Should Minimum Cementitious Contents for Concrete Be Specified?

Karthik H. Obla, Rongjin Hong, Colin L. Lobo, and Haejin Kim

Minimum cementitious contents are commonly specified in project specifications. The primary focus of this study was to examine the influence of the cementitious content on concrete performance at specific water-to-cementitious materials ratios. The experimental variables included water-to-cementitious materials ratios ranging from 0.40 to 0.55, mixtures containing portland cement only, and mixtures containing 40% slag cement or 25% fly ash. Concrete performance was evaluated through laboratory tests on workability, strength, and durability. The results showed that at a given water-to-cementitious ratio a higher cementitious content results in higher paste volumes and poorer concrete performance. On the basis of these results the value of maintaining minimum cementitious content requirements in project specifications is questioned.

In the United States many state highway agencies specify a minimum cement content between 550 and 600 lb/yd^3 for slip-form pavement mixtures (*1*). Most state highway agencies also establish classes of concrete for various elements in transportation construction projects. These classes of concrete are typically defined by minimum content of cementitious materials (CM) among other parameters. For the most part, consensus-based industry standards in the United States, such as those from the American Concrete Institute (ACI) (*2, 3*), do not include requirements for minimum CM content for concrete mixtures. An industry survey conducted in 2014 revealed that minimum cementitious content was included in 46% of all project specifications (*4*).

Minimum limits on CM specified by state highway agencies typically exceed the quantity required for intended performance parameters, such as workability, strength, and durability. This practice results in increased cost and a higher carbon footprint, and it often negatively affects the performance of these concrete mixtures. The performance implied or intended by the minimum CM content is most often not clear or enforceable. Minimum CM limits in specifications for concrete restrict mixture optimization for performance, and as a result there is little incentive for concrete producers and contractors to become more knowledgeable about the ingredient materials and mixtures. Specifications that include these requirements do not allow concrete producers and contractors to target lower average strengths by reducing standard deviation through improved concrete quality, and as a result they do not provide any incentive for investing in improved quality management systems (*5*). These requirements prevent the evolution to performance-based specifications.

Wasserman et al. (*6*) identified three possible reasons for specifying a minimum cementitious content:

1. It provides assurance that a low water-to-cementitious materials ratio (w:cm) is attained, even if good control of the mixing water content is not exercised;
2. It ensures there is enough paste to fill the voids between the aggregates and provide adequate workability; and
3. It offers corrosion protection by chemically binding the chlorides and the carbon dioxide that penetrate the concrete.

Wasserman et al. (*6*) and Dhir et al. (*7*) reported that at any given w:cm, increasing cement contents leads to similar compressive strengths and carbonation rates but higher absorption and chloride penetration. A mixture with a higher cement content had an increased chloride threshold concentration to initiate corrosion, but this benefit was offset by a higher level of chloride penetration, which could cause the initiation of reinforcement corrosion. Dhir et al. (*7*) also reported that for mixtures with similar w:cm values, increasing cement contents led to similar flexural strengths, modulus of elasticity, and levels of deicer salt scaling. However, increasing cement contents led to reduced sulfate resistance, increased chloride diffusion, greater air permeability, and higher length change due to shrinkage. These studies concluded that minimum CM content should not be specified for concrete durability. Yurdakul et al. (*8*) also concluded that for a given w:cm, increasing the volume of paste increased chloride penetrability and air permeability.

The present study examined the influence of the cementitious content on concrete performance at specific w:cm. Concrete performance was evaluated through laboratory tests on workability, strength, and durability.

MATERIALS AND MIXTURE PROPORTIONS

Non-air-entrained concrete mixtures were evaluated, and concrete mixtures with fixed w:cm were prepared with different paste volumes. Change in paste volume at the specific w:cm was accomplished by changing the CM content. Based on a fixed ratio of coarse to fine aggregate, the volume of voids in the combined aggregate was determined. The paste volume in the concrete mixtures was varied from less than to substantially greater than the volume of voids in the combined aggregate.

The following materials were used for the concrete mixtures (ASTM C29, C33, C39, C138, C143, C157, C192, C231, C403, C494,

K. H. Obla and C. L. Lobo, National Ready Mixed Concrete Association, 900 Spring Street, Silver Spring, MD 20910. R. Hong, National Ready Mixed Concrete Association, 5600 Branchville Road, College Park, MD 20740. H. Kim, FHWA Turner–Fairbank Highway Research Center, U.S. Department of Transportation, 6300 Georgetown Pike, McLean, VA 22101. Corresponding author: K. H. Obla, kobla@nrmca.org.

Transportation Research Record: Journal of the Transportation Research Board, No. 2629, 2017, pp. 1–8.
http://dx.doi.org/10.3141/2629-01

C618, C989, C1064, C1202, C1240, C1556, C1585; ASTM C150; AASHTO M 6, M 80, M 85, M 194, M 295, M 302, T 227):

- ASTM C150 Type II portland cement (AASHTO M 85),
- ASTM C989 slag cement (AASHTO M 302),
- ASTM C618 class F fly ash (AASHTO M 295),
- ASTM C33 No. 57 crushed coarse aggregate (AASHTO M 80),
- ASTM C33 natural sand with a fineness modulus of 2.88 (AASHTO M 6),
- ASTM C494 Type F high-range water-reducing admixture (HRWRA) (AASHTO M 194), and
- A defoaming agent.

For all concrete mixtures, the coarse aggregate absolute volume was set at 58.4% of the total aggregate absolute volume. This method ensured that the combined aggregate grading and void content remained the same for all mixtures. The coarse aggregate quantity was based on ACI 211.1, assuming an average paste volume (*9*). Paste volume was defined as the volume of CM, mixing water, and entrapped air, which was assumed to be 2%. Combined aggregate void content was measured as outlined in ASTM C29. The required quantity of coarse and fine aggregate by mass were placed in a pan and blended with a scoop. The blended combined aggregate was placed in three layers in a container with a capacity of 0.25 ft^3, and each layer was rodded 25 times. The void content was calculated from the measured bulk density and the relative density of aggregate. The test was repeated three times with separate blending of aggregate. The average void content of the combined aggregate was calculated as 25.4%.

For this study, 20 non-air-entrained concrete mixtures were evaluated. Of these, 12 mixtures contained slag cement at 40% by mass of the CM. For these 12 mixtures, the w:cm was varied at 0.40, 0.47, and 0.55. At each w:cm the paste volumes were varied at 24%, 26%, 29%, and 33% of total concrete volume. Four mixtures contained fly ash at 25% by CM mass, and the remaining four mixtures were made with portland cement only. For these eight mixtures only one level of w:cm at 0.47 was used, with the paste volumes varied at 24%, 26%, 29%, and 33% of total concrete volume. Mixture designations were assigned by the w:cm followed by the supplementary CM type and paste volume. Mixtures with portland cement use the designation PC. FA refers to fly ash, and SL refers to slag cement. For example, 0.40SL29 refers to a mixture with a w:cm of 0.40, slag cement as part of the CM, and paste volume of 29%. In some plots the paste volume is not indicated in the mixture designation; such a mixture would be reported as, for example, 0.40SL.

The concrete mixture variables are shown in Table 1. Mixture proportions and test results of the 12 concrete mixtures containing slag cement are shown in Table 2. Mixture proportions and test results of the remaining eight concrete mixtures with fly ash and with only portland cement are shown in Table 3. Calculated batch quantities were based on the measured density of fresh concrete. Slump was not controlled because of the constraints of the mixture proportions, but if the measured slump was below 1 in. an HRWRA was added to achieve a measurable slump. A small dosage of an defoaming agent was added because during trial batches, high entrapped air contents were measured, even in the absence of air-entraining admixtures.

EXPERIMENTAL PROCEDURES

Concrete mixtures were mixed in a revolving drum laboratory mixer in accordance with ASTM C192. Fresh concrete was tested for slump (ASTM C143), temperature (ASTM C1064), air content by the pressure method (ASTM C231), and density (ASTM C138).

TABLE 1 Concrete Mixture Variables

w:cm	CM Type	Paste Volume (%)	Target CM Content
0.40	40% slag cement	24	510
		26	556
		29	625
		33	718
0.47	40% slag cement	24	465
		26	507
		29	570
		33	655
0.55	40% slag cement	24	422
		26	461
		29	518
		33	595
0.47	25% fly ash	24	449
		26	490
		29	551
		33	633
0.47	PC (portland cement–only mixture)	24	471
		26	513
		29	577
		33	663

The setting time of the concrete mixtures was estimated from the temperature profile measured by using commercially available equipment that maintains specimens in an insulated semiadiabatic environment. The equipment contains four cells with time and temperature data loggers. Concrete was molded in 4- × 8-in. cylinders and placed in the equipment. The thermal signature was monitored, and the initial and final setting times were estimated as the elapsed time corresponding to 21% and 42% of peak temperature, respectively. This method provided a relative comparison of estimated time of setting for the mixtures evaluated. Note that the estimated time of setting from the thermal signature curve is not the same as that which is measured using the penetration resistance method (ASTM C403).

Cast specimens were kept in a moist room at 73°F ± 3°F, and the molds were stripped at 24 h. Two types of specimen curing were used:

- Standard curing, in which specimens were stored in a moist room at 73°F ± 3°F for the duration prior to testing; and
- Accelerated curing, in which specimens were stored in a moist room at 73°F ± 3°F for 7 days followed by 21 days immersion in water at 100°F. Accelerated curing was only used for some of the rapid index test specimens as outlined below.

Compressive strength (C39) tests were conducted using 4- × 8-in. standard-cured cylindrical specimens. Reported strengths are the average of two specimens tested at 1, 7, and 28 days. Length change (C157) was measured on three 3- × 3- × 11¼-in. prisms, with 7 days standard curing followed by up to 90 days of air drying in a 70°F, 50% relative humidity environment.

Rapid index tests to measure the transport characteristics of concrete mixtures included the rapid indication of chloride ion penetrability test (RCPT) (ASTM C1202, AASHTO T 227), the rapid migration test (RMT), and the initial sorptivity test (ASTM C1585) (*10*). The RCPT and RMT test specimens were subjected to accelerated curing and tested at an age of 28 days. The sorptivity test specimens were standard cured for 28 days prior to testing. After conditioning,

TABLE 2 Yield-Adjusted Mixture Proportions and Test Results for Slag Cement Mixtures

	Mixture Designation											
	0.55SL33	0.55SL29	0.55SL26	0.55SL24	0.47SL33	0.47SL29	0.47SL26	0.47SL24	0.40SL33	0.40SL29	0.40SL26	0.40SL24
Calculated Batch Quantities												
Total cementitious (lb/yd^3)	602	517	459	417	655	571	507	465	720	627	557	505
PC (lb/yd^3)	361	310	275	250	393	343	304	279	432	376	334	303
Slag cement (lb/yd^3)	241	207	184	167	262	228	203	186	288	251	223	202
SCM (%)	40	40	40	40	40	40	40	40	40	40	40	40
Coarse aggregate (lb/yd^3)	1,929	2,015	2,095	2,135	1,905	2,025	2,102	2,159	1,910	2,028	2,107	2,143
Fine aggregate (lb/yd^3)	1,245	1,301	1,353	1,379	1,230	1,307	1,357	1,394	1,233	1,309	1,360	1,384
Mixing water (lb/yd^3)	331	284	252	229	308	268	238	218	288	251	223	202
w:cm	0.55	0.55	0.55	0.55	0.47	0.47	0.47	0.47	0.40	0.40	0.40	0.40
HRWRA (oz/cwt)	0.0	0.0	0.0	7.7	0.0	0.0	2.8	7.7	0.0	1.2	7.1	12.0
Defoaming agent (ml)	17	17	17	15	17	17	15	15	10	10	15	15
Yield-adjusted paste volume (%)	32.3	28.4	25.9	23.7	32.6	28.5	26.0	23.7	33.5	28.8	25.9	23.7
Paste-to-void ratio	1.27	1.12	1.02	0.93	1.28	1.12	1.02	0.93	1.32	1.13	1.02	0.93
Fresh Concrete Properties												
ASTM C143, slump before HRWRA (in.)	8.25	6.50	1.25	0.00	7.75	1.75	0.00	0.00	2.50	0.25	0.00	0.00
ASTM C143, slump after HRWRA (in.)	NA	NA	NA	2.00	NA	NA	1.50	3.50	NA	1.50	8.00	1.25
ASTM C231, air (%)	1.0	1.5	2.0	2.0	1.6	1.5	2.0	1.7	2.4	1.7	1.8	1.9
ASTM C138, density (lb/ft^3)	152.9	153.3	154.9	154.9	152.5	155.3	156.5	157.7	154.5	156.9	158.1	157.7
ASTM C1064, temperature (°F)	74	75	75	75	76	76	74	74	73	74	75	72
Thermal initial setting (h:min)	3:26	3:25	3:28	4:48	3:29	3:22	3:44	5:32	3:27	2:51	5:01	8:01
Thermal final setting (h:min	4:55	5:02	5:03	6:22	4:59	4:55	5:09	7:11	4:57	4:13	6:42	9:55
Hardened Concrete Properties												
ASTM C39, compressive strength (psi)												
1 day	1,040	720	860	900	1,270	1,250	1,360	1,280	1,770	1,890	2,150	1,690
7 days	2,980	2,860	2,830	3,160	3,840	4,040	4,240	4,510	5,170	5,480	6,260	5,820
28 days	6,300	5,700	5,450	6,010	6,850	7,170	7,480	7,800	8,100	8,780	8,800	8,560
ASTM C1202, RCPT, 28-day accelerated (coulombs)	1,218	791	822	532	1,079	803	785	547	908	709	484	465
AASHTO TP 64, RMT, 28-day accelerated (mm/vph)	0.0163	0.0156	0.0139	0.0095	0.0126	0.0115	0.0115	0.0075	0.0098	0.0078	0.0069	0.0060
ASTM C157, length change (%)												
28 days	0.044	0.032	0.036	0.036	0.041	0.034	0.037	0.027	0.030	0.027	0.023	0.020
3 months	0.053	0.043	0.046	0.044	0.054	0.048	0.044	0.035	0.044	0.039	0.034	0.031
ASTM C1585, rate of water absorption, initial sorptivity (10^{-4} mm/s$^{1/2}$)	4.02	NA	1.89	1.93	3.42	2.53	NA	2.49	5.85	NA	2.13	1.87
ASTM C1556, chloride concentration at different depths (% by weight of concrete)												
9 mm	1.040	0.964	0.710	0.567	1.193	0.750	1.012	0.881	1.039	0.655	0.559	0.602
11 mm	0.994	0.929	0.579	0.545	0.916	0.707	0.794	0.750	0.758	0.601	0.506	0.494
17 mm	0.513	0.633	0.398	0.435	0.624	0.433	0.311	0.372	0.326	0.332	0.313	0.275
19 mm	0.430	0.579	0.409	0.368	0.573	0.347	0.277	0.312	0.191	0.203	0.194	0.205
73 mm	0.007	0.012	0.015	0.023	0.006	0.007	0.048	0.009	0.059	0.005	0.040	0.015

NOTE: SCM = supplementary cementitious materials; NA = not available.

TABLE 3 Yield-Adjusted Mixture Proportions and Test Results for Fly Ash and Portland Cement Concrete Mixtures

	Mixture Designation							
	0.47FA33	0.47FA29	0.47FA26	0.47FA24	0.47PC33	0.47PC29	0.47PC26	0.47PC24
Calculated Batch Quantities								
Total cementitious (lb/yd^3)	641	553	491	451	670	581	512	471
PC (lb/yd^3)	481	415	368	338	670	581	512	471
Fly ash (lb/yd^3)	160	138	123	113	0	0	0	0
SCM (%)	25	25	25	25	0	0	0	0
Coarse aggregate (lb/yd^3)	1,930	2,028	2,109	2,165	1,924	2,035	2,097	2,160
Fine aggregate (lb/yd^3)	1,246	1,309	1,362	1,398	1,242	1,314	1,354	1,395
Mixing water (lb/yd^3)	301	260	231	212	315	273	240	221
w:cm	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
HRWRA (oz/cwt)	0.0	0.0	5.9	10.4	0.0	0.0	4.8	14.6
Defoaming agent (ml)	0	0	17	17	17	17	17	17
Yield-adjusted paste volume (%)	32.5%	28.6%	26.3%	24.0%	32.7%	28.8%	25.6%	23.9%
Paste-to-void ratio	1.28	1.12	1.03	0.94	1.29	1.13	1.01	0.94
Fresh Concrete Properties								
ASTM C143, slump before HRWRA (in.)	6.00	1.50	0.00	0.00	7.50	2.00	0.00	0.00
ASTM C143, slump after HRWRA (in.)	NA	NA	1.25	0.50	NA	NA	1.75	1.25
ASTM C231, air (%)	1.1	1.5	2.2	1.9	1.4	1.6	1.7	1.9
ASTM C138, density (lb/yd^3)	153.3	154.5	156.1	157.3	154.5	156.5	156.5	158.1
ASTM C1064, temperature (°F)	78	77	78	78	78	78	85	83
Thermal initial setting (h:min)	NA	NA	3:30	5:15	2:35	2:47	3:34	4:35
Thermal final setting (h:min)	NA	NA	5:00	7:13	3:56	4:09	4:48	5:54
Hardened Concrete Properties								
ASTM C39, compressive strength (psi)								
1 day	1,770	1,790	2,050	1,860	2,780	2,870	2,890	3,180
7 days	3,500	3,750	4,060	3,720	5,270	5,480	5,120	5,280
28 days	5,460	5,630	5,900	5,600	6,810	7,160	6,510	7,170
ASTM C1202, RCPT, 28-day accelerated (coulombs)	1,367	1,256	1,027	959	3,790	3,317	2,966	2,602
AASHTO TP 64, RMT, 28-day accelerated (mm/vph)	0.0279	0.0279	0.0271	0.0263	0.0408	0.0402	0.0386	0.0395
ASTM C157, length change (%)								
28 days	0.027	0.024	0.027	0.023	0.027	0.023	0.023	0.024
3 months	0.043	0.039	0.038	0.035	0.046	0.039	0.038	0.038
ASTM C1585, rate of water absorption (sorptivity), initial rate (10^{-4} mm/s$^{1/2}$)	5.83	5.47	5.13	6.43	4.69	NA	4.79	4.47

the sorptivity test specimens were subject to water absorption only for 6 h, and therefore only the initial sorptivity result was measured. Results of rapid index tests were the average of two 4- × 8-in. cylindrical specimens for each test and test age. The specimens were cut, and the top 2 in. from the finished surface was tested.

A modified chloride bulk diffusion test (ASTM C1556) was conducted. One 4- × 8-in. cylindrical specimen was cast for each mixture and standard cured for 28 days. After this curing period, the specimens were cut at 3 in. from the finished surface. All sides of the specimens except for the finished surface were coated with an epoxy, and the specimens were immersed in an aqueous solution of sodium chloride for about 45 months. This process permitted chloride penetration from the finished surface of the specimen. At the end of the exposure period, the specimens were profiled in layers of 2-mm thickness. Chloride contents were measured at depths of 9, 11, 17, 19, and 73 mm and are reported as percentage by weight of concrete in Table 2.

RESULTS AND DISCUSSION

Slump

Figure 1 shows the relation between the mixing water content and the measured slump prior to adding HRWRA (typically referred to as water slump) for all the concrete mixtures. Figure 1 indicates that for the mixtures evaluated a mixing water content of 250 to 265 lb/yd^3 was needed to attain a water slump of 1 in. The corresponding yield-adjusted paste volumes were calculated as between 25.7% and 29.8%.

At a fixed mixing water content the slump decreased as the w:cm decreased. This effect became more pronounced at greater mixing water contents. This finding showed the expected trend that without the use of HRWRA, higher CM contents increased the mixing water required for a target slump.

Tables 2 and 3 indicate the mixtures in which there was no measurable slump with the quantity of mixing water used, and HRWRA

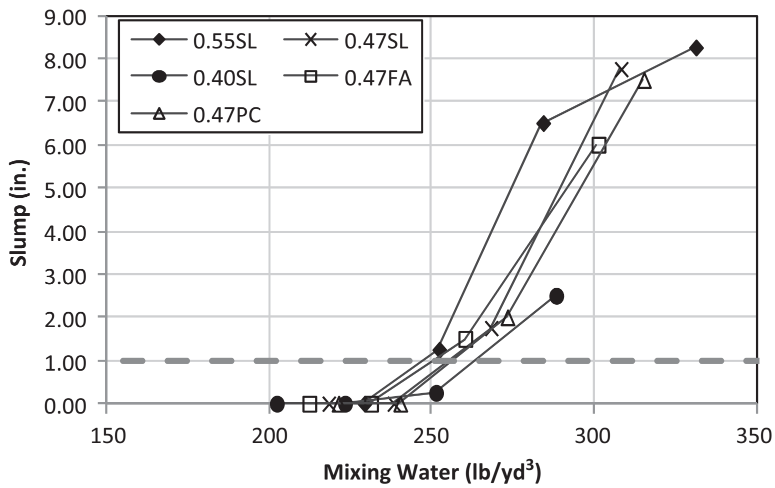

FIGURE 1 Influence of mixing water content on measured slump before adding any HRWRA.

was needed to achieve a measurable slump. By observation these mixtures appeared to be rocky and sticky. So if a water slump of 1 in. was not targeted, HRWRA could be added to attain target slump levels for all the mixtures. These mixtures had a yield-adjusted paste volume as low as 23.7%. Even though these mixtures attained the desired slumps, their workability would have to be examined to see if it was satisfactory for the intended application.

Thermal Setting Time

The initial and final setting times of the mixtures increased as the CM content decreased at each w:cm. This result is attributed to the retarding effect of the HRWRA used. Mixtures with no HRWRA had similar setting times regardless of the CM contents.

Compressive Strength

The 1- and 28-day compressive strengths of the mixtures containing slag cement are plotted against total CM content in Figure 2. As expected, strength at all ages increased with a reduction in w:cm from 0.55 to 0.40. Despite a wide range of about 200 lb/yd^3 of the CM content in these mixtures, the compressive strengths are relatively similar at a specific w:cm. At a w:cm of 0.40, when the total CM content varied between 505 and 720 lb/yd^3, the 28-day compressive strength varied between 8,560 and 8,100 lb/in.^{2} (psi). It is expected that reducing the paste volume to less than the void content of the combined aggregate would increase the void content of the concrete as placed, thereby reducing strength and durability. However, the minimum CM requirements typically seen in project specifications do not get close to causing a deficiency of paste volume in concrete mixtures.

Rapid Indication of Chloride Ion Penetrability Test

RCPT results for all the mixtures are plotted against total CM content in Figure 3. At a given w:cm the charge passed in Coulombs increased with an increase in the CM content. A higher charge passed indicated higher chloride ion penetrability. This was an expected trend because transport of ions was through the paste; the data showed that at

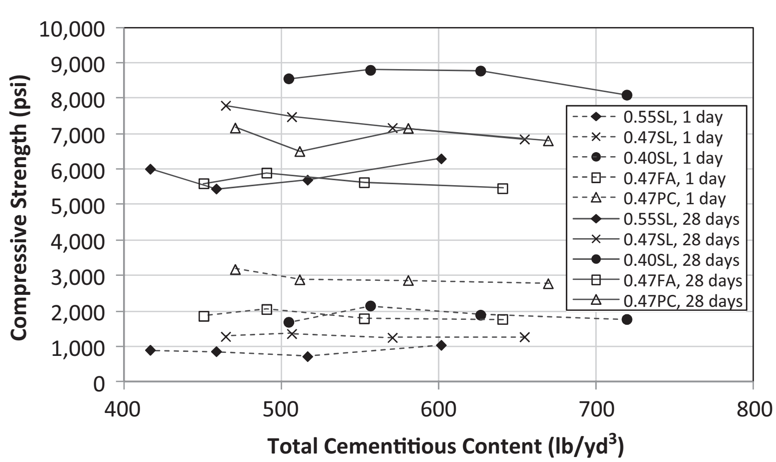

FIGURE 2 Influence of cementitious content on compressive strength.

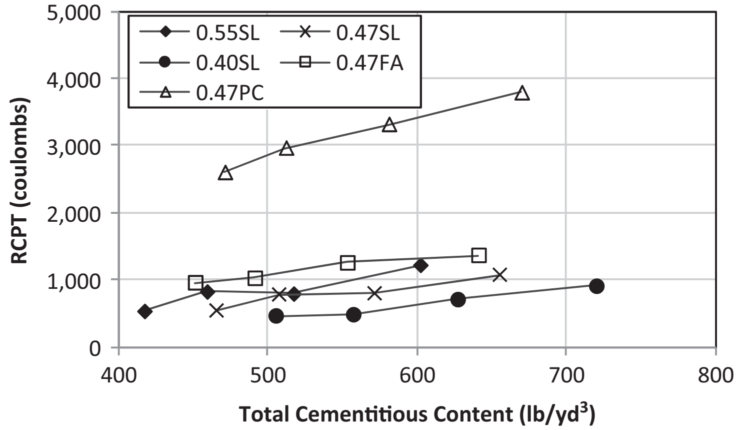

FIGURE 3 Influence of cementitious content on rapid indication of chloride ion penetrability.

a fixed w:cm and CM composition, the charge passed increased as the paste volume increased. As expected, at the same w:cm, the charge passed was considerably lower for the mixtures containing slag cement and fly ash compared to the mixtures containing only portland cement.

Rapid Migration Test

The RMT results, which represent the average depth of chloride ion penetration under an electrical current, of all the mixtures are plotted against total CM content in Figure 4. At a given w:cm the RMT results increased or stayed the same with an increase in the CM content. A higher RMT result indicated a greater depth of penetration of chlorides. Reduced depth of penetration was observed for the mixtures with slag cement and fly ash compared to the portland cement mixtures. These results were consistent with the observations for the RCPT results.

Initial Sorptivity

The initial sorptivity results for all the mixtures are plotted against total CM content in Figure 5. At a given w:cm the initial sorptivity increased or stayed the same with an increase in the CM content. A higher sorptivity result indicated a greater rate of moisture ingress, and hence, potentially reduced durability. The observations were consistent with those made for the RCPT results.

Chloride Penetration

The chloride contents of the slag cement mixtures at a depth of 18 mm from the surface exposed to chlorides are plotted against total CM content in Figure 6. The chloride content at 18 mm depth was the average of the measured chloride contents at depths of 17 and 19 mm. As the w:cm decreased from 0.55 to 0.40, the chloride penetration decreased as expected. For a given w:cm, the chloride contents increased as the cementitious content increased for the mixtures with a w:cm of 0.47 and 0.55, and they were constant in the case of the 0.40 w:cm mixtures as the CM content varied.

Length Change Due to Drying Shrinkage

The 90-day length change results of all the mixtures are plotted against paste volume in Figure 7. As the paste volume increased, the average length change increased. This result was as expected

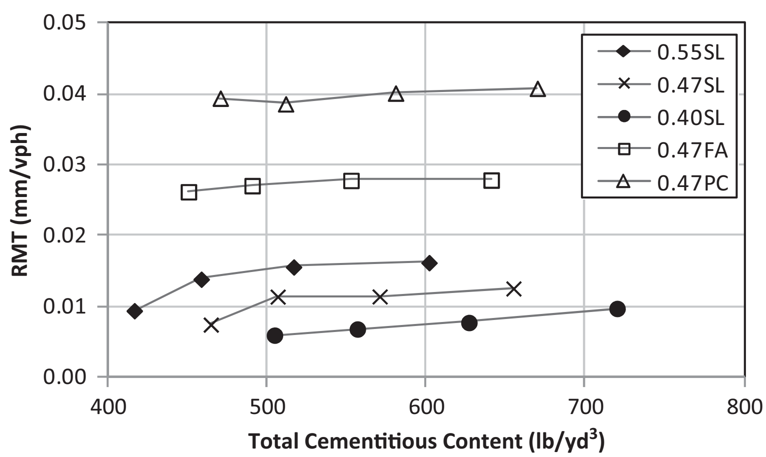

FIGURE 4 Influence of cementitious content on rapid migration test results.

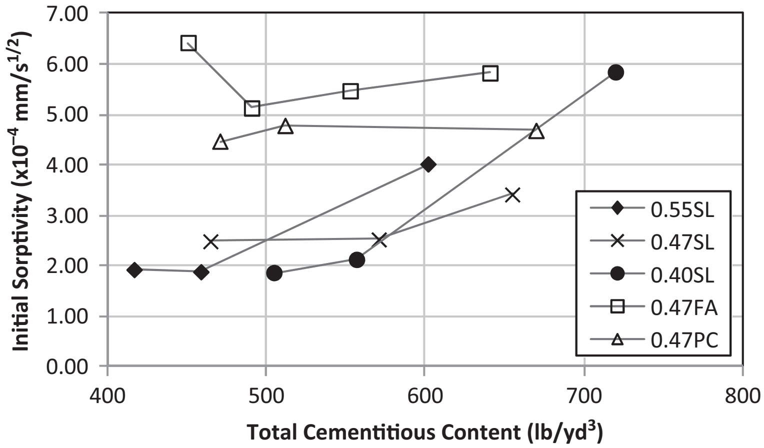

FIGURE 5 Influence of cementitious content on initial sorptivity test results.

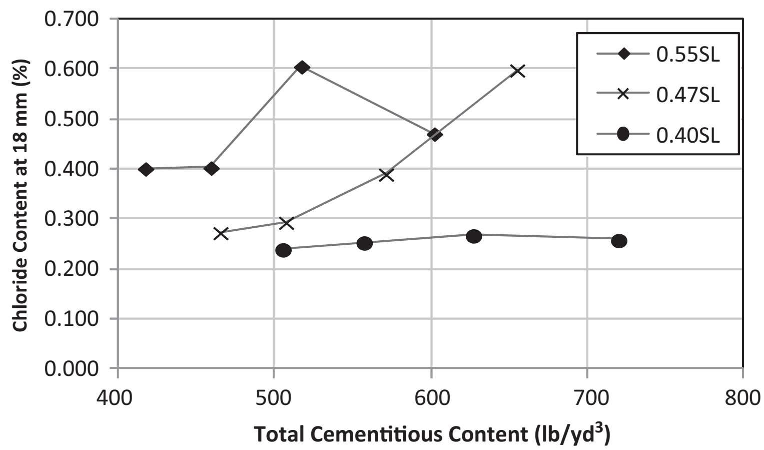

FIGURE 6 Influence of cementitious content on chloride concentration at 18-mm depth after 45 months of immersion in a salt solution.

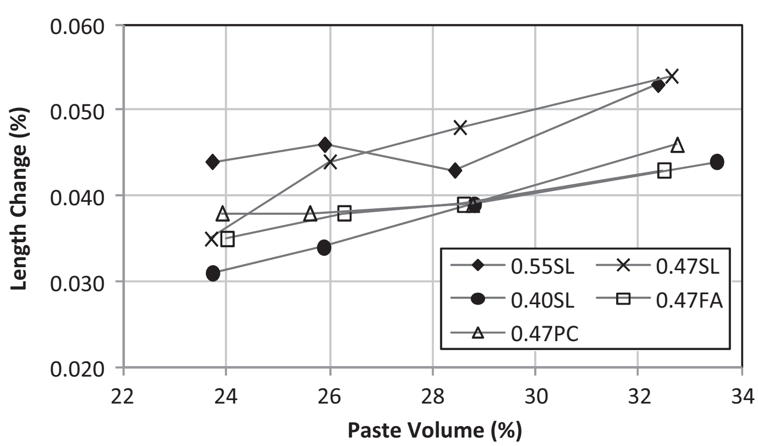

FIGURE 7 Influence of paste volume on 90-day drying shrinkage.

because, for a particular aggregate, concrete shrinkage is affected by paste volume. At a given paste volume, shrinkage generally increased as w:cm increased.

CONCLUSIONS

The main findings from this study are summarized below:

1. Higher CM contents increased the mixing water demand of concrete. For a given w:cm, increasing CM content resulted in similar compressive strengths but also resulted in increased chloride penetrability, increased initial sorptivity, and greater length change due to drying shrinkage. The reduced concrete performance of the mixtures with higher CM contents was due to the higher paste volumes. These results clearly show that at a given w:cm requiring a higher CM content is counterproductive because it leads to poorer concrete performance.
2. If the strength and durability requirements for a project are defined, there is no technical basis for specifying the minimum CM content. Workability can be evaluated by test pours or documentation of successful past field history. If the main purpose of specifying a minimum CM content is to get assurance of a low w:cm, it is better to specify an appropriate compressive strength, which is a better indicator of w:cm. In summary, moving to a performance-based specification facilitates removing the minimum CM content requirement in specifications.
3. For the aggregates used in this study a mixing water content of 250 to 265 lb/yd^3 was needed to attain a slump of 1 in., without the use of a water-reducing admixture and independent of the w:cm or composition of CM used. This finding indicates the current ACI 211.1 mixture-proportioning approach of assigning a target mixing water content for target slump is reasonable. However, if the aggregates are changed, or if the concrete mixtures are air-entrained, these mixing water contents may be different.
4. For a 1-in. water slump the required minimum paste volume varied from 25.7% to 29.8%. If a water slump of 1 in. was not targeted and HRWRA was used to attain target slump, a concrete mixture with 23.7% paste volume with these materials provided adequate slump and hardened concrete performance. However, the workability of these low-paste-volume mixtures would have to be examined to see if it is satisfactory for the intended application.

ACKNOWLEDGMENTS

The authors thank Soliman Ben-Barka and Stuart Sherman, who performed the testing at the National Ready Mixed Concrete Association Research Laboratory, and Haejin Kim, who supervised the testing. Funding for the study was provided by the RMC Research & Education Foundation.

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The Standing Committee on Concrete Materials and Placement Techniques peer-reviewed this paper.