Optimizing Cementious Content in Concrete Mixtures for Required Performance

National Concrete Pavement Technology Center

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January 2012

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16. Abstract

This research investigated the effects of changing the cementitious content required at a given water-to-cement ratio (w/c) on workability, strength, and durability of a concrete mixture.

An experimental program was conducted in which 64 concrete mixtures with w/c ranging between 0.35 and 0.50, cementitious content ranging from 400 to 700 per cubic yard (pcy), and containing four different supplementary cementitious material (SCM) combinations were tested. The fine-aggregate to total-aggregate ratio was fixed at 0.42 and the void content of combined aggregates was held constant for all the mixtures. Fresh (i.e., slump, unit weight, air content, and setting time) and hardened properties (i.e., compressive strength, chloride penetrability, and air permeability) were determined.

The hypothesis behind this study is that when other parameters are kept constant, concrete properties such as strength, chloride penetration, and air permeability will not be improved significantly by increasing the cement after a minimum cement content is used.

The study found that about 1.5 times more paste is required than voids between the aggregates to obtain a minimum workability. Below this value, water-reducing admixtures are of no benefit. Increasing paste thereafter increased workability. In addition, for a given w/c, increasing cementitious content does not significantly improve compressive strength once the critical minimum has been provided. The critical value is about twice the voids content of the aggregate system. Finally, for a given w/c, increasing paste content increases chloride penetrability and air permeability.

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OPTIMIZING CEMENTITIOUS CONTENT IN CONCRETE MIXTURES FOR REQUIRED PERFORMANCE

Final Report
January 2012

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INTRODUCTION

Concrete is the most commonly used material for all types of construction, and cement is a primary component. The cement content of a mixture is commonly perceived to control concrete strength. Based on this perception, a minimum cement content is often specified that may exceed the amount needed to achieve the desired strength and durability. This excess amount has a negative impact on cost and the environment for the following reasons:

- Cement is the most expensive component in concrete
- Cement contributes about 80 percent of the carbon dioxide (CO_2) burden of a concrete mixture
- Cement production emits approximately 5 percent of global CO_2 and consumes about 5 percent of global energy

Previous studies suggest that increasing cement content in a mixture does not necessarily contribute to increasing strength (Wasserman et al. 2009, Popovics 1990). In addition, the high cement content will cause the mixture to become sticky and may lead to increased risk of shrinkage and cracking problems. Therefore, cement content should be balanced to achieve the required performance while minimizing risk of these problems. Despite the published studies and documentation, there continues to be a misconception that more cement in a mixture design means a better performing mixture.

Increasing cement content can have a negative impact on performance and durability by increasing shrinkage and the consequent risk of cracking. Although workability is increased by increasing cement content, it causes higher internal temperatures in the concrete during the finishing and curing processes.

Reducing excess cement content in concrete mixtures helps to reduce costs as well as the environmental and energy impacts associated with making cement.

This study investigates the effects of changing cement content and paste volume on strength and durability.

Research Goal and Objective

The goal of this project is to help the concrete industry use the right amount of cement with an appropriate water-to-cement (w/c) or water-to-cementitious materials (w/cm) ratio to meet given workability, strength, and durability requirements, and so to optimize carbon dioxide emissions, energy consumption, and costs.

The hypothesis behind this study is that when other parameters are kept constant, concrete properties such as strength and durability will not be improved significantly by adding additional cement after a certain minimum cement content is used. Figure 1 illustrates this hypothesis.

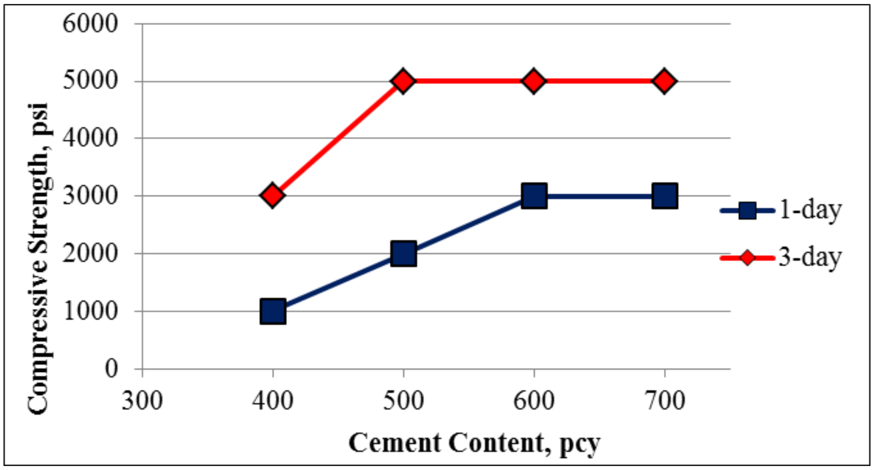


Figure 1. Effect of cement content on concrete compressive strength

The scope of this study is to investigate strength, chloride penetration, and air permeability as indicators of performance of concrete mixtures with various w/cm and cementitious contents using a variety of binders. Fresh concrete properties such as slump, setting time, and air content are also tested.

LITERATURE REVIEW

This section presents a review of literature focusing on four major areas:

- Workability
- Strength
- Durability
- Shrinkage

Each concrete property is discussed as it is affected by mixture composition. The five mixture characteristics covered include the following:

- Cement content
- Water-to-cementitious materials ratio (w/cm)
- Aggregates
- Chemical admixtures
- Supplementary Cementitious Materials (SCM)

A section on sustainability is also provided because a purpose of this study is to investigate methods for using cement more efficiently.

Concrete durability is commonly specified by defining minimum cement content, minimum strength, and maximum w/c (Arachchige 2008). The w/c is the primary factor affecting concrete strength where reducing w/c leads to increasing strength. However, it is also believed by many practitioners that concrete strength is controlled by the cement content. Based on this belief, many specifications require a minimum cement content.

Information in the literature regarding the effect of mixture design decisions is discussed in the following sections.

Workability

The American Concrete Institute (ACI) Committee 116R (2000) 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 can be identified by three main parameters (Kosmatka et al. 2002, Chen and Duan 2000):

- Cohesiveness: the resistance to segregation
- Consistency: the ease of flow
- Plasticity: the ease of molding

Workability is commonly assessed using the slump test (ASTM C143) even though the test is of limited value because it does not fully characterize concrete flow (Ferraris and Gaidis 1992). The slump test, however, is a useful indicator of uniformity between batches (Kosmatka et al. 2002).

A number of factors can influence the workability of a mixture as discussed below.

Water Content

Increasing the water content in concrete will increase workability (Mindess et al. 2003, Kosmatka et al. 2002). However, excessive water content should be avoided to reduce the risk of segregation and bleeding (Taylor et.al. 2006, Mindess et al. 2003, Mehta and Monteiro 1993).

Cement Content

Workability is affected by paste volume, because the paste lubricates the aggregates (Ferraris and Gaidis 1992). For a given water content, decreasing the cement content increases stiffness of the paste and reduces the concrete workability (Lamond and Pielert 2006, Mehta and Monteiro 1993). Concrete with high cement content exhibits high cohesiveness and can become sticky (Lamond and Pielert 2006, Kosmatka et al. 2002, Mehta and Monteiro 1993).

Aggregates

Aggregates constitute 60 to 75 percent of the total volume of concrete; therefore, they strongly influence mixture performance. Gradation, shape, porosity, and surface texture of aggregates affect the workability of concrete (Kosmatka et al. 2002). Well-graded aggregate improves workability because there is less interlock between single-sized particles (Taylor et. al. 2006, Mindess et al. 2003, Shilstone and Shilstone 2002, Mehta and Monteiro 1993) Spherical, well-rounded, with smooth-surfaced aggregates, increase workability; whereas, angular, elongated, rough-surfaced aggregates decrease workability and cause segregation (Mindess et al. 2003).

Chemical Admixtures

Cement particles normally carry surface charges, which causes them to flocculate and trap water between them. Water-reducing agents neutralize these charges, thereby freeing up the water, and also driving the cement particles apart, improving their ability to move past each other (see Figure 2) (Mindess et al. 2003). Therefore, for a given water content, the addition of a water-reducing admixture will increase workability (Taylor et. al. 2006, Mindess et al. 2003, Kosmatka et al. 2002, Mehta and Monteiro 1993).

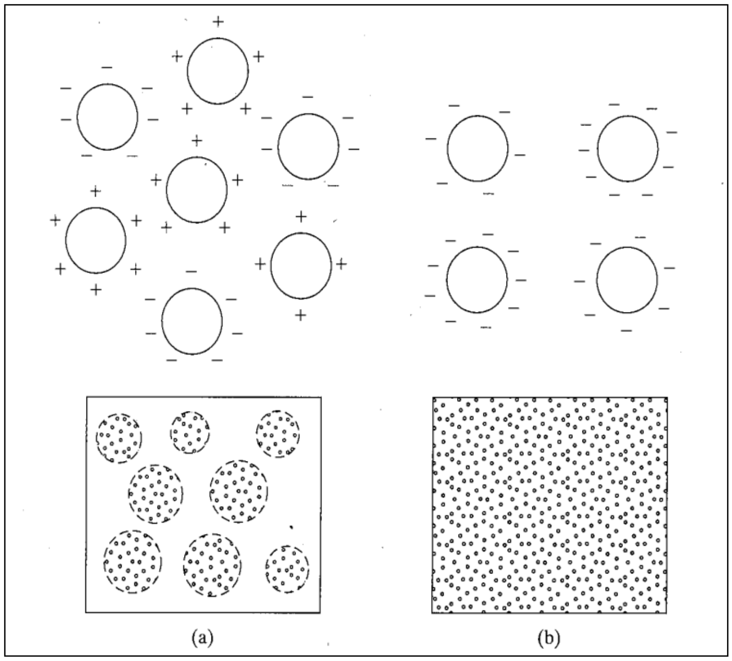


Figure 2. Dispersing action of water-reducing agents a) flocculated paste and b) dispersed paste (Mindess et al. 2003)

Supplementary Cementitious Materials

Supplementary cementitious materials generally improve the workability of concrete (Taylor et. al. 2006, Mindess et al. 2003, Kosmatka et al. 2002, Wong et al. 2001, Collins and Sanjayan 1999, Mehta and Monteiro 1993). On the other hand, silica fume increases the water requirement and stickiness of a concrete mixture because of its high surface area (Taylor et. al. 2006, Obla et al. 2003, Kosmatka et al. 2002, and Ferraris et al. 2001).

Strength

Concrete compressive strength is affected by the following factors.

Cement Content

Strength is considered to be a function of w/c and independent of cement content for a given w/c, therefore, increasing cement content should not affect strength (Wassermann et al. 2009, Dhir et al. 2004). Furthermore, according to Abrams rule, paste content does not affect strength; however, strength is affected by the paste quality (Wassermann et al. 2009).

Water-to-Cement Ratio

The strength at any particular age is a function of w/c and the degree to which the cementitious materials have hydrated because they affect the porosity of both cement paste and the interfacial transition zone between the coarse aggregate and cement paste (Wassermann et al. 2009, Taylor et. al. 2006, Mindess et al. 2003, Kosmatka et al. 2002, Mehta and Monteiro 1993).

Strength decreases with increasing w/c (Figure 3) because the capillary porosity increases as presented in Figure 4 (Wassermann et al. 2009, Taylor et. al. 2006, Dhir et al. 2004, Mindess et al. 2003, Kosmatka et al. 2002, Mehta and Monteiro 1993). To increase strength, it is more efficient to reduce the water content than to use more cement (Popovics 1990).

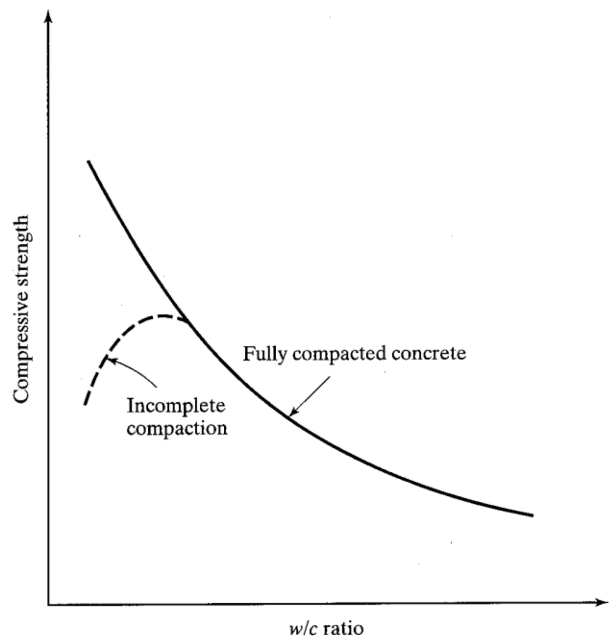


Figure 3. Relationship between compressive strength and water-to-cement ratio (Mindess et al. 2003)

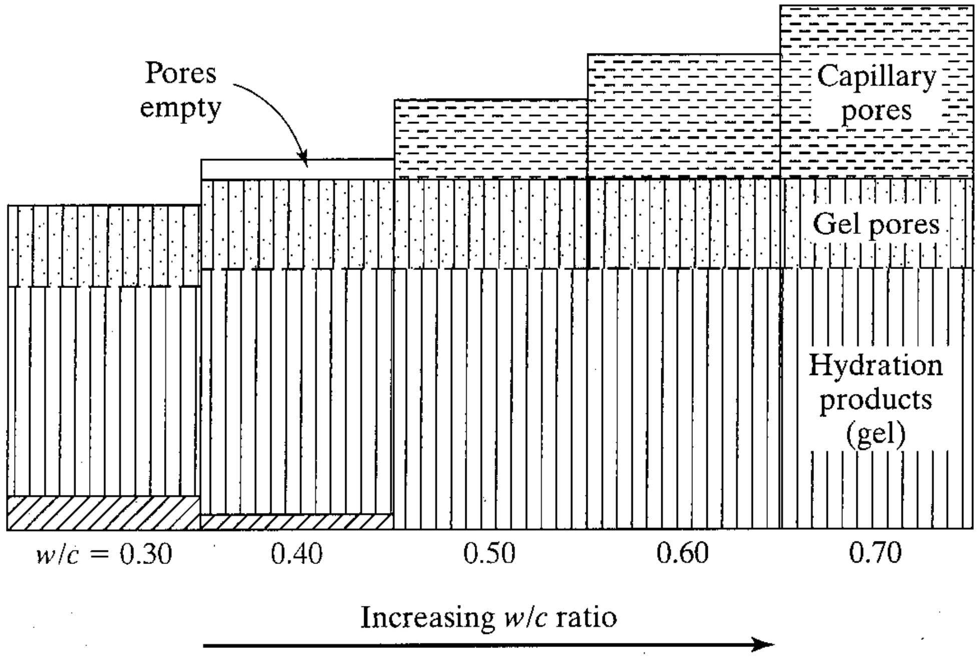


Figure 4. Relationship between porosity and w/c (Mindess et al. 2003)

Aggregates

Rough aggregates will tend increase strength because they form a stronger mechanical bond with the cement paste (Taylor et. al. 2006, Mindess et al. 2003, Kosmatka et al. 2002, Mehta and Monteiro 1993).

The maximum size of aggregate also affects the concrete strength (see Figure 5). Large aggregate particles tend to reduce compressive strength by setting up higher stress concentrations in the paste when subjected to compressive load (Mindess et al. 2003).

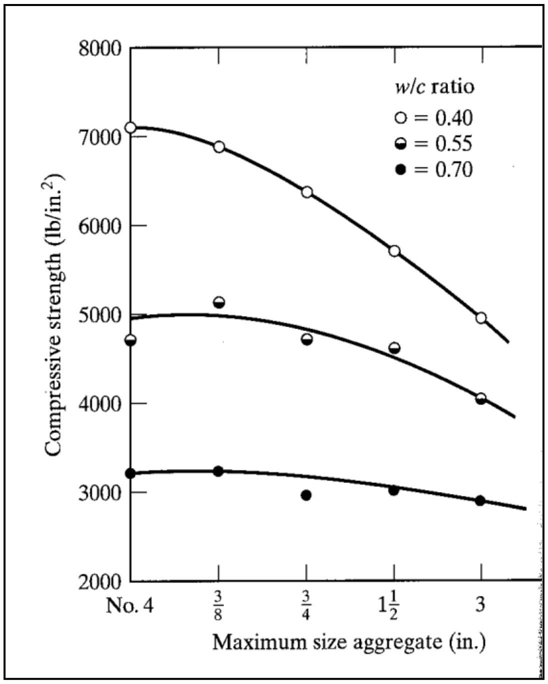


Figure 5. Effect of maximum size of aggregate on compressive strength (Cordon and Gillespie 1963)

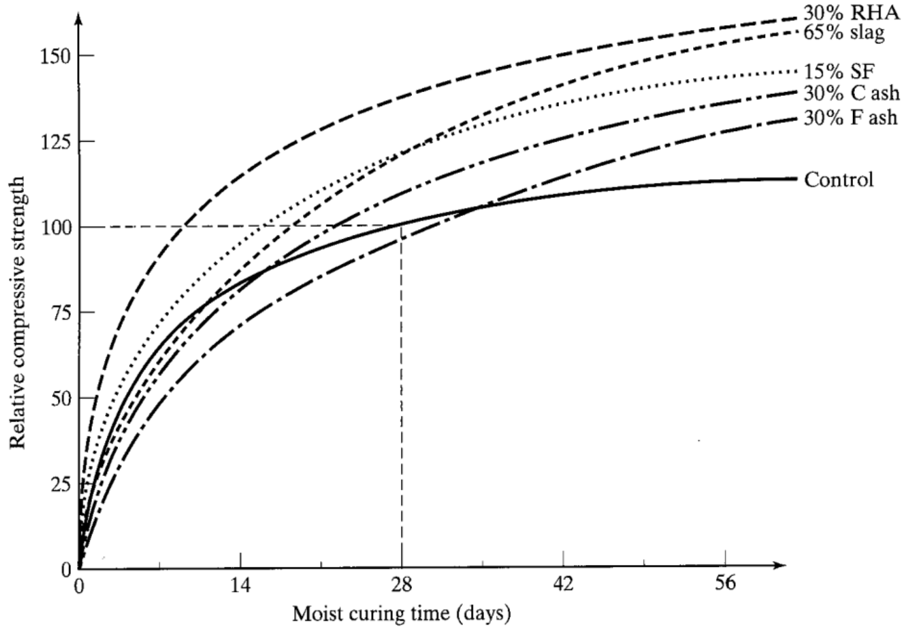
Water-reducing agents

Water-reducing agents may indirectly increase strength because w/c is reduced (Kosmatka et al. 2002). In addition, at a given w/c, water-reducing admixtures may increase the rate of strength gain; however, the ultimate strengths are generally not significantly affected (Mindess et al. 2003, Mehta and Monteiro 1993).

Supplementary Cementitious Materials

The addition of supplementary cementitious materials such as silica fume, slag, metakaolin, and fly ash reduce both pore size and porosity, and thereby increase strength (Barbhuiya et al. 2009, Taylor et. al. 2006, Mindess et al. 2003, Obla et al. 2003, Kosmatka et al. 2002, Mehta and Monteiro 1993). However, the chemistry, fineness and dosage of the supplementary cementitious material affect the early strength development of concrete as presented in Figure 6 (Taylor et. al. 2006, Mindess et al. 2003).

For example, silica fume is very reactive and therefore increases both the early- and later-age strength by affecting cement hydration immediately (Taylor et. al. 2006, Mindess et al. 2003, Mehta and Monteiro 1993). On the other hand, class F fly ash and ground granulated blast-furnace slag increase the ultimate strength, but they decrease the early strength (Taylor et. al. 2006, Mehta and Monteiro 1993).



RHA = rice husk ash
SF = silica fume

Figure 6. Relationship between relative compressive strength and supplementary cementitious materials (Mindess et al. 2003)

Durability

ACI Committee 201 (2008) 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."

All deterioration mechanisms involve the presence or movement of fluids. Therefore, it is not unreasonable to state that potential durability is directly affected by the permeability of a mixture. Kosmatka et al. (2002) define permeability as "the amount of water migration through concrete when the water is under pressure or to the ability of concrete to resist penetration by water or other substances (liquid, gas, or ions)."

The overall permeability is a function of the following (Kosmatka et al. 2002):

- Permeability of paste
- Permeability of aggregate
- Quality and quantity of paste and aggregate transition zone

One approach to assessing permeability is to measure the rate of chloride ion penetration, particularly using an ionic diffusion test accelerated by imposing an electrical potential. Chloride ions can penetrate into concrete by capillary absorption, hydrostatic pressure, and diffusion

(Stanish et al. 1997). Alternatives include assessing sorption and fluid penetration under pressure (Alexander et.al. 1999).

Cement Content

For a given w/c, increasing cement content may decrease durability because high cement content increases both chloride penetration and shrinkage (Wassermann et al. 2009, Dhir et al. 2004). Increasing shrinkage will increase the risk of cracking in concrete, which will shorten the longevity of concrete (Mehta and Monteiro 1993).

ACI Committee 302 (1996) recommends minimum cementitious material contents, as shown in Table 1, to achieve the desired workability, finishability, abrasion resistance, and durability (Kosmatka et al. 2002).

Table 1. Minimum requirements of cementitious materials for concrete used in flatwork (adapted from ACI 302 1996)

Nominal maximum size of aggregate, mm (in.)	Cementitious content, kg/m^3 (lb/yd^3)*
37.5 (1½)	280 (470)
25 (1)	310 (520)
19 (¾)	320 (540)
12.5 (½)	350 (590)
9.5 ($^3/_8$)	360 (610)

* Cementing materials quantities may need to be greater for severe exposure. For example, for deicer exposures, concrete should contain at least 335 kg/m^3 (564 lb/yd^3) of cementitious materials.

Water-to-Cement Ratio

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 (Taylor et. al. 2006, Dhir et al. 2004, Mindess et al. 2003, Kosmatka et al. 2002, Mehta and Monteiro 1993). This trend is illustrated in Figure 7 (Mindess et al. 2003).

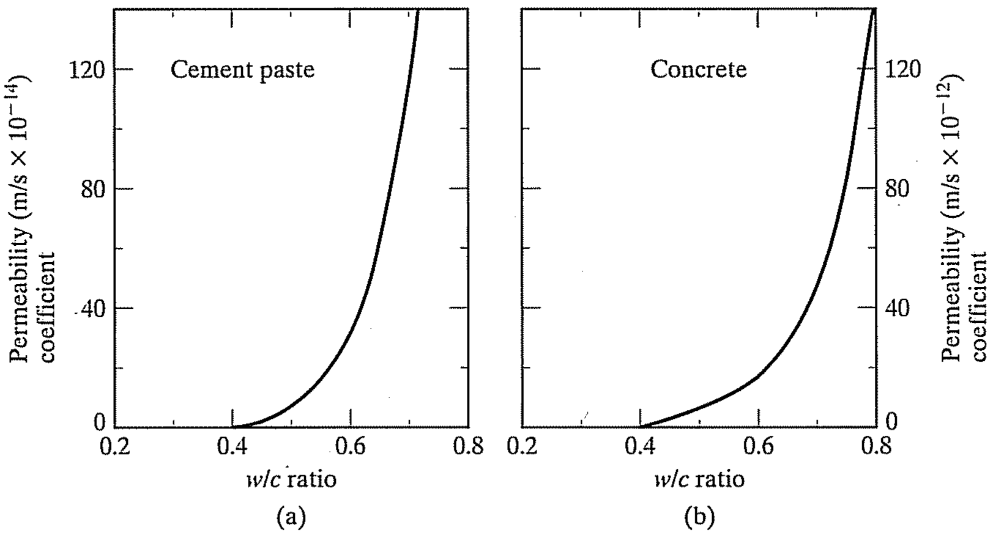


Figure 7. Influence of w/c on the permeability of (a) cement paste and (b) concrete (Mindess et al. 2003)

The effect of w/c on the capillary volume is presented in Figure 8. Permeability increases for concrete with w/c greater than 0.42 as a result of the increased capillary volume (Mindess et al. 2003).

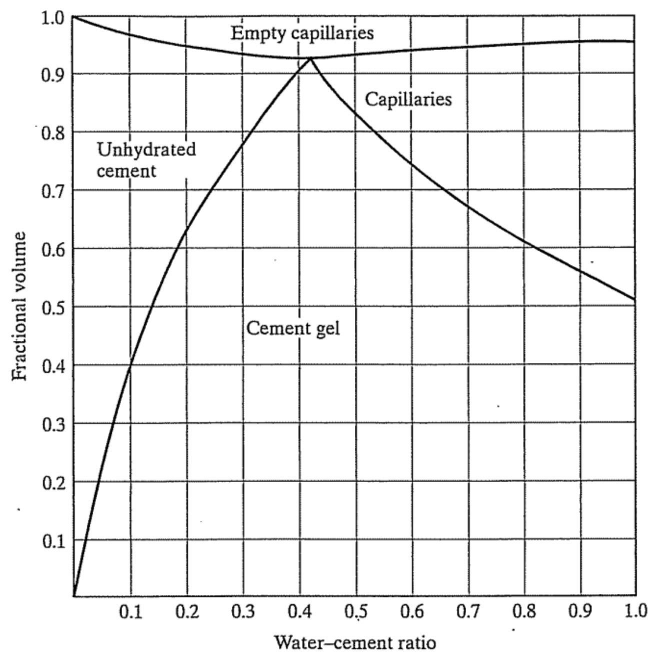


Figure 8. Composition of sealed and fully hydrated portland cement paste (Hansen 1986)

Aggregates

Increasing the maximum size of aggregate will increase potential durability by decreasing the cement paste content that is normally the component sensitive to physical or chemical attack (Mindess et al. 2003).

However, aggregates should not be prone to internal stress when water inside the aggregate is frozen (D-cracking). The degree of saturation, porosity, permeability, and size of aggregate determines this stress (Mindess et al. 2003).

In addition, aggregates should not be prone to alkali aggregate reaction or, if it is unavoidable, measures must be taken in the mixture to control the expansive reactions (Mindess et al. 2003).

The effect on various aggregate properties on durability is shown in Table 2.

Table 2. Durability of concrete influenced by aggregate properties (Mindess et al. 2003)

Durability	**Relevant Aggregate Property**
Resistance to freezing and thawing	Soundness, porosity, pore structure, permeability, degree of saturation, tensile strength, texture and structure, clay minerals
Resistance to wetting and drying	Pore structure, modulus of elasticity
Resistance to heating and cooling	Coefficient of thermal expansion
Abrasion resistance	Hardness
Alkali-aggregate reaction	Presence of particular siliceous constituents

Water-Reducing Agents

Water-reducing agents are used to decrease w/c and so reduce the concrete porosity and improve resistance to de-icing salts and acidic waters (Mindess et al. 2003, Mehta and Monteiro 1993).

Supplementary Cementitious Materials

Increasing the supplementary cementitious materials content, up to a limit, will generally increase concrete durability in terms of improving impermeability, resistance to thermal cracking, and alkali-aggregate expansion (Taylor et. al. 2006, Obla et al. 2003, Mindess et al. 2003, Kosmatka et al. 2002, Mehta and Monteiro 1993). In addition, using supplementary cementitious materials in concrete usually improves the resistance to sulfates, seawater, and acids by reducing pore size, permeability, and calcium hydroxide content of the hydrated product (Mindess et al. 2003, Mehta and Monteiro 1993).

Sustainability

The World Commission on Environment and Development (1987) defines sustainable development as "meeting the needs of the present without compromising the ability of future generations to meet their own needs."

This study investigates the methods to use cement more efficiently, thereby providing tools to improve sustainability in the concrete construction industry without compromising engineering quality. This approach is likely to be effective because of the following:

- The cement industry contributes 5 percent of the total global industrial energy consumption (World Energy Council, 1995)
- Cement production contributes 5 percent of total global CO_2 emissions as presented in Figure 9 (IEA 2003, Battelle 2002)

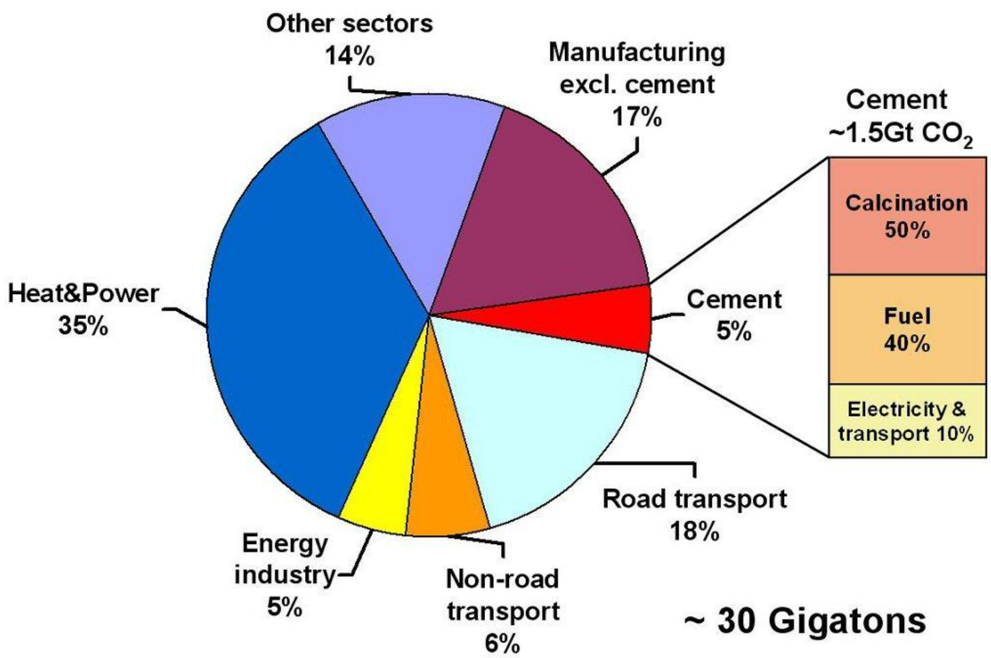


Figure 9. Global CO_2 production (IEA 2003, Battelle 2002)

A simple approach to improving sustainability for the concrete construction industry is to use cement more efficiently. As discussed in the previous sections, after the cement content of a mixture reaches an optimum value, using more cement does not increase performance. In some cases, excessive cement content may affect durability and cracking risk adversely.

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 identify the minimum cementitious content for a given w/cm that results in required workability, strength, and durability requirements for a concrete pavement mixture.

Variables

To determine the effect of concrete components on overall concrete behavior, cementitious combination, cementitious content, and w/cm were selected as variables.

The ranges of some variables were selected to include the extremes to clearly show the effects of going to these extremes. Therefore, variables were selected as follows:

- Four cementitious contents – 400, 500, 600, and 700 pounds per cubic yard (pcy)
- Four w/cm – 0.35, 0.40, 0.45, and 0.50
- Four cementitious combinations –portland cement (P), 20 percent class F fly ash (F), 20 percent class C fly ash (C), and 40 percent slag cement (S)

In the experimental program, a full factorial design yielding 64 mixes was executed. The mix identification is based on the three variables. For example, 35P700 refers to a mix of 0.35 w/cm with 700 pcy of plain portland cement.

A high-range water-reducing admixture was used in the drier mixtures to improve workability. Slump values were recorded.

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. No air-entraining agent was added to the mixtures.

Materials

Cementitious Materials

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

The chemical composition of the cementitious materials is presented in Table 3.

Table 3. Chemical composition of the cementitious materials

	Portland cement	Class F fly ash	Class C fly ash	Slag*
	% by mass			
Silicon dioxide (SiO_2)	20.22	49.71	36.71	37.20
Aluminum oxide (Al_2O_3)	4.43	15.29	19.42	9.48
Ferric oxide (Fe_2O_3)	3.19	7.16	6.03	0.47
Calcium oxide (CaO)	62.71	15.66	25.15	40.10
Magnesium oxide (MgO)	3.51	5.29	4.77	10.99
Sulfur trioxide (SO_3)	3.24	0.87	1.97	1.11
Potassium oxide (K_2O)	0.69	2.17	0.46	0.41
Sodium oxide (Na_2O)	0.08	1.73	1.64	0.26
Equivalent alkali (Na_2O_{eq})	0.54	3.16	1.94	0.53
Loss on ignition	-	0.09	0.33	0.00

** Sample analysis from a different batch.*

Aggregates

Local aggregates were used in the study—No.4 natural sand and 1 in. crushed limestone.

The researchers decided to keep the void content of the combined aggregate system constant for all mixtures. Selection of the aggregate ratios was based on assessment of three different gradation charts as follows:

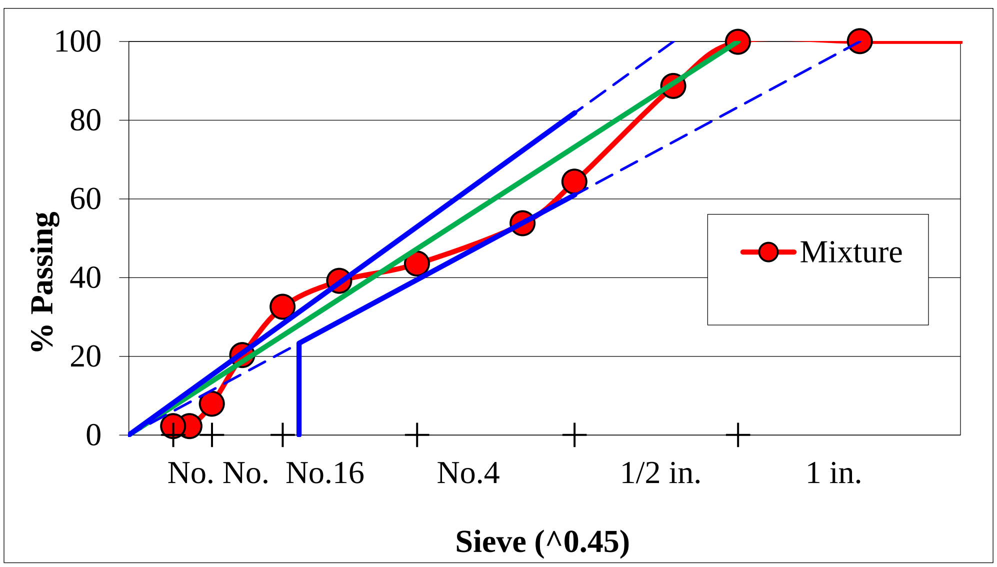
- 0.45 Power curve. The "solver" function on a spreadsheet was used to determine the ratio of fine-to-total aggregate that would provide a gradation as close as possible to the optimum 0.45 plot. Based on this work, the preferred ratio was determined to be 0.45 (see Figure 11a).
- Shilstone workability factor chart. The fine-to-total aggregate was varied to place the combined system data point within or close to Zone II on the workability factor chart (see Figure 11b). Based on this, the preferred ratio was determined to be 0.42.

- Specific surface approach. The specific surface values of aggregates were used on the 2 in. to #200 sieves to determine the fine-to-total aggregate ratio (see Figure 11c). Based on this work, the preferred ratio was determined as 0.39.

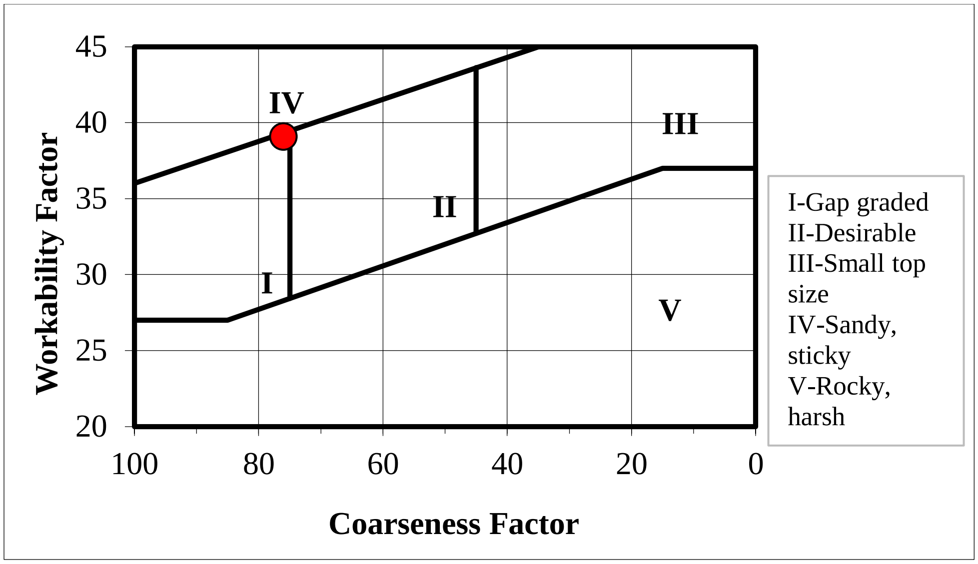
Based on the three values determined above, the value of 0.42 was selected because it was an average of the above.

The combined gradation was plotted as follows:

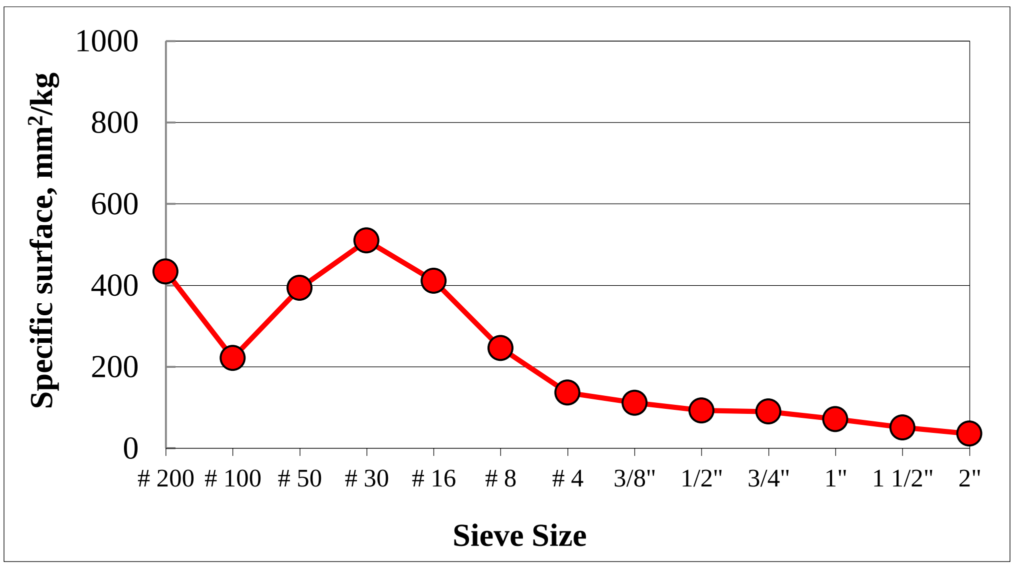
- ASTM C33 plot (Figure 11d). This plot shows both the individual gradation trends of fine and coarse aggregates and the combined aggregate system. The combined gradation trend was compared with the ASTM C33 gradation trend to determine the appropriateness of the selected fine-to-coarse aggregate ratio.
- "Haystack" plot (Figure 11e). This plot shows a shortage of materials on the #8 and #16 sieves. This is not 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 project.



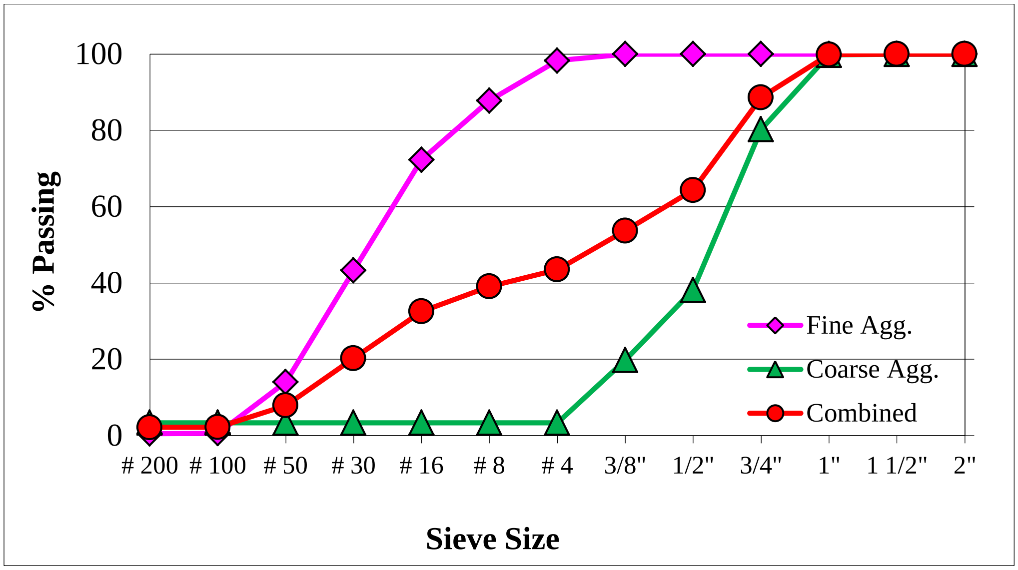
a) Power 45 gradation curve



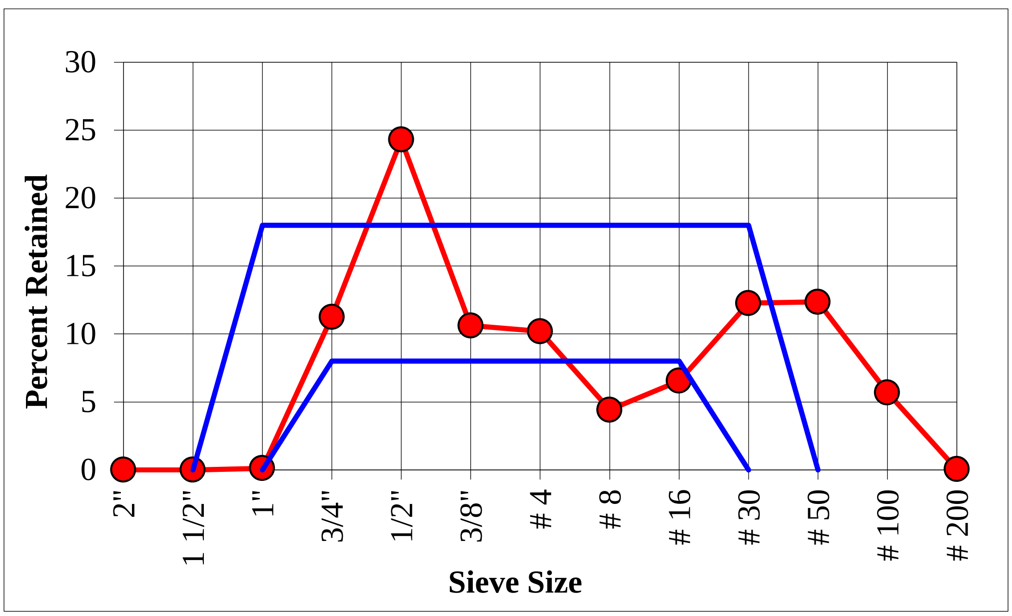
b) Shilstone workability factor chart



c) Specific surface chart



d) ASTM C33 gradation graph



e) Haystack plot

Figure 10. 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 and the void percentage was 19.8 percent.

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 1.0 percent, respectively. The

SSD specific gravity and absorption values of the fine aggregate were 2.62 and 1.1 percent, respectively.

Mix Proportions

The mix proportions for the 64 mixtures are given in Table 4.

Table 4. Mix proportions

No.	Mix ID	Cement (pcy)	F Ash (pcy)	C Ash (pcy)	Slag (pcy)	Binder (pcy)	Water (pcy)	WRA (oz/100 lb)	Fine Agg. (pcy)	Coarse Agg. (pcy)	w/cm
1	35P400	400				400	140	34.63	1,535	2,120	0.35
2	35F400	320	80			400	140	34.63	1,528	2,120	0.35
3	35C400	320		80		400	140	34.63	1,531	2,114	0.35
4	35S400	240			160	400	140	34.63	1,530	2,113	0.35
5	35P500	500				500	175	23.30	1,461	2,017	0.35
6	35F500	400	100			500	175	23.30	1,452	2,005	0.35
7	35C500	400		100		500	175	23.30	1,456	2,010	0.35
8	35S500	300			200	500	175	20.78	1,455	2,009	0.35
9	35P600	600				600	210	13.64	1,387	1,915	0.35
10	35F600	480	120			600	210	13.64	1,377	1,901	0.35
11	35C600	480		120		600	210	13.64	1,381	1,907	0.35
12	35S600	360			240	600	210	13.64	1,379	1,905	0.35
13	35P700	700				700	245	8.09	1,313	1,813	0.35
14	35F700	560	140			700	245	8.09	1,301	1,796	0.35
15	35C700	560		140		700	245	8.09	1,306	1,803	0.35
16	35S700	420			280	700	245	5.40	1,304	1,801	0.35
17	40P400	400				400	160	22.04	1,513	2,089	0.40
18	40F400	320	80			400	160	23.61	1,505	2,079	0.40
19	40C400	320		80		400	160	23.61	1,508	2,083	0.40
20	40S400	240			160	400	160	19.68	1,508	2,082	0.40

No.	Mix ID	Cement (pcy)	F Ash (pcy)	C Ash (pcy)	Slag (pcy)	Binder (pcy)	Water (pcy)	WRA (oz/100 lb)	Fine Agg. (pcy)	Coarse Agg. (pcy)	w/cm
21	40P500	500				500	200	20.15	1,433	1,979	0.40
22	40F500	400	100			500	200	18.89	1,424	1,967	0.40
23	40C500	400		100		500	200	18.89	1,428	1,972	0.40
24	40S500	300			200	500	200	18.89	1,427	1,971	0.40
25	40P600	600				600	240	5.77	1,353	1,869	0.40
26	40F600	480	120			600	240	5.77	1,343	1,855	0.40
27	40C600	480		120		600	240	0.00	1,348	1,861	0.40
28	40S600	360			240	600	240	5.77	1,346	1,859	0.40
29	40P700	700				700	280	3.60	1,274	1,759	0.40
30	40F700	560	140			700	280	3.60	1,262	1,743	0.40
31	40C700	560		140		700	280	0.90	1,267	1,749	0.40
32	40S700	420			280	700	280	3.60	1,266	1,748	0.40
33	45P400	400				400	180	10.23	1,490	2,058	0.45
34	45F400	320	80			400	180	10.23	1,484	2,049	0.45
35	45C400	320		80		400	180	11.02	1,487	2,053	0.45
36	45S400	240			160	400	180	10.23	1,486	2,052	0.45
37	45P500	500				500	225	6.93	1,406	1,941	0.45
38	45F500	400	100			500	225	7.56	1,397	1,929	0.45
39	45C500	400		100		500	225	7.56	1,400	1,934	0.45
40	45S500	300			200	500	225	7.56	1,399	1,932	0.45
41	45P600	600				600	270	0.00	1,320	1,823	0.45

No.	Mix ID	Cement (pcy)	F Ash (pcy)	C Ash (pcy)	Slag (pcy)	Binder (pcy)	Water (pcy)	WRA (oz/100 lb)	Fine Agg. (pcy)	Coarse Agg. (pcy)	w/cm
42	45F600	480	120			600	270	0.00	1,310	1,809	0.45
43	45C600	480		120		600	270	0.00	1,314	1,815	0.45
44	45S600	360			240	600	270	0.00	1,313	1,813	0.45
45	45P700	700				700	315	0.00	1,235	1,706	0.45
46	45F700	560	140			700	315	0.00	1,223	1,689	0.45
47	45C700	560		140		700	315	0.00	1,228	1,696	0.45
48	45S700	420			280	700	315	0.00	1,227	1,694	0.45
49	50P400	400				400	200	11.02	1,469	2,028	0.50
50	50F400	320	80			400	200	11.02	1,461	2,018	0.50
51	50C400	320		80		400	200	11.02	1,464	2,022	0.50
52	50S400	240			160	400	200	11.02	1,463	2,021	0.50
53	50P500	500				500	250	5.04	1,377	1,902	0.50
54	50F500	400	100			500	250	5.04	1,369	1,891	0.50
55	50C500	400		100		500	250	5.04	1,372	1,895	0.50
56	50S500	300			200	500	250	5.04	1,372	1,894	0.50
57	50P600	600				600	300	0.00	1,287	1,777	0.50
58	50F600	480	120			600	300	0.00	1,277	1,763	0.50
59	50C600	480		120		600	300	0.00	1,281	1,769	0.50
60	50S600	360			240	600	300	0.00	1,280	1,767	0.50
61	50P700	700				700	350	0.00	1,196	1,652	0.50
62	50F700	560	140			700	350	0.00	1,184	1,635	0.50

No.	Mix ID	Cement (pcy)	F Ash (pcy)	C Ash (pcy)	Slag (pcy)	Binder (pcy)	Water (pcy)	WRA (oz/100 lb)	Fine Agg. (pcy)	Coarse Agg. (pcy)	w/cm
63	50C700	560		140		700	350	0.00	1,189	1,640	0.50
64	50S700	420			280	700	350	0.00	1,188	1,640	0.50

Experimental Work

Fifteen cylinders were prepared from each mixture. The tests conducted are given in Table 5. Mixtures were prepared in accordance with ASTM C 192. Cylindrical 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 5. Test matrix

	Method	**# of Specimens tested**	**Age (days)**
Fresh Concrete Property			
Slump/ Slump flow	ASTM C143/ ASTM C1611	1	-
Air Content	ASTM C231	1	-
Setting Time	ASTM C403	1	-
Hardened Concrete Property			
Compressive Strength	ASTM C39	2 per age	1, 3, 28, 90
Rapid Chloride Penetration	ASTM C1202	2 per age	28, 90
Air Permeability	University of Cape Town Method	2 per age	1, 3, 28, 90

Although slump, setting time and air content tests were not assessed as control parameters, they were measured to evaluate the effect of the variables on concrete behavior.

When the slump was more than 8 in., the slump flow was determined.

At early ages, the rapid chloride penetration samples tended to boil; therefore, tests were only conducted after 28 days.

The air permeability test was also conducted on two specimens per mixture at 1, 3, 28, and 90 days using the University of Cape Town Air Permeability Method (Alexander et al., 1999, 2007) using the equipment shown in Figure 11.

Figure 11. Air permeability cell

RESULTS AND DISCUSSION

Test results are presented and discussed under the following categories:

- Workability
- Setting time
- Strength
- Chloride penetration
- Air permeability

The experimental data are presented in Table 6 and Table 7.

Many of the data are presented in figures in which the horizontal axis is the volume of paste divided by the volume of voids in the aggregate system (Vp/Vvoid). This is because the properties of the mixture are governed by the paste volume and the paste quality. If there is insufficient paste to fill all of the voids between the aggregate particles, performance is likely to be compromised. Once sufficient paste is provided to fill the voids and coat the aggregate particles, the quality of paste should dominate the trends. The aim of the work was to investigate where this transition occurs.

Table 6. Fresh concrete properties

No.	Mix ID	Fresh Properties				
		Slump (in)	Slump flow (in)	Air content (%)	Set time (min)	
					Initial	Final
1	35P400	0.0		2.8	290	417
2	35F400	0.0		4.5	331	500
3	35C400	0.3		3.5	396	620
4	35S400	0.0		2.2	-	-
5	35P500	0.0		1.5	200	300
6	35F500	2.0		4.0	340	529
7	35C500	1.5		3.0	395	507
8	35S500	0.3		2.3	354	504
9	35P600	2.0		1.8	203	265
10	35F600	2.8		3.3	263	370
11	35C600	5.8		3.3	341	450
12	35S600	3.0		3.2	266	370
13	35P700	1.5		1.8	161	241
14	35F700	3.0		1.5	206	289

No.	Mix ID	Fresh Properties				
		Slump (in)	Slump flow (in)	Air content (%)	Set time (min)	
					Initial	Final
15	35C700	4.3		2.2	258	339
16	35S700	2.5		2.2	229	334
17	40P400	0.0		3.5	211	342
18	40F400	0.0		2.8	329	592
19	40C400	1.5		4.8	267	363
20	40S400	2.0		2.8	350	530
21	40P500	3.5		3.5	291	373
22	40F500	3.0		2.3	237	329
23	40C500	3.3		4.5	323	421
24	40S500	4.8		3.5	262	441
25	40P600	2.5		2.0	201	286
26	40F600	3.0		2.5	329	464
27	40C600	2.0		2.5	255	350
28	40S600	3.0		2.3	227	417
29	40P700	4.5		2.2	204	274
30	40F700	9.0		1.0	262	368
31	40C700	4.3		1.5	289	367
32	40S700	2.5		2.3	240	363
33	45P400	0.0		2.6	173	265
34	45F400	0.0		2.0	307	495
35	45C400	0.0		3.3	300	459
36	45S400	0.3		3.0	224	408
37	45P500	1.0		2.8	189	276
38	45F500	2.5		3.0	289	439
39	45C500	3.0		2.8	359	477
40	45S500	0.8		2.8	257	391
41	45P600	4.0		3.3	195	260
42	45F600	8.5		1.5	226	374
43	45C600	7.3		2.3	270	399
44	45S600	3.0		2.2	259	376

No.	Mix ID	Fresh Properties				
		Slump (in)	Slump flow (in)	Air content (%)	Set time (min)	
					Initial	Final
45	45P700	6.0		3.5	217	278
46	45F700		22.3	0.5	291	370
47	45C700		21.0	1.5	342	505
48	45S700	3.8		2.0	288	396
49	50P400	0.0		3.5	225	340
50	50F400	8.0		3.5	354	490
51	50C400	1.5		2.5	318	425
52	50S400	5.0		3.0	337	584
53	50P500	3.0		3.0	214	305
54	50F500	7.5		2.8	335	451
55	50C500	3.5		2.3	320	412
56	50S500	3.0		3.3	265	464
57	50P600	9.0	16.0	0.8	230	293
58	50F600	10.5	19.3	1.8	319	448
59	50C600		20.8	0.8	276	367
60	50S600	10.0		1.3	333	455
61	50P700		20.0	0.5	248	338
62	50F700		21.5	1.3	349	457
63	50C700		22.3	0.5	314	431
64	50S700	11.0		1.0	368	527

Table 7. Hardened concrete properties

No.	Mix ID	Hardened Properties									
		Strength (psi)				RCP (coulombs)		API			
		1	3	28	90	28	90	1	3	28	90
1	35P400	1,120	2,467	3,919	4,573	-	-	-	-	-	-
2	35F400	1,027	1,833	2,698	3,304	-	-	-	-	-	-
3	35C400	956	2,342	4,950	6,091	-	1,256	9.27	9.32	10.09	10.15
4	35S400	585	1588	3,286	3,881	-	-	-	-	-	-
5	35P500	3,909	6,403	8,208	9,520	1,199	1,208	10.61	10.81	10.61	11.34
6	35F500	1,475	2,850	4,801	6,305	1,950	524	9.01	9.44	10.30	9.64
7	35C500	2,078	4,369	7,938	9,251	1,748	1,019	10.21	10.57	10.93	11.17
8	35S500	1,074	2692	5,711	6,075	748	657	8.29	8.89	9.86	9.77
9	35P600	3,930	5,640	8,427	9,532	1,770	1,392	10.45	10.81	11.06	11.29
10	35F600	2,645	4,726	7,769	9,612	2,185	681	10.34	10.65	10.91	11.15
11	35C600	2,295	4,482	8,200	9,521	1,879	1,314	10.14	10.58	10.87	11.18
12	35S600	1,778	4291	9,041	9,255	871	602	10.33	10.54	10.58	10.55
13	35P700	3,907	5,337	8,137	8,986	1,980	1,533	10.22	10.66	10.92	11.03
14	35F700	2,408	4,290	7,190	8,904	1,881	1,039	10.03	10.57	10.62	10.23
15	35C700	2,978	5,289	7,742	9,265	2,131	1,102	10.08	10.48	10.53	10.78
16	35S700	2,519	4,552	8,283	9,502	1,103	743	10.16	10.32	-	10.36
17	40P400	1,584	2,886	4,314	5,284	-	-	-	-	-	-
18	40F400	833	1,607	2,988	3,845	-	-	8.48	9.00	10.03	9.60
19	40C400	1,762	3,740	7,162	7,463	1,710	955	10.25	10.50	10.91	11.16
20	40S400	638	1,758	3,723	4,615	966	741	8.45	8.21	8.54	8.75
21	40P500	2,410	3,714	6,029	6,998	2,288	1,266	9.93	10.25	9.98	11.10
22	40F500	1,075	2,255	4,229	5,697	2,148	988	9.74	9.80	10.55	11.30
23	40C500	2,096	3,690	7,308	9,325	2,185	824	9.96	10.26	10.76	10.79

		Hardened Properties									
		Strength (psi)				RCP (coulombs)		API			
No.	Mix ID	1	3	28	90	28	90	1	3	28	90
24	40S500	882	2,307	5,006	5,282	1,146	654	8.80	8.44	9.53	9.73
25	40P600	2,744	4,099	6,492	7,840	2,505	2,206	10.12	10.51	10.70	10.70
26	40F600	1,386	2,851	5,657	7,258	3,576	1,097	9.55	10.11	10.63	10.90
27	40C600	2,218	4,049	7,317	8,655	2,635	1,650	10.00	10.16	10.51	10.88
28	40S600	1,129	3,155	7,499	8,443	1,225	846	9.66	10.23	10.81	10.80
29	40P700	2,901	4,327	6,715	7,977	2,511	1,938	9.93	10.45	10.56	10.31
30	40F700	1,664	2,972	6,421	7,692	3,940	1,361	9.58	10.11	10.83	11.06
31	40C700	2,359	4,014	7,364	8,673	3,023	2,328	9.96	10.27	10.56	10.55
32	40S700	1,371	3,359	8,600	9,730	1,057	1,067	9.76	10.17	10.71	10.63
33	45P400	1,962	3,362	4,793	4,690	-	-	-	-	-	-
34	45F400	1,043	2,507	4,832	6,139	1,959	1,069	9.20	9.07	10.34	10.63
35	45C400	1,530	3,141	4,272	5,348	-	-	-	-	-	-
36	45S400	884	2,489	5683	6,691	1,121	591	9.60	10.09	9.91	10.67
37	45P500	1,649	3,729	6,521	7,541	2,626	-	10.01	10.40	10.65	10.67
38	45F500	976	2,525	5,481	6,984	2,800	1,411	9.51	9.77	10.95	11.06
39	45C500	1,283	2,826	6,086	6,922	2,951	1,488	9.56	10.14	10.43	10.65
40	45S500	997	2,315	6268	7,403	492	798	9.45	9.79	10.63	10.49
41	45P600	2,311	3,868	5,960	7,171	3,677	2,063	9.88	10.44	10.70	10.56
42	45F600	1,179	3,178	5,863	7,451	4,238	1,782	9.41	9.87	10.88	10.91
43	45C600	1,943	3,378	6,780	8,108	-	2,553	9.69	10.28	10.68	10.69
44	45S600	1,075	2,476	6,938	8,189	2,032	1,282	9.47	9.83	10.25	10.56
45	45P700	2,197	3,519	5,693	6,775	3,540	2,854	9.85	10.30	10.66	10.44
46	45F700	1,234	2,742	5,045	7,605	4,572	2,519	9.45	9.80	10.37	11.02
47	45C700	2,080	3,381	6,855	7,919	-	3,576	9.64	10.15	10.58	10.46

No.	Mix ID	Hardened Properties									
		Strength (psi)				RCP (coulombs)		API			
		1	3	28	90	28	90	1	3	28	90
48	45S700	1,158	2,782	7095	7,804	1,766	1,170	9.36	9.94	10.22	10.36
49	50P400	1,947	3,370	4,876	5,262	-	-	-	-	-	-
50	50F400	794	1,736	3,705	6,318	2,352	1,265	9.14	9.74	10.49	10.88
51	50C400	1,222	2,709	5,570	7,094	2,790	1,083	9.38	9.98	10.73	10.99
52	50S400	444	1,016	2,853	3,690	1,224	1,089	-	8.30	-	-
53	50P500	1,950	3,225	5,849	6,934	3,062	2,561	10.33	10.21	10.62	10.66
54	50F500	955	1,988	4,321	6,057	-	1,955	9.22	9.72	10.50	10.75
55	50C500	1,335	2,651	5,957	6,852	2,937	1,355	9.25	9.93	10.44	10.66
56	50S500	941	2,217	6,316	7,304	944	717	9.35	9.99	10.53	10.36
57	50P600	1,897	2,978	5,475	5,912	4,104	2,566	9.62	10.15	10.52	10.24
58	50F600	850	2,333	4,695	6,645	5,436	2,605	9.10	9.68	9.98	10.33
59	50C600	1,546	2,874	6,039	7,590	4,077	2,757	9.53	9.98	10.44	10.47
60	50S600	711	2,126	6,720	8,730	2,424	899	9.01	9.75	10.51	10.57
61	50P700	1,708	2,747	4,915	6,589	6,050	4,259	9.32	9.25	10.56	11.03
62	50F700	875	2,645	4,817	6,142	5,618	2,627	8.32	9.27	10.08	10.40
63	50C700	1,206	2,712	5,560	7,127	4,510	4,610	9.36	9.73	10.16	10.85
64	50S700	769	2,140	6,475	8,253	2,247	1,357	8.84	9.62	10.04	10.08

Workability

Low paste content mixes (i.e., 400 pcy and 500 pcy) were difficult to consolidate. Regardless of the cementitious combination, the 400 pcy mixes produced zero slump and harsh mixtures that could not be consolidated (see Figure 12).

Figure 12. 400 pcy of plain portland cement content mixes, from left to right, w/c of 0.35, 0.40, 0.45, and 0.50

The lack of consolidation, in turn, affected the hardened properties. These mixtures could not be improved even if the water-reducing agent dosage was increased. These findings were expected, but the mixtures were deliberately made to investigate how little paste could be used before problems were experienced.

The plots in Figure 13 indicate that, for the aggregate gradation tested, a minimum paste content is needed to obtain a workable mixture. For the plain cement mixtures, at least 150 percent Vp/Vvoids was required to achieve any workability. Below this, any amount of admixture was not beneficial. This is not surprising because, if there is insufficient paste (i.e., lubricant) in the mixture, the quality of the paste/lubricant is not a significant factor. At greater paste contents, the admixture could increase slump. The critical value for all of the mixtures containing SCMs was about 125 percent.

This approach means that binder content can be selected based on the volume of voids in the aggregate. Further work is needed to investigate how the critical value changes for different aggregate systems.

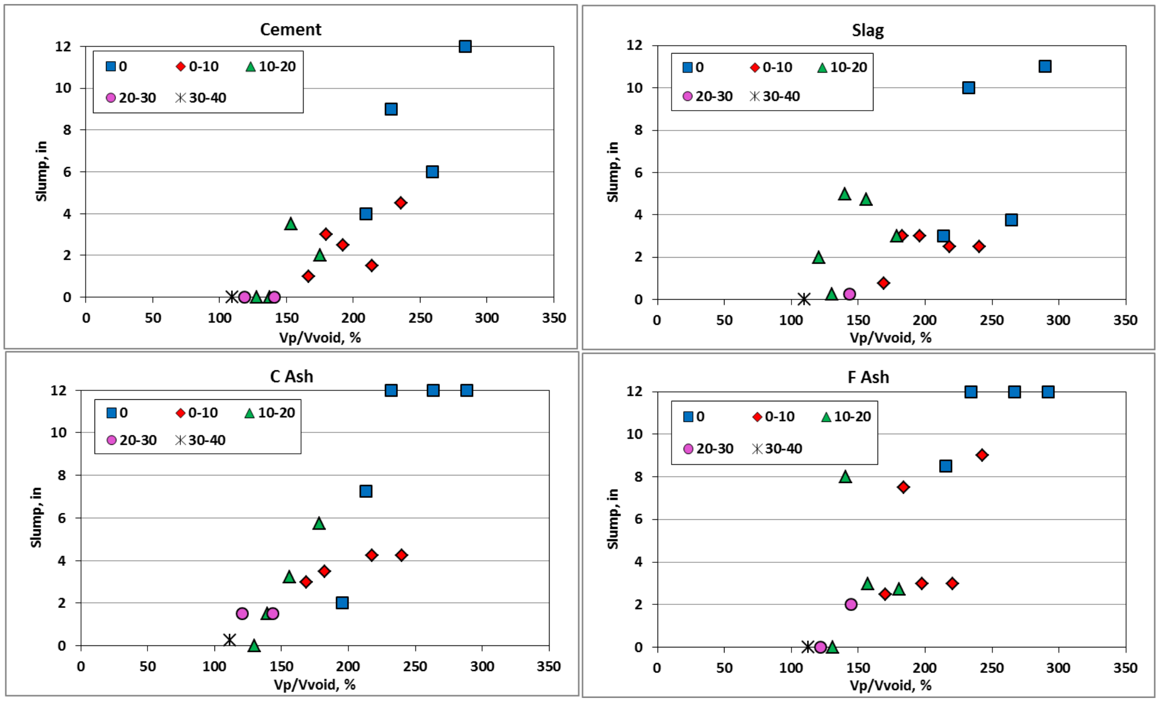


Figure 13. Plots of slump versus paste volume/volume of aggregate voids ratio

The symbols in Figure 13 reflect the water-reducing admixture dosage in oz/cwt. (Mixtures in which slump flow were recorded are shown here as 12 in. slump.)

Setting Time

The setting time results are given in Table 6. The data for final set are also shown in Figure 14 plotted against cementitious content, and repeated in Figure 15, plotted against Vp/Vvoid.

Figure 14 shows that, in general, mixes with supplementary cementitious materials have longer final setting times compared to the plain portland cement mixes. The plots also show a slight trend toward reducing setting time with increasing binder content, although there is a lot of noise in this trend.

Figure 15shows little effect of increasing Vp/Vvoid, although it could be argued that the very low paste mixture exhibited slightly longer setting times up to about 200 percent. Thereafter, the trend appears to be flat or slightly upward again. These are likely to be because the low paste mixtures contained higher admixture dosages, which may contribute to retardation. Physical effects with the aggregates such as paste thickness are not relevant here because the coarse aggregate is removed from the sample before testing is started.

The symbols in these figures reflect the water-reducing admixture dosage in oz/cwt.

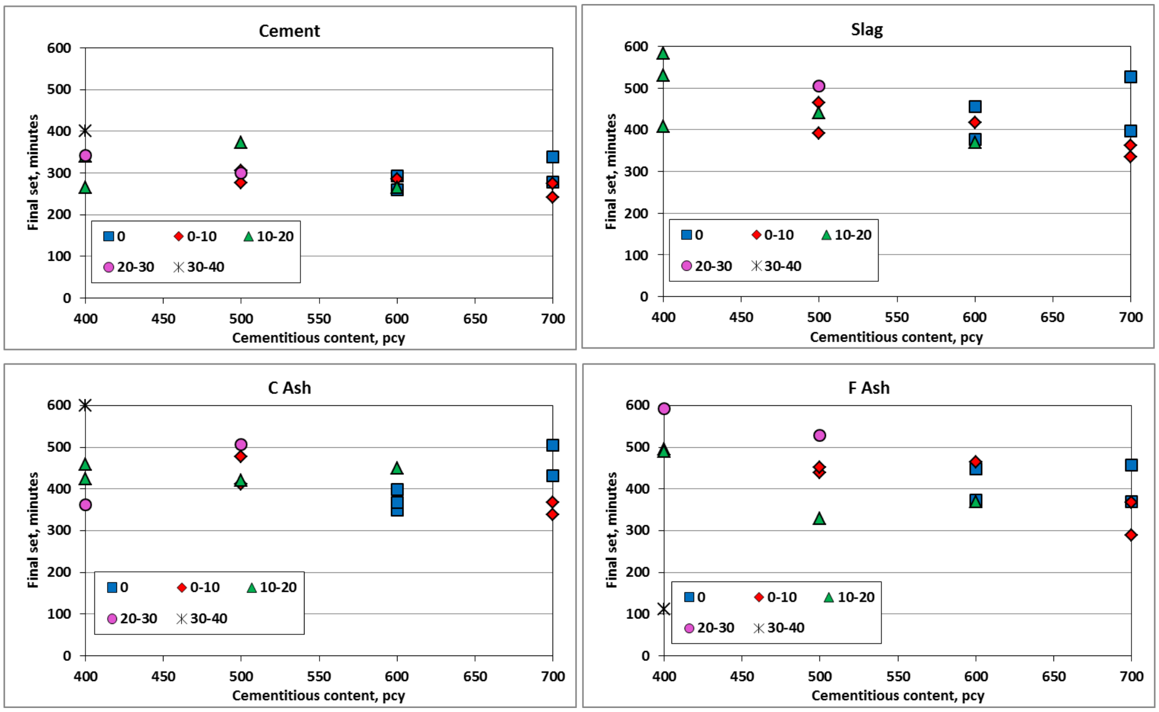


Figure 14. Plots of final set versus cementitious content

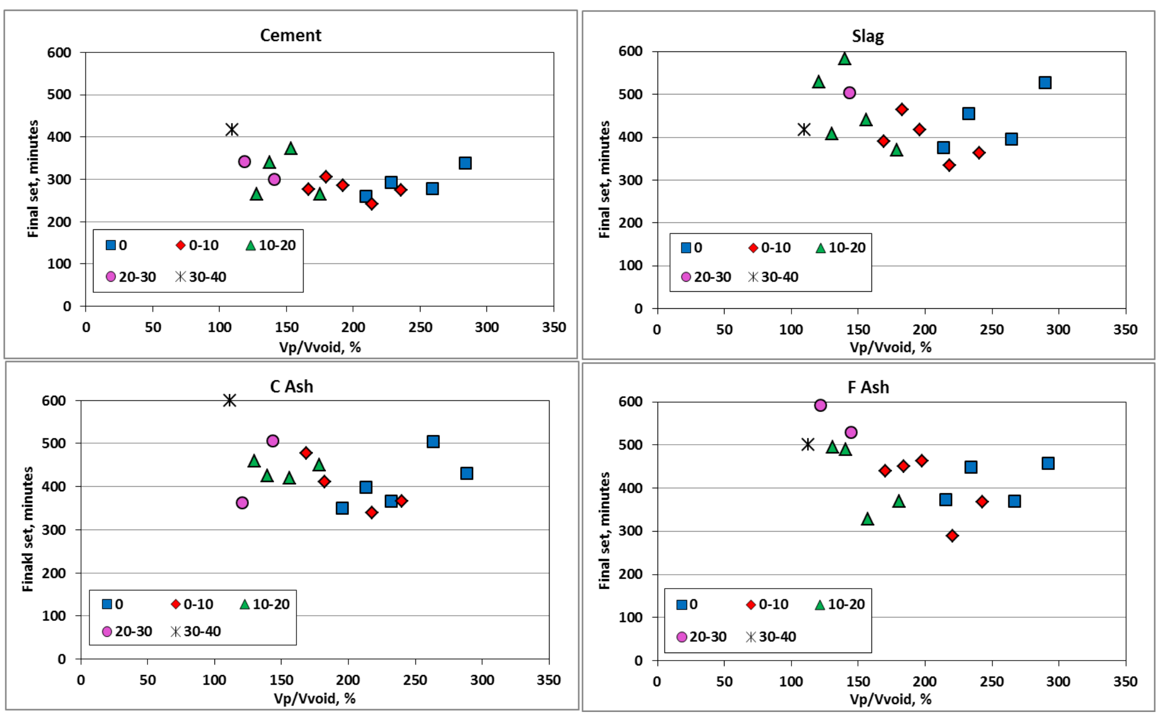


Figure 15. Plots of final set versus paste volume/volume of aggregate voids ratio

It is sometimes argued that increasing w/cm may increase setting times because cement grains are further apart, but this was not observed as a general trend in these tests, except in the very high-binder content mixtures (e.g., Figure 16).

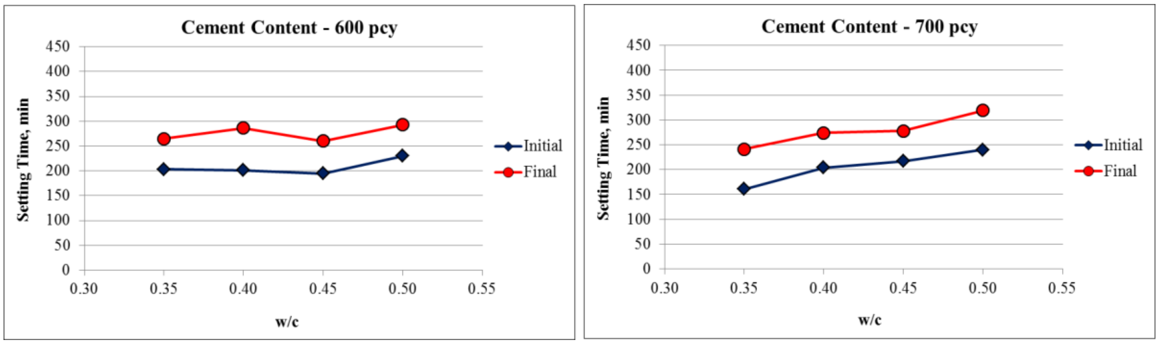


Figure 16. Typical effects of changing w/cm for different binder contents, in this case plain portland cement

Strength

The results are given in Table 7. The data for final set are also shown in Figure 17.

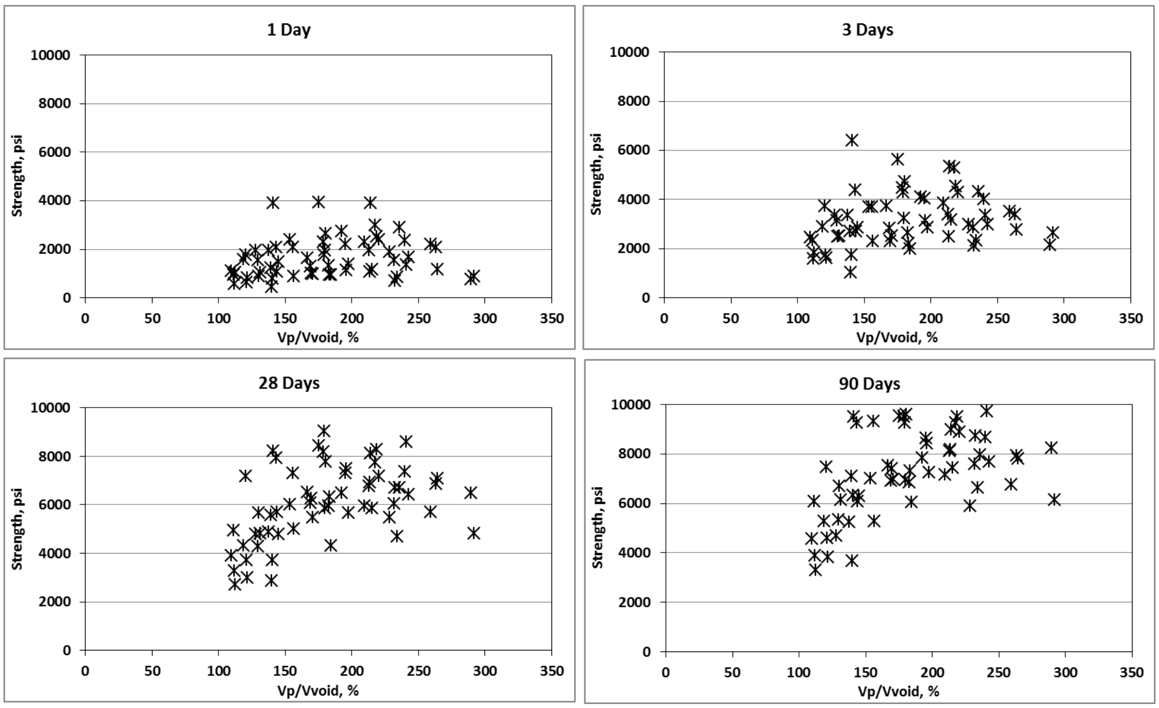


Figure 17. Overview of the effect of Vp/Vvoid on strength for all mixtures at various ages

The overview in Figure 17 illustrates the development in strength over time for most mixtures. The development is most notable for the mixtures with a Vp/Vvoid ratio greater than about 150 percent. This supports the contention that performance is controlled primarily by the paste volume up to a limit; thereafter, increasing paste content does not increase strength.

The data in Figure 18 also demonstrate that increasing paste content increases strength up to a point, after which no added benefit is observed. This is, again, presumed to be due to the need to provide sufficient paste to fill all the voids between aggregate particles and to coat each particle with “glue.” It is interesting that the critical amount varies by binder type: PC and C Ash = 500 pcy while Slag and F Ash = 600 pcy. This difference is likely more marked because of the relatively large increments in the amount of binder used in each mixture. The causes behind these differences are unknown.

The plots clearly indicate that decreasing w/cm leads to increasing strength for all mixtures. This is consistent with the literature.

Similar trends are apparent other ages. The symbols in these figures reflect the w/cm of each mixture.

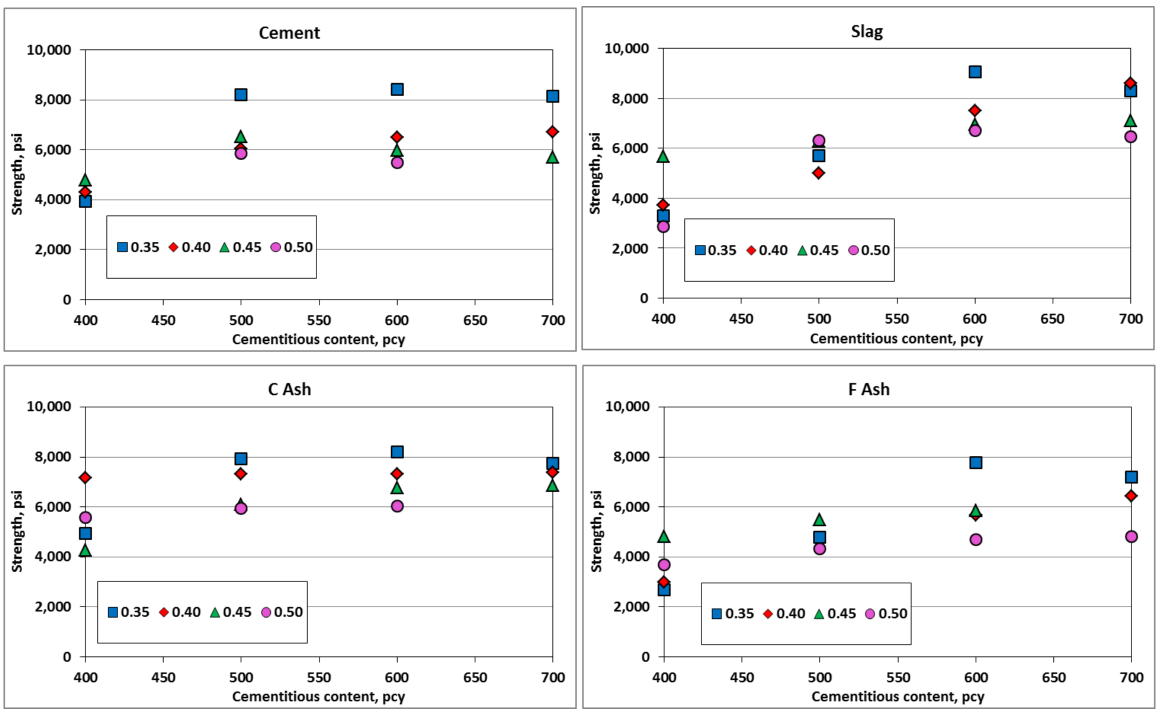


Figure 18. Compressive strengths for different binder systems at 28 days as a function of binder content

Figure 19 clearly demonstrates the trend that increasing paste does not control strength above a certain value. For the aggregates used in this work, the critical values are about 150 percent for PC and C Ash mixtures and about 175 percent for Slag and F Ash mixtures. As expected, strengths and strength development rates are influenced by the binder type.

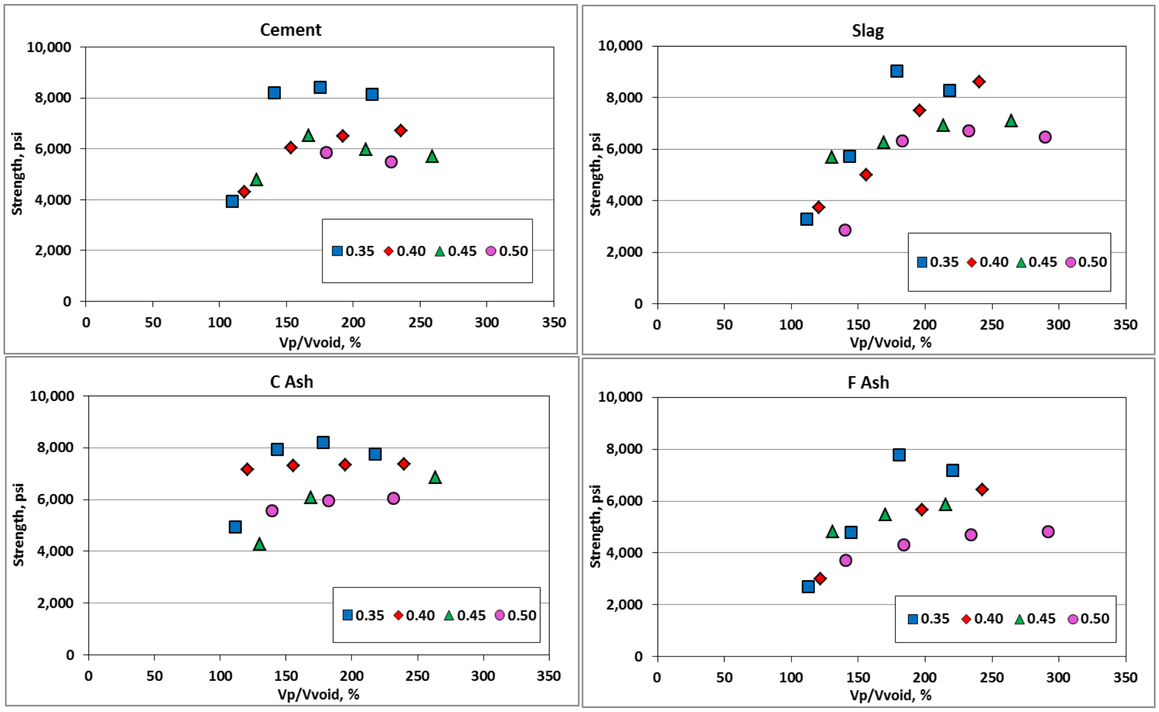


Figure 19. Compressive strengths for different binder systems at 28 days as a function of Vp/Vvoid

Figure 20 shows the effect of cementitious content on cement efficiency in terms of compressive strength per pound of cementitious material. Again, there is a peak for each type of binder at similar values to those reported above. It is interesting that the peak efficiencies are higher for the PC and C Ash mixtures, and lower for the F Ash and Slag mixtures. It is also notable that the effect of w/cm on efficiency is relatively small. Decreasing efficiency with increasing binder content indicates that the cost effectiveness and sustainability of rich mixtures is not optimized.

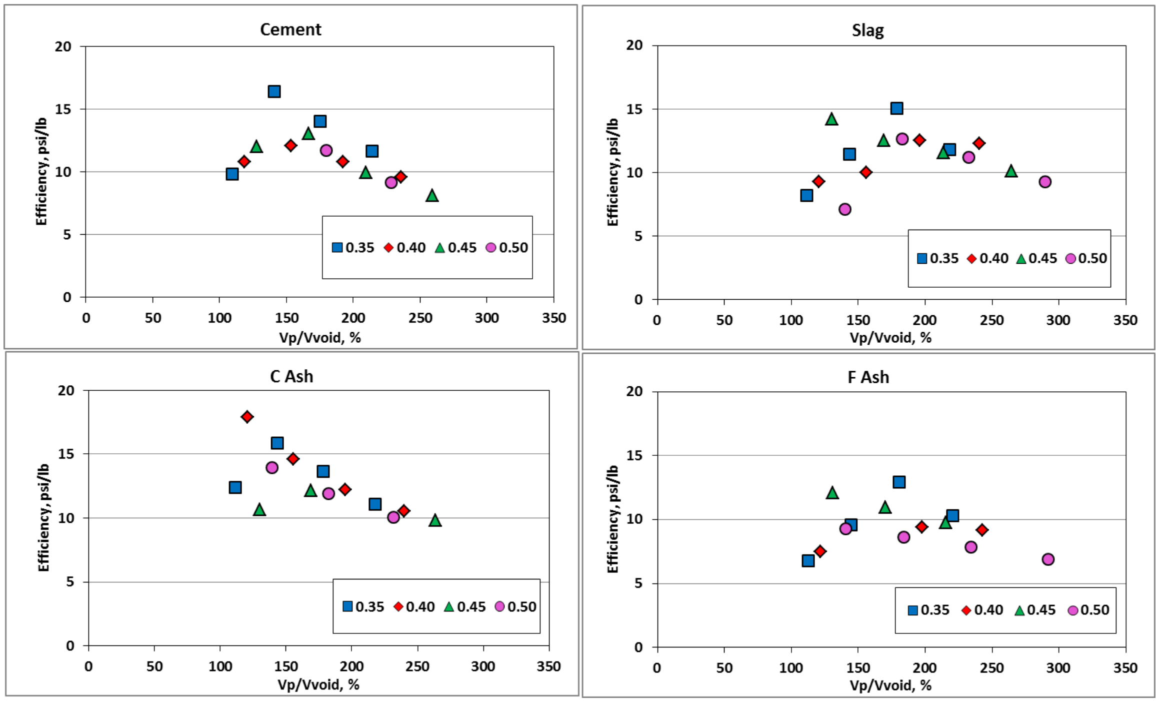


Figure 20. Cementing efficiency of different binder systems at 28 days as a function of Vp/Vvoid

The correlation between the early-age strength, 28 day strength, and ultimate strength (given as 91 day strength) was summarized as the average of 16 mixes for each cementitious material combination in Figure 21. As expected, plain portland cement mixes have a higher early-age to 28 day age strength ratio.

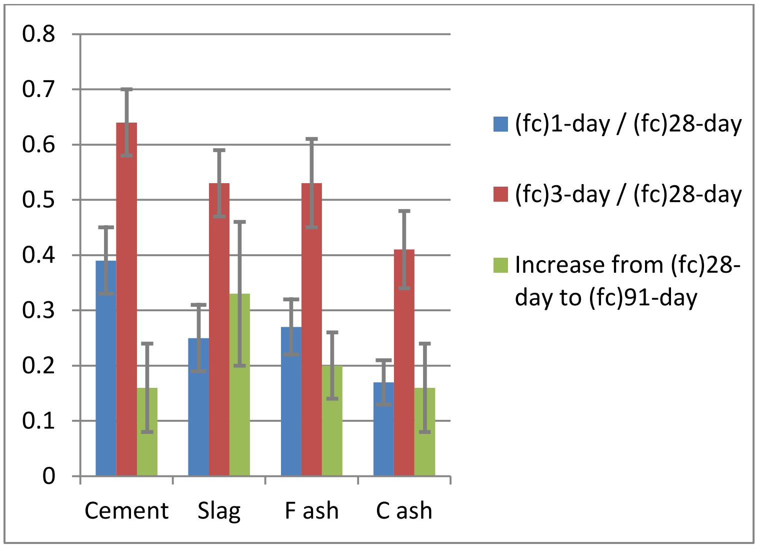


Figure 21. Correlations between early-age, 28 day, and ultimate (or 91 day) strengths

Rapid Chloride Penetration

The results for rapid chloride penetration tests are also given in Table 7. The data for final set are also shown in Figure 22.

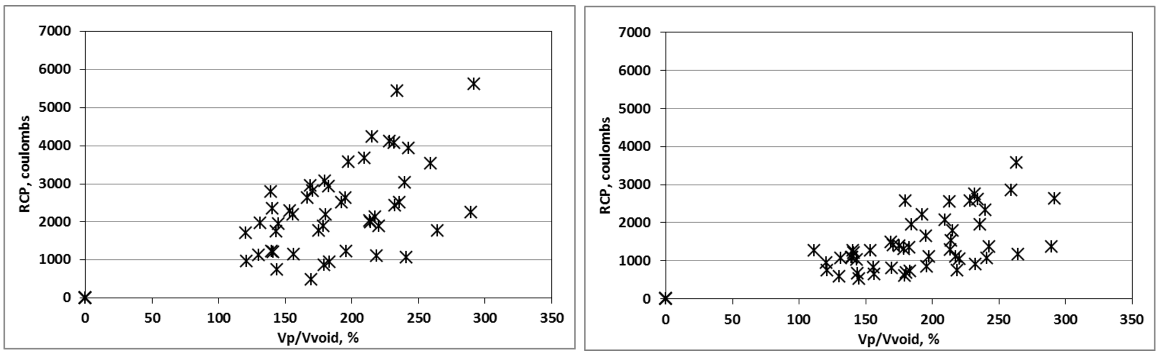


Figure 22. Overview of the effect of Vp/Vvoid on penetrability for all mixtures at 28 and 90 days

No data is provided for ages less than seven days because the low binder content samples exhibited such high conductivity that no data could be obtained. This is likely because the low paste content samples were so porous that the voids were percolated through the full thickness of the sample at early ages (See Figure 12).

Later hydration helped to fill some of the voids and reduce penetrability. The continued reduction in penetrability is illustrated in the overview plots in Figure 22. Also notable in the figure is the general trend toward increasing penetrability with increasing binder content. This is to be expected because paste has a greater conductivity than aggregate (Kosmakta et. al. 2002).

The data presented in Figure 23 makes the trends described above even clearer: in all cases, penetrability increases with increasing paste. Also notable are marked reductions in penetrability in the Slag and C Ash mixtures. While the F ash does not exhibit the same effect at 28 days, it is apparent at 90 days, as is consistent with the literature. Decreasing w/cm also decreases penetrability, most notably in the plain cement mixtures.

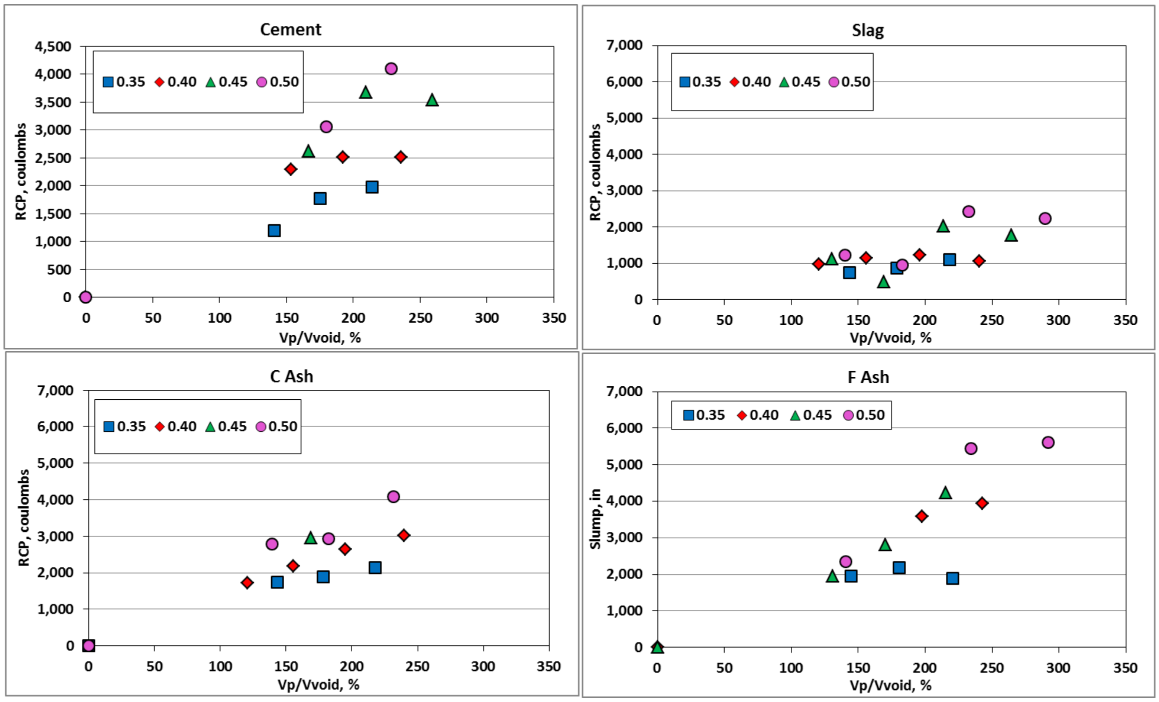


Figure 23. Penetrability data for different binder systems at 28 days as a function of Vp/Vvoid

Air Permeability

The air permeability index is the negative log of the Darcy coefficient of permeability (m/s) (Buenfeld and Okundi 1998) determined in a falling head permeameter. Therefore, a lower air permeability index (API) indicates lower permeability. As reported by Alexander and Beushausen (2010), the following interpretation can be applied to the results: >10.0 - Excellent, 9.5 to 10.0 – Good, 9.0 to 9.5 – Poor and < 9.0 – Very poor.

Similar to the RCP tests, air permeability tests could not be conducted on several low-paste content mixes (Figure 24).

Figure 24. Porosity of mixture with 400 pcy of plain portland cement content with 0.40 of w/c

The overview of all of the data in Figure 25 illustrates similar trends to those discussed above. Above a given Vp/Vvoid value, all of the samples may be classified as “excellent” at 90 days. Below a value of about 150 percent, the probability of a poor result increases significantly. Some improvement is observed between 28 and 90 days.

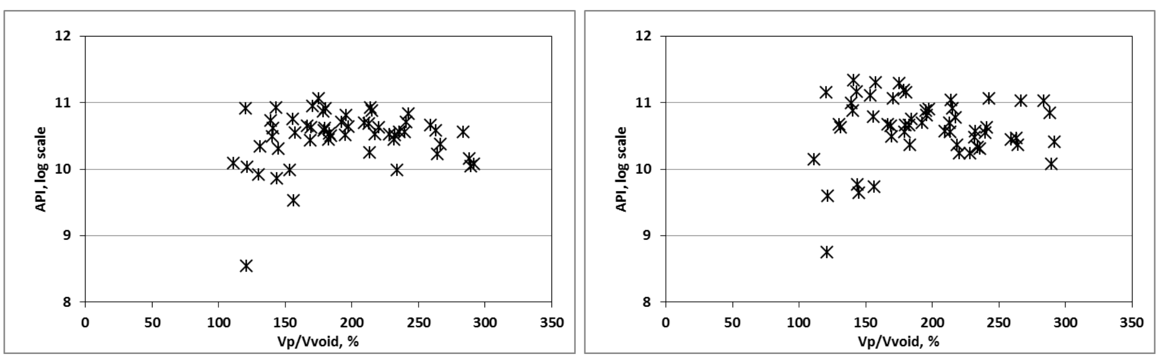


Figure 25. Overview of the effect of Vp/Vvoid on API for all mixtures at 28 and 90 days.

As before, when there is insufficient paste in the mixture, API is poor, but once sufficient paste is in the mix, increasing paste has little or no benefit (Figure 26). There is some benefit with decreasing w/cm, while the type of binder does not appear to have a significant effect at this age. It is not surprising that the 90 day data are better than the 28 day set.

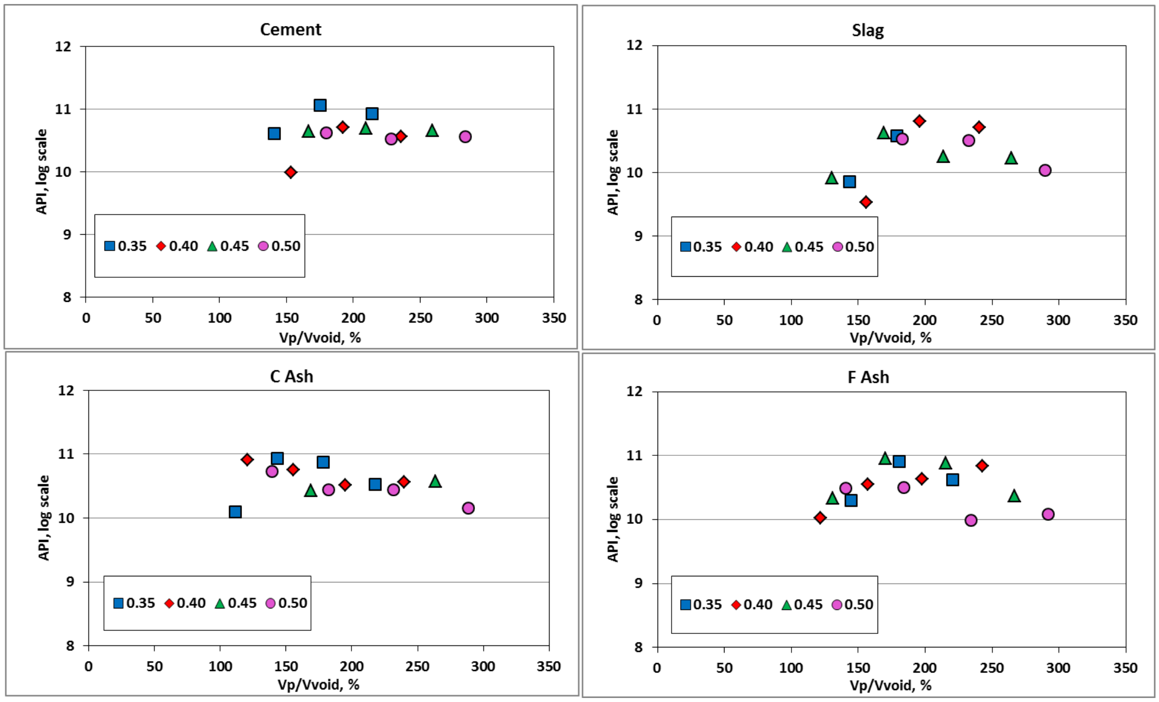


Figure 26. API data for different binder systems at 28 days as a function of Vp/Vvoid

The observed results are consistent with the information in the literature (Alexander et al. 2007, Dinku et al. 1997).

Summary

Consideration was given to the effects of the thickness of the paste layer on all of the parameters discussed in this work. A Paste Thickness Index (PTI) was calculated based on the assumption that all aggregate particles were spherical and that all were coated by a layer of constant thickness. Neither of these assumptions is true, but the approach provides a reasonable point of comparison. It was found that there was a linear relationship between the PTI and the Vp/Vvoid ratio; therefore, there were no changes to the conclusions.

The PTI values ranged from 100 to 250 µm. This is of interest because the interfacial transition zone (ITZ) is typically reported (Prokopski and Halbiniak 2000) to be from 40 to 50 thick µm, which is a significant fraction of the nominal paste thickness. If about one-third to one-half of the paste is functionally ITZ, approaches that modify the quality of the ITZ will have a marked effect on system performance.

In general, two different trends were observed. In all cases, very low paste contents led to poor performance of the mixture. Above a certain threshold, performance was either constant or deteriorated slightly. Deterioration in performance was observed generally in permeability tests with increasing paste, which is to be expected because permeability of paste is lower than that of aggregate. Other parameters such as strength were generally constant with increasing paste.

The threshold varied between tests and between binder systems. These are summarized in Table 8.

Table 8. Critical minimum paste required for performance expressed as Vp/Vvoid percent

	Binder System			
Property	**Plain Cement**	**40% Slag**	**20% C Ash**	**20% F Ash**
Workability	150	125	125	150
Setting time	200	225	200	225
Compressive Strength	150	175	150	175
API	175	200	125	175

Values are not provided for RCP because it was found that the ability to consolidate the samples was dominant and, as soon as sufficient paste was provided to achieve this, performance fell off with increasing paste content.

In broad terms, then, about 1.5 to 2 times more paste is required than the space between the combined aggregate particles. This is to ensure that all the space is filled and to coat all of the aggregate particles, providing lubrication in the fresh concrete when the mixture is being handled, and to glue the particles together in the hardened state. This is true for the single aggregate system tested here. It is possible that these numbers may change for different aggregate forms (river gravel as opposed to crushed limestone) and gradations.

CONCLUSIONS

The goal of this study was to investigate the minimum cementitious material content required with an appropriate water-to-cementitious ratio (w/cm) to meet given workability, strength, and durability requirements in concrete mixtures and, in turn, reduce carbon dioxide emissions, energy consumption, and costs.

The hypothesis that guided this study was, for a certain binder combination, when other parameters are kept constant, after a required cementitious content is reached, concrete properties such as strength, chloride penetration, and air permeability will not be improved by increasing the binder content. Although compressive strength test results verified the hypothesis, results showed that increasing cement content increases chloride penetration and air permeability.

The following conclusions are made based on the results:

- About 1.25 to 1.5 times more paste is required than voids between the aggregates to obtain a minimum workability. Below this value, water reducing admixtures are of no benefit. Increasing paste thereafter increased workability.
- For a high cement content, decreasing w/c reduces setting time because cement grains are closer to each other, reducing the time needed for hydration products to become interconnected.
- For a given w/cm, increasing cementitious content does not significantly improve compressive strength once the critical minimum has been provided. The critical value is about twice the voids content of the aggregate system.
- For a given w/cm, increasing paste content increases the chloride penetrability.
- For a given w/cm, increasing cement content increases the air permeability.

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