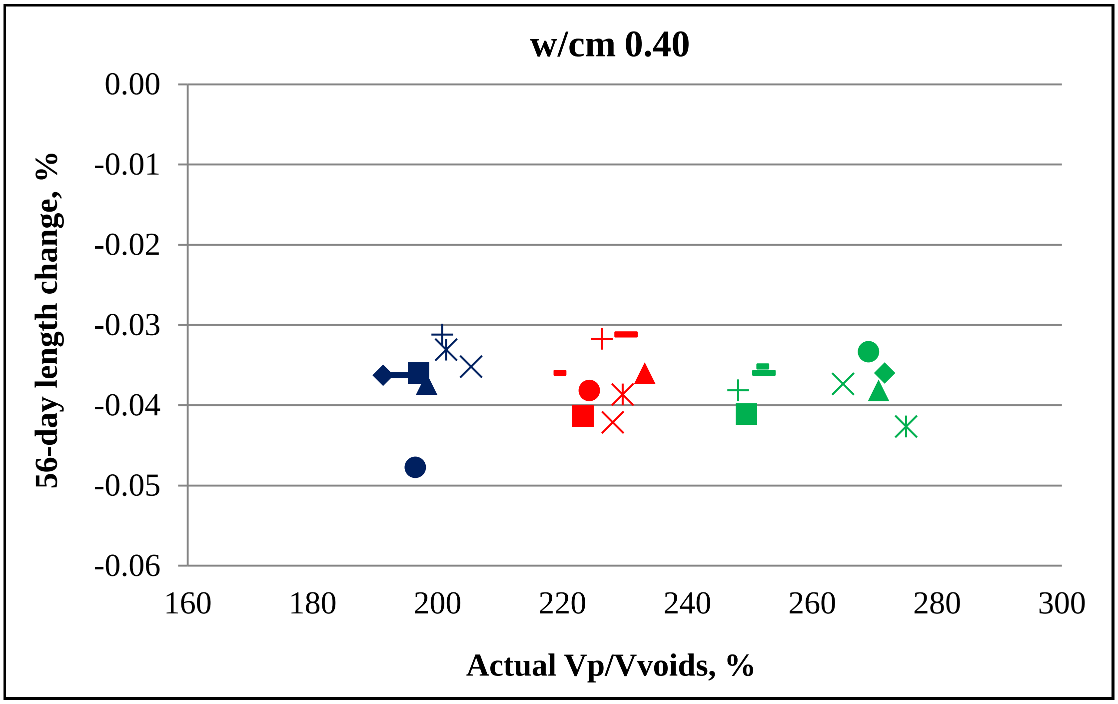


Figure 29. The relationship between Vp/Vvoids and 56-day length change for a w/cm of 0.40

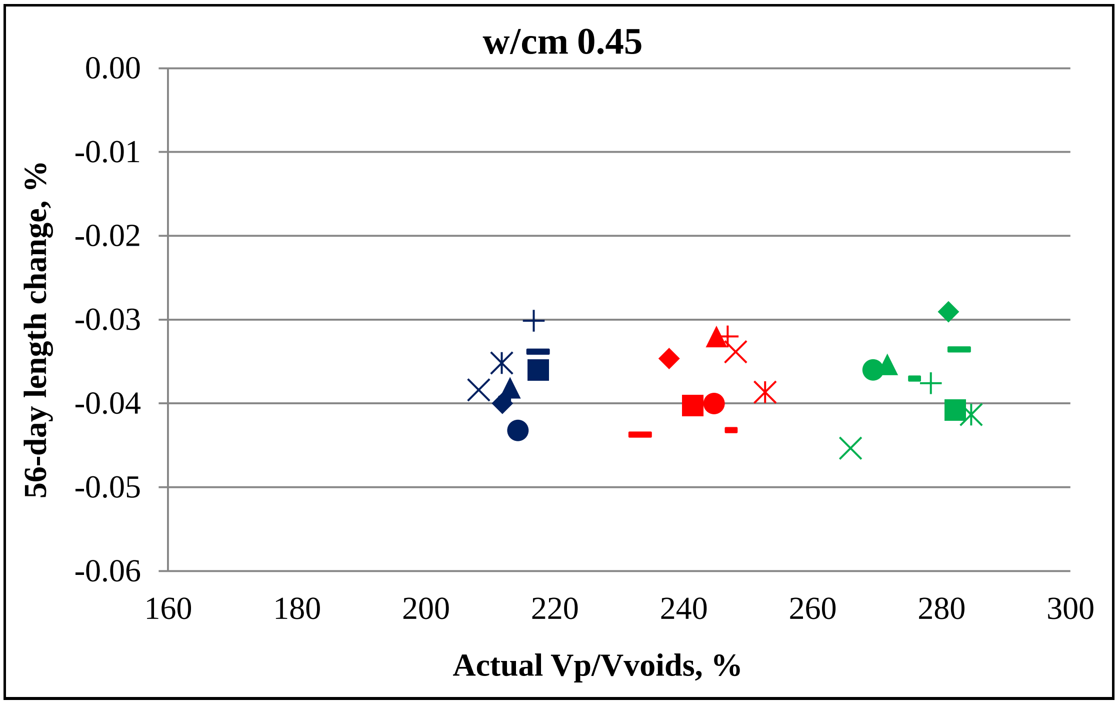


Figure 30. The relationship between Vp/Vvoids and 56-day length change for a w/cm of 0.45

CONCLUSIONS

The effect of the paste quality and mixture characteristics (w/cm, SCM, and air-void system) was investigated on workability, setting time, strength, surface resistivity, and shrinkage in both binary and ternary mixtures. The following conclusions are made based on the results:

- The effects of paste variables on workability are more marked at the higher w/cm. Increasing F ash had the most effect, while slag had little measurable influence. Ternary mixtures performed in accordance with their ingredients.
- The effects of paste variables on workability are slightly more marked at the higher w/cm. Increasing C ash had the most effect, while slag had little measurable influence. Ternary mixtures performed in accordance with their ingredients.
- As expected, the compressive strength is strongly influenced by the paste quality, dominated by w/cm and air content.
- Surface resistivity is improved by inclusion of Class F fly ash and slag cement, especially at later ages.
- The results do not show a clear relationship between paste quality and shrinkage.
- The data collected will be used to develop models that will be part of an innovative mix proportioning procedure.

REFERENCES

1. Taylor, P. and A. United States. Federal Highway. *Optimizing cementitious content in concrete mixtures for required performance*. 2012; Available from: http://www.intrans.iastate.edu/reports/taylor_ocm_w_cvr2.pdf.
2. Committee, A., *Cement and concrete terminology*. 2000, Farmington Hills, Mich.: American Concrete Institute.
3. Su, N. and B. Miao, *A new method for the mix design of medium strength flowing concrete with low cement content.* Cement & concrete composites., 2003. **25**(2): p. 215-222.
4. Mehta, P.K. and P.J.M. Monteiro, *Concrete: microstructure, properties, and materials*. 2006, New York: McGraw-Hill.
5. Peter C. Taylor, S.H.K., Gerald F. Voigt, et al. *Integrated materials and construction practices for concrete pavement: a state-of-the-practice manual / edited by Peter C. Taylor [et al.]*, ed. P.C. Taylor and A. United States. Federal Highway. 2006, Ames, Iowa: Ames, Iowa : National Concrete Pavement Technology Center, Iowa State University.
6. Ferraris, C., Gaidis, JM, *Connection between the rheology of concrete and rheology of cement paste* Aci Materials Journal, 1992. 89(4): p. 388-393.
7. Kosmatka, S.H., B. Kerkhoff, and W.C. Panarese, *Design and control of concrete mixtures*. 14th ed., 4th printing, rev. / by Steven H. Kosmatka, Beatrix Kerkhoff, and William C. Panarese. ed. 2008, Skokie, Ill.: Portland Cement Association. x, 358 p.
8. Mindess, S., J.F. Young, and D. Darwin, *Concrete*. 2nd ed. 2003, Upper Saddle River, NJ: Prentice Hall. xi, 644 p.
9. Mehta, P.K. and P.J.M. Monteiro, *Concrete : structure, properties, and materials*. 1993, Englewood Cliffs, N.J.: Prentice Hall.
10. Wong, G.S., et al. *Portland-cement concrete rheology and workability final report*. 2001.
11. Collins, F. and J. Sanjayan. *Effects of ultra fine materials on workability and strength of concrete containing alkali activated slag as a binder*. 1999; Available from: http://arrow.monash.edu.au/hdl/1959.1/235878.
12. Chengzhi, Z., et al., *The Filling Role of Pozzolanic Material.* Cement and concrete research., 1996. 26(6): p. 943.
13. Megat Johari, M.A., et al., *Influence of supplementary cementitious materials on engineering properties of high strength concrete.* Construction and Building Materials, 2011. 25(5): p. 2639-2648.
14. Johansen, V., P.C. Taylor, and P.D. Tennis, *Effect of cement characteristics on concrete properties*. 2006, Skokie, Ill.: Portland Cement Association.
15. Ferraris, C.F., K.H. Obla, and R. Hill, *The influence of mineral admixtures on the rheology of cement paste and concrete.* Cement and Concrete Research Cement and Concrete Research, 2001. 31(2): p. 245-255.
16. Obla, K.H., et al., *Properties of Concrete Containing Ultra-Fine Fly Ash.* ACI materials journal., 2003. 100(5): p. 426.
17. Abrams, D.A., *Design of concrete mixtures*. 1920, Chicago: Structural Materials Research Laboratory, Lewis Institute.
18. Wassermann, R., A. Katz, and A. Bentur, *Minimum cement content requirements: a must or a myth?* Materials and Structures, 2009. 42(7): p. 973-982.

19. Kennedy, C.T., *The design of concrete mixes.* Journal of the American Concrete Institute, 1940. 36(2): p. 373-400.
20. Dhir, R., et al., *Role of cement content in specifications for concrete durability: cement type influences.* Proceedings of the Institution of Civil Engineers-Structures and Buildings, 2004. 157(2): p. 113-127.
21. Popovics, S., *Analysis of the concrete strength versus water-cement ratio relationship.* ACI Materials Journal, 1990. 87(5): p. 517-529.
22. Barbhuiya, S.A., et al., *Properties of fly ash concrete modified with hydrated lime and silica fume.* Construction & building materials., 2009. 23(10): p. 3233-3239.
23. Khatri, R.P., et al. *Effect of different supplementary cementitious materials on mechanical properties of high performance concrete*. 1995, [S.l.]: CSIRO. Division of Building, Construction and Engineering.
24. Toutanji, H., et al., *Effect of supplementary cementitious materials on the compressive strength and durability of short-term cured concrete*. CEMENT AND CONCRETE RESEARCH, 2004. 34(2): p. 311-319.
25. Soutsos, M., *Concrete durability : a practical guide to the design of durable concrete structures*. 2010, London: Thomas Telford.
26. Cho, M.-S., J.-M. Noh, and Y.-C. Song, *EVALUATION OF A PENETRATION-REINFORCING AGENT TO PREVENT THE AGING OF CONCRETE.* Nuclear Engineering and Technology Nuclear Engineering and Technology, 2009. 41(8): p. 1127-1134.
27. Lane, D.S., R.J. Detwiler, and R.D. Hooton, *Testing Transport Properties in Concrete.* CONCRETE INTERNATIONAL -DETROIT-, 2010. 32(11): p. 33-38.
28. Dinku, A. and H. Reinhardt, *Gas permeability coefficient of cover concrete as a performance control.* Materials and Structures, 1997. 30(201): p. 387-393.
29. Collepardi, M., A. Marcialis, and R. Turriziani, *Penetration of Chloride Ions into Cement Pastes and Concretes.* J American Ceramic Society Journal of the American Ceramic Society, 1972. 55(10): p. 534-535.
30. Hilsdorf, H. and J. Kropp. *Performance Criteria for Concrete Durability*. 1995; Available from: http://public.eblib.com/EBLPublic/PublicView.do?ptiID=183054.
31. Hansen, T.C., *Physical structure of hardened cement paste. A classical approach.* Materials and Structures Materials and Structures, 1986. 19(6): p. 423-436.
32. 302, A., *Guide for concrete floor and slab construction*. 1996, Detroit, Mich.: American Concrete Institute.
33. Liu, R., et al., *Optimization of Cementitious Material Content for Sustainable Concrete Mixtures.* Journal of Materials in Civil Engineering Journal of Materials in Civil Engineering, 2012.
34. Bagheri, A.R. and H. Zanganeh, *Comparison of Rapid Tests for Evaluation of Chloride Resistance of Concretes with Supplementary Cementitious Materials.* Journal of Materials in Civil Engineering Journal of Materials in Civil Engineering, 2012.
35. Papadakis, V.G., *Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress.* CEMENT AND CONCRETE RESEARCH, 2000. 30(2): p. 291-299.
36. Neville, A., *The question of concrete durability the Answer: We can made good concrete today.* Concrete International, 2000. 22(7): p. 21-26.

37. Yurdakul, E. *Optimizing concrete mixtures with minimum cement content for performance and sustainability*. 2010; Available from: http://gateway.proquest.com/openurl?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&res_dat=xri:pqdiss&rft_dat=xri:pqdiss:1488069.
38. Wang, K. and A. United States. Federal Highway, *Self-consolidating concrete, applications for slip form paving phase I (feasibility study)*. 2005, Ames, Iowa: Center for Portland Cement Concrete Pavement Technology, Iowa State University.
39. Hale, W.M., et al., *Properties of concrete mixtures containing slag cement and fly ash for use in transportation structures.* Construction & building materials., 2008. **22**(9): p. 1990-2000.
40. 211, A., *Standard practice for selecting proportions for normal, heavyweight, and mass concrete*. 1997, Detroit, Mich.: American Concrete Institute.
41. Wang, K., A. United States. Federal Highway, and E. Iowa State University. Center for Transportation Research and, *Improving variability and precision of air-void analyzer (AVA) test results and developing rational specification limits*. 2008, Ames, Iowa: Iowa State University, Center for Transportation Research and Education.
42. Wang, K., et al., *Investigation into freezing-thawing durability of low permeability concrete with and without air entraining agent*. 2009, Ames, IA: National Concrete Pavement Technology Center, Iowa State University.
43. Tikalsky, P., C. Iowa State University. National Concrete Pavement Technology, and A. United States. Federal Highway, *Development of performance properties of ternary mixtures : laboratory study on concrete: final report*. 2011, Ames, Iowa: National Concrete Pavement Technology Center, Iowa State University.
44. Obla, K.H., *Specifying Fly Ash for Use in Concrete*, in *Concrete in Focus*2008. p. 60-66.
45. Cannon, R.W., *Proportioning Fly Ash Concrete Mixes for Strength and Economy.* ACI Journal, 1968. 65(75): p. 969-979.
46. Rupnow, T.D., et al., *Evaluation of surface resistivity measurements as an alternative to the rapid chloride permeability test for quality assurance and acceptance*. 2011, Baton Rouge, LA: Louisiana Transportation Research Center.