International Journal of Concrete Structures and Materials
Vol.5, No.2, pp.119~123, December 2011
http://dx.doi.org/10.4334/IJCSM.2011.5.2.119

Effect of Slag Grade and Cement Source on the Properties of Concrete

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(Received May 30 2011, Revised August 9, 2011, Accepted August 23, 2011)

Abstract: Presented in the paper are findings of a project that examined the effect of slag grade and cement source on the performance of concrete mixtures. Slag cement contents were 20, 40, and 60 percent of the total cementitious material content. Two grades of slag cement were examined (Gr. 100 and Gr. 120) along with two sources of Type I cement. Compressive strength, durability, and permeability were measured. The results showed that the cement source affected the early age strength of the mixtures. At 28 days of age, mixtures containing Gr. 120 slag cement had higher compressive strengths than mixtures containing Gr. 100 slag cement, but by 90 days of age, the trend reversed. As for the chloride ion penetrability, mixtures cast with Gr. 100 slag cement passed fewer coulombs at 28 and 90 days of age than similar mixtures containing Gr. 120 slag. Mixtures containing Gr. 120 slag had the greatest durability factors.

Keywords: slag cement, durability, permeability, strength

1. Introduction

The production of portland cement is energy intensive and consumes approximately 5.5 GJ of energy for every metric ton of cement produced.[1] After aluminum and steel, the "production of portland cement is the third most energy intensive material production process".[2] In addition to being very energy intensive, the production of cement also contributes significantly to the quantity of greenhouse gases. For every ton of cement manufactured, one ton of CO_2 is released into the atmosphere. Cement production accounts for "approximately seven percent of the total world CO_2 production".[2] In 2010, it was estimated that 3.3 billon metric tons of cement was produced in the world which corresponds to 3.3 billon metric tons of CO_2.[3] By the replacing a portion of the cement in a concrete mixture with a supplementary cementing material (SCM) such as slag cement, the current supply of portland cement is extended and possibly more importantly, the impact on the environment is lessened. Isaia et al. reported that by replacing 90 percent of the portland cement with SCMs (70 percent slag cement and 20 percent), 76 to 81 percent reduction in CO_2 emissions were observed for the two compressive strength levels (40 MPa and 55 MPa) examined in their study.[1]

American Concrete Institute (ACI) Committee 233, *Slag Cement in Concrete and Mortar*, defines slag cement as "granulated blast-furnace slag that has been finely ground and that is a hydraulic cement".[4] Slag cement is a recycled material that is produced during the production of iron-the blast furnace yields molten iron and a byproduct, blast furnace slag, which floats above the pool of molten iron. The slag is a nonmetallic product composed primarily of silicates and aluminosilicates of calcium. ACI 233R-03 further states that during the pozzolanic reaction the slag cement reacts with sodium and potassium alkali and calcium hydroxide (lime) to produce calcium-silicate hydrate (CSH) in addition to the CSH produced by portland cement hydration. But unlike portland cement hydration the reaction of slag cement is significantly slower. Based on the slag cement's reactivity, it can be classified as Gr. 80, Gr. 100, or Gr. 120 slag cement.[4] As the grade increases, slag cement's reactivity also increases. For example, at 28 days of age, a mortar mixture cast with 50 percent portland cement and 50 percent Gr. 80 slag cement has a compressive strength of at least 75 percent of the control mixture (100 percent portland cement). For Gr. 120 slag cement, the slag cement and portland cement mortar has a compressive strength of at least 115 percent of the control mixture at 28 days of age. Therefore the grade of slag impacts the performance of the concrete.

The effect of slag cement on the hardened properties has been well documented. Many researchers have examined mixtures with slag cement contents ranging from 25 to 75 percent (5, 6, 7, 8). Generally, researchers have observed lower early age strengths for mixtures containing slag cement when compared to control mixtures containing only portland cement. Beyond seven days, mixtures containing slag cement generally had compressive strengths that exceeded the control mixtures. Likewise, durability improved and chloride ion penetrability decreased when mixtures containing slag cement where compared to control mixtures. There has been concern regarding increased surface scaling caused by the application of deicing salts in mixtures containing high volumes of slag cement. Researchers performed a series of laboratory tests and visited 28 field sites. They determined that construction practices contributed more to scaling than slag cement content.[9] Although

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there have been numerous projects that examined the performance of mixtures containing slag cement, one area of limited research is the effect of slag grade and cement source on the performance of concrete. This program examines the performance of concrete containing Gr. 100 or Gr. 120 slag cement and examines the effect of cement source

2. Experimental program

The research program examined the performance of concrete mixtures cast with either Gr. 100 or Gr. 120 slag cement and two sources of Type I cement. The project also examined the fresh and hardened properties of concrete containing 20, 40, or 60 percent slag cement. The research results were used for recommending replacement rates for slag cement to the Arkansas State Highway and Transportation Department (AHTD). AHTD was primarily concerned with strength development and performance of concrete mixtures containing slag cement, the effects of slag cement grade, and its interaction with various sources of cements. The batching and testing matrix is shown in Table 1.

2.1 Materials

Two sources of Type I portland cement were used in this study. The two cement sources are identified as Cement A and Cement B. The chemical analyses of the cements are shown in Table 2. The fine aggregate was washed rived sand. The coarse aggregate was crushed limestone with a maximum size aggregate of 25 mm. The chemical compositions and the slag activity indices of the ASTM C 989 Gr. 100 and Gr. 120 slag cements are shown in Table 3 and 4, respectively. The slag activity index is the ratio of the compressive strength of the slag cement mortar to the reference mortar (100 percent portland cement) multiplied by 100. By definition (ASTM C 989), Gr. 100 slag cement has a slag activity index of at least 75 and 95 at seven and 28 days of age, respectively. Likewise, Gr. 120 slag cement has a slag activity index of at least 95 and 115 at seven and 28 days of age, respectively.

2.2 Mixtures

The control mixture was representative of a standard mixture design used in transportation related structures by AHTD. The control mixture had a w/cm of 0.45, contained 385 kg/m^3 of cement, and 1,123 kg/m^3 of coarse aggregate. The slag cement mixtures were similar to the control mixture, with the exception of slag cement content and fine aggregate content. All mixtures were developed using the Absolute Volume Method, and therefore, the fine aggregate content varied due to the small changes in volume associated with the slag cement volume.

The mixtures are identified by cement source (A or B), slag cement content (0, 20, 40, or 60% of the total cementitious material), and slag grade (100 or 120). For example, mixture B/60/120 contained cement from source B, and 60% of the cement was replaced with Gr. 120 slag cement. The control mixtures are labeled A/0/0 and B/0/0. The mixture proportions are shown below in Table 5. Two batches of concrete were cast from each mixture design in order to test the repeatability of the mixtures and the properties of the concrete.

Finally, to identify the effects of slag cement on the fresh and hardened concrete properties, chemical admixtures were not used in the study. A high range water reducer (HRWR) or air entraining agent could have used to increase working and improve durability, but the effect of slag cement might have been less pronounced.

Table 1 Testing matrix.

Cement Source	Slag Cement Grade	Slag Cement Replacement Rate (%)[1]			
A	120	0	20	40	60
B	120	0	-	-	60
A	100	0	20	40	60
B	100	0	-	-	60

1 = replacement by weight

Table 2 Cement mineral compositions. (%)

Compounds	Cement A	Cement B
C_3S	56.7	61.0
C_2S	-[A]	13.0
C_3A	10.7	5.9
C_4AF	-[A]	10.3
Na_2O	0.22	-[A]
K_2O	0.29	-[A]
Blaine Fineness (m^2/kg)	367	365

A = Values not provided by cement manufacturer.
C = CaO; S = SiO_2; A = Al_2O_3; F = Fe_2O_3

Table 3 Slag cement chemical compositions. (%)

Oxides	Gr. 100	Gr. 120
SiO_2	40.0	32.0
Al_2O_3	8.0	12.0
Fe_2O_3	0.4	0.6
CaO	36.4	42.0
MgO	12.2	9.0
SO_3	1.06	0.15
Blaine Fineness (m^2/kg)	476	527

Table 4 Slag activity index.

Slag Grade	7 day	28 day
Gr. 100	90	128
Gr. 120	103	131

2.3 Testing procedure

A series of fresh and hardened concrete tests were performed on each mixture. The fresh concrete tests included slump (ASTM C 143), unit weight (ASTM C 138), air content (ASTM C 231), and temperature (ASTM C 1064). The hardened concrete tests included compressive strength (ASTM C 39), freeze-thaw durability (ASTM C 666 A), resonant frequency (ASTM C 215), and rapid chloride ion permeability test (RCPT) (ASTM C 1202).

3. Results & discussions

3.1 Fresh concrete properties

The results from the fresh concrete tests are shown in Table 6. The results shown in the table are the average value of the two

Table 5 Mixture proportions.

Materials	Mixture Proportions (kg/m^3)						
	A/0/0[1]	A/20/100	A/20/120	A/40/100	A/40/120	A/60/100[1]	A/60/120[1]
Cement	385	308	308	231	231	154	154
Slag Cement	0	77	77	154	154	231	231
Coarse Agg.	1123	1123	1123	1123	1123	1123	1123
Fine Agg.	687	682	682	676	676	671	671
Water	173	173	173	173	173	173	173
w/cm	0.45	0.45	0.45	0.45	0.45	0.45	0.45

1. Mixtures were also batched with cement B.

batches cast from each mixture. Limited conclusions can be drawn from the results. For the control mixtures, B/0/0 had a greater slump than its counterpart, A/0/0. This difference could be due to the differences in fresh concrete temperatures or the chemical composition of the cements. The higher ambient temperatures when A/0/0 was cast may have increased evaporation when compared to B/0/0 which would have decreased slump. Another explanation is the higher C_3S content in Cement A. C_3S contributes to early age strength and liberates a significant amount of heat during hydration which could reduce slump.

Mixtures containing Gr. 120 slag cement generally exhibited less slump than their Gr. 100 counterparts which can be attributed to the 51 m^2/kg difference in slag fineness between the two grades of slag cement. When compared to the control mixtures, the addition of Gr. 100 slag increased slump at replacement rates of 20 and 40 percent and no change in slump was observed at 60 percent replacement. For the Gr. 120 slag, at replacement rates of 40 and 60 percent for both cements, a decrease in slump was observed when compared to the control mixtures. This decrease in slump was due to the increase in slag cement fineness when compared to portland cement.

Amongst all mixtures, there was little difference in the unit weight and air content. Since the mixtures contained only entrapped air, the fresh air content ranged from 1.2 to 1.7 percent. The unit weights ranged from 2,382 kg/m^3 to 2,428 kg/m^3.

3.2 Hardened concrete properties

3.2.1 Compressive Strength

Compressive strength was tested at 1, 7, 28, and 90 days of age. The compressive strengths are listed in Table 7. The compressive strength results are the average of six test specimens, three from each of the replicate batches.

The one day values (Table 7) show that increases in slag content for Gr. 100 and Gr. 120 slag decreased compressive strength. For the Cement A mixtures, the mixtures containing Gr. 120 slag performed better than their Gr. 100 counterparts. The results also show that at early ages, Cement B did not perform as well as Cement A at a replacement rate of 60 percent. At one day of age, Cement A mixtures containing 60 percent slag cement (Gr. 100 and Gr. 120) had achieved 4.9 and 5.6 MPa but the identical mixtures containing Cement B had not reached final set. Upon examination of the cement compositions in Table 2, the differences could be attributed to the lower C_3A content in Cement B (10.7 percent versus 5.9 percent) which plays a significant role in the setting of portland cement concrete.

At seven days of age, all mixtures had achieved at least 28 MPa which is equal to or greater than the required 28 day compressive strength for pavements and bridge decks in AR. With the exception of one mixture (A/40/100), all mixtures containing slag had compressive strengths less than their respective control mixture. Unlike the one day results, there were no evident trends in the performance of mixtures containing Gr. 100 slag cement versus mixtures containing Gr. 120 slag cement. Likewise, with the exception of mixture A/40/100, it appears that cement source had little effect on strength (the decrease in compressive strength was approximately same for the Cement A and Cement B mixtures).

At 28 days of age, Cement A mixtures containing Gr. 120 slag cement had lower compressive strengths than the control mixture. This was also the case for two of the Gr. 100 mixtures (A/20/100 and A/60/100). However, there were no definite trends regarding

Table 6 Fresh concrete properties.

Mixture Designation	Slump (mm)	Unit Weight, (kg/m^3)	Air Content, (%)	Concrete Temp. (°C)
A/0/0	45	2,426	1.4	32.1
A/20/100	65	2,428	1.6	28.0
A/20/120	65	2,397	1.5	27.6
A/40/100	65	2,395	1.3	26.9
A/40/120	20	2,410	1.5	20.3
A/60/100	45	2,384	1.4	28.3
A/60/120	20	2,399	1.6	22.5
B/0/0	80	2,403	1.7	26.7
B/60/100	80	2,386	1.2	27.8
B/60/120	70	2,382	1.5	25.6

Table 7 Hardened concrete properties.

Mixture Designation	Compressive Strength (MPa)				RCPT (Coulombs)		Durability Factor (%)
	1 day	7 days	28 days	90 days	28 days	90 days	
A/0/0	15.7	45.0	54.1	56.9	4,265	3,611	2
A/20/100	12.7	39.4	43.9	59.5	1,957	701	10
A/20/120	14.1	39.5	49.1	57.8	2,442	1,433	24
A/40/100	8.5	50.1	58.1	63.1	1,035	625	6
A/40/120	9.1	40.2	52.8	61.3	1,719	630	23
A/60/100	4.9	31.7	50.1	55.8	480	398	1
A/60/120	5.6	35.5	47.6	54.6	937	565	23
B/0/0	14.3	34.3	43.7	54.1	1,568	1,442	3
B/60/100	0	29.9	40.2	54.3	533	341	15
B/60/120	0	31.9	44.1	47.9	821	669	7

slag content or slag grade. For half of the mixtures, those containing Gr. 100 slag had greater compressive strengths than the Gr. 120 mixtures. This is somewhat expected since the slag activity index is almost identical for the two slags at 28 days of age.

By 90 days of age, mixtures containing Gr. 100 slag cement had higher compressive strengths than like mixtures containing Gr. 120 slag cement. This was most likely due to similar slag activity indices at 28 days of age for the two slag cements. Also, all mixtures except for the two containing 60 percent slag, had higher strengths than the control mixtures.

3.2.2 Rapid Chloride Penetrability Test

The Rapid Chloride Penetrability Test (RCPT) was performed according to ASTM C 1202. The results of the test are shown in Table 7. The permeability values reported in Table 7 are the average of eight specimens, four specimens from each of the twin batches. Table 8 shows the corresponding penetrability values associated with the charge passed.

At 28 days, the addition of slag cement reduced the penetrability when compared to the control mixtures. For both cements, mixtures containing Gr. 100 slag cement saw a greater reduction in penetrability than their Gr. 120 counterparts. Mixtures containing Gr. 120 slag cement and mixtures containing Gr. 100 slag cement decreased in penetrability for each 20 percent increase in replacement rate. This trend was also observed at 90 days. As with the compressive strength results, at both 28 day and 90 days of age, mixtures containing Gr. 100 slag cement had lower penetrability values than their Gr. 120 counterparts.

3.2.3 Durability

The mixtures' durability was measured using ASTM C 666, Procedure A (mixtures were frozen and thawed in water). The durability factors, a comparison of the dynamic modulus of elasticity of the sample before and after testing, are shown in Table 7. Most researchers agree that concrete mixtures with durability factors of 60 or more have adequate frost resistance.

As previously mentioned, the mixtures were not air entrained to identify true differences in the durability of the mixtures. As expected, all mixtures performed poorly. However, there were some trends in the data. When compared to the control mixtures, the addition of slag cement improved concrete durability. The mixtures containing GR. 120 slag performed better their respective control mixtures. For Cement A, Gr. 120 slag cement mixtures possessed better durability than like mixtures containing Gr. 100 slag. Also for Cement A and Gr. 120 slag cement, replacement rate had little effect on durability. However, this was not the case for the Gr. 100 mixtures cast with Cement A. The durability factors decreased as Gr. 100 slag cement content increased.

When comparing Cement A to Cement B, the control mixtures' performance was very similar. However, at 60 percent replacement rate, Cement B's GR.100 mixture (B/60/100) displayed a slightly improved durability (DF = 15) when compared to Cement A's mixture (A/60/100) which had a DF of 1. Furthermore, Cement B performed better with Gr. 100 slag cement than Gr. 120 slag cement.

There are concerns regarding the MgO content and concrete durability. The hydration of MgO is an expansive reaction that can deteriorate the cement matrix.[10] The MgO content for the slag cement included in this study was 12.2 percent for the Gr. 100 slag and 9.0 for the Gr. 120 slag. It is possible that the MgO content of the Gr. 100 slag cement played a role in reducing the durability of the Cement A mixtures. Other researchers have reported durability that was equal to or better in slag cement mixtures with MgO content of 8.76 when compared to control mixtures.[11] However, others have observed greater expansion in slag cement prisms with a content of 13.7 percent when compared to control specimens.[12] Likewise, others have reported lower permeability in slag cement mixtures with MgO content of 14.7 percent.[13] Therefore MgO content should not necessarily be a deterrent from using certain slag cements, but the users should be aware of possible expansion reactions that may occur which could lead to cracking and durability problems when using high volumes of slag cement.

4. Conclusions

The research results show that higher replacements of cement by weight with slag cement is beneficial. The results show that slag cement contents that account for 60 percent of the cementitious improve concrete durability and reduced permeability while being able to achieve the required 28 day compressive strength of 28 MPa. As for slag cement grade, there was little difference in the performance of the Gr. 100 and Gr. 120 mixtures which was due to the slag activity index of the Gr. 100 slag. If a Gr. 100 slag cement had been used that had lower a 28 day slag activity index, differences in concrete performance would have been more evident. Finally, the slag cement performed well when used with either Cement A or Cement B. The differences in strength between Cement A and Cement B mixtures were due to the cement which is evident by the lower compressive strength attained by the control mixture cast with Cement B.

Acknowledgements

The authors would like to thank the Arkansas Highway and Transportation Department for providing the support for the research project. The authors would also like to thank Buzzi Unicem USA, Headwaters Resources Inc., Ash Grove Cement, and Holcim Inc. for providing the materials used in the project. The views and opinions expressed by the authors do not reflect the views of opinions of the research sponsor.

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