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DAMAGE DUE TO ABRASION IN SCC CONTAINING DIFFERENT SUPPLEMENTARY CEMENTING MATERIALS

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Abstract: This investigation evaluates and compares the abrasion resistance of various self-consolidating concrete (SCC) mixtures. A normal concrete (NC) mixture with higher coarse-to-fine aggregate ratio was also tested for comparison. Various supplementary cementing materials (SCMs) were tested under the rotating cutter method for abrasion resistance. The effect of using different SCMs in SCC mixtures including fly ash, metakaolin (MK), silica fume, and slag on the abrasion resistance of SCC was examined. Results from the abrasion tests indicated that the SCC mixture containing MK had the highest abrasion resistance among all tested mixtures. The results also indicated that SCC mixtures showed improved abrasion resistance compared to NC mixture in terms of average wear depth and percent of weight loss.

1 INTRODUCTION

Self-consolidating concrete (SCC) is a highly workable concrete intended for use in heavily reinforced or hard-to-reach areas (Rao et al. 2012, Safiuddin et al. 2012, Aslani 2013, Abouhussien et al. 2015). SCC can be produced through the use of chemical admixtures to reduce the water content, decreasing the proportions of coarse aggregate in the mixture and/or incorporating supplementary cementing materials (SCMs) such as fly ash, silica fume, metakaolin, and/or natural pozzolans (Lachemi et al. 2007, Das and Chatterjee 2012, Karahan et al. 2012, Abouhussien and Hassan 2014). Similar to any concrete, SCC can be subject to various types of deterioration, depending on the type of the structure and its exposure condition. One of the most important types of this deterioration is the abrasion of concrete surfaces.

Abrasion is a form of natural attack on concrete, which can be defined as the process of scraping or wearing away of a material. Concrete abrasion can occur in several ways, including wear on floors due to human traffic, wear due to vehicles, abrasive substances in flowing water, and/or high-velocity waters that create cavitation (Scott and Safiuddin 2015). Abrasion can also occur in areas with heavy ice flow when concrete is used in Arctic environments (Scott and Safiuddin 2015). Resistance to abrasion depends on the hardness of the concrete (aggregate and paste hardness combined) and the aggregate/paste bond (Papenfus 2003). Aggregate hardness is a very important aspect as it makes up the majority of the mix proportions (Papenfus 2003). In the case of SCC, less coarse aggregate is used, putting more dependence for the abrasion resistance on the paste.

Abrasion resistance of concrete can be increased by increasing the binder content (at a given water content), using SCMs (which may depend on the age of testing), using superplasticizers to optimize the water content, applying sufficient consolidation, and/or using more durable aggregates (Papenfus 2003, Turk and Karatas 2011). Abrasion resistance of concrete can be tested in a variety of ways according to the available ASTM standards. For example, ASTM C779 tests the abrasion resistance of horizontal concrete surfaces in three different test setups depending on the type and degree of abrasive force (ASTM 2012a). Also, the ASTM C418 method evaluates the abrasion resistance of concrete via sandblasting (ASTM 2012b). This procedure simulates the action of waterborne abrasives and abrasives under traffic on concrete surfaces. On the other hand, ASTM C1138 is an underwater concrete abrasion test intended to simulate the behaviour of swirling water containing transported solid objects that produce abrasion of concrete and cause potholes and related effects (ASTM 2012c). The simplest abrasion test setup used in the literature on various concrete types is the ASTM C994 rotating cutter method (ASTM 2012d). This test method has proven successful in past studies of highway and bridge concrete surfaces subject to traffic (Dong et al. 2013).

The utilization of SCMs in the SCC mixtures is anticipated to improve their abrasion resistance. Previous studies on normal-vibrated concretes confirmed that fly ash class C and F showed better abrasion resistance than Portland cement concrete (Liu 1981). Similarly, silica fume concrete has shown to be more resistant to wear with increasing amounts of the material, up to 10% (Ghafoori and Diawara 1999). Turk and Karatas (2011) evaluated the abrasion of SCC with varying dosages of fly ash and silica fume through the use of the ASTM C779 test. Their results showed that the SCC with silica fume had the least amount of wear (Turk and Karatas 2011). Yet, the effect of including other types of SCMs (such as metakaolin and slag) on the abrasion resistance of SCC mixtures is lacking. The main objective of this study is to evaluate the abrasion resistance of variable SCC mixtures (with different SCMs) in comparison with normal-vibrated concrete.

2 EXPERIMENTAL PROCEDURE

2.1 Materials Properties and Mixture Design

Six concrete mixtures were developed and tested in this study. Four of the six mixtures were SCC containing fly ash (FA), metakaolin (MK), silica fume (SF), and ground granulated blast furnace slag (SG). The other two tested mixtures were plain SCC and normal concrete (NC), chosen to act as control mixtures. The four mixtures with SCMs had replacement proportions of 30% FA, 20% MK, 8% SF, and 30% SG. These replacement levels were obtained from a previous study (Abouhussien and Hassan 2015) conducted to evaluate the optimum percentage of each of these SCMs in concrete. All tested mixtures had a total cementitious content of 500 kg/m^3. The water-to-binder (W/B) ratio was set at a constant value of 0.4 in this investigation. The coarse-to-fine aggregate (C/F) ratio was 0.7 for the SCC mixtures and 2.0 for the normal-concrete mixture. The normal-concrete mixture was designed with the same binder content and W/B ratio as the other tested SCC mixtures to highlight the influence of increasing the C/F ratio on the abrasion resistance. A high-range water-reducing admixture (HRWRA) was used in the SCC admixtures to maintain proper workability and to create adequate slump flow in the range of ~700 ± 50 mm, as per ASTM C1611 (ASTM 2009). Each of the six tested mixtures used type GU Canadian Portland cement conformed to ASTM Type I with a specific gravity of 3.15 (ASTM 2017). The two types of aggregate used were natural sand and 10-mm coarse aggregate. Both aggregates had a specific gravity of 2.6 and water absorption of 1%. The specific gravities of FA, MK, SF, and SG were 2.38, 2.5, 2.27, and 2.9, respectively. The HRWRA used was similar to that described in ASTM C 494 Type F (ASTM 2013), with a specific gravity of 1.2 and pH of 9.5. Table 1 shows the details of the six mixtures developed in this study.

Table 1: Mixture proportions

Mixture Type	Cement (kg/m^3)	SCM (%)	SCM (kg/m^3)	C/F	W/B	C.A. (kg/m^3)	F.A. (kg/m^3)	Water (kg/m^3)	HRWRA (l/m^3)
NC	500	0	0	2.0	0.4	1111.5	555.8	200	0
SCC	500	0	0	0.7	0.4	686.5	980.8	200	2.37
FA	350	30% FA	150	0.7	0.4	670.0	957.2	200	2.08
MK	400	20% MK	100	0.7	0.4	677.7	968.1	200	5.42
SF	460	8% SF	40	0.7	0.4	681.3	973.2	200	4.17
SG	350	30% SG	150	0.7	0.4	682.1	974.5	200	2.25

2.2 Test Sample Details and Abrasion Test

For each mixture, three cylinders and three prisms were cast. All specimens were cured at 25°C in a moist-curing room for a period of 28 days before testing. The cylinder samples were used to test the compressive strength according to ASTM C39 (ASTM 2011), while the prism samples were cut into three 100-mm cubes for the preparation of the ASTM C944 abrasion test (ASTM 2012d). The abrasion test consisted of a drill press with a chuck capable of holding and rotating the cutter and constantly applying a force of 98 N on the specimen being tested (Figure 1). The abrasion test was set to run for six rounds, one-minute intervals each, with a total abrasion time of six minutes. The weight loss of the specimens was taken after each of the one-minute intervals to calculate the mass loss due to abrasion. In addition to measuring the weight loss, the depth of wear resulting from abrasion was also estimated using electronic calipers. Each mixture has three samples undergo the abrasion and compression testing to estimate the average result.

Figure 1: Abrasion test setup

3 RESULTS AND DISCUSSION

As previously stated, the weight loss for each sample was measured during the abrasion test at one-minute intervals for a total of six minutes. The wear depth was also measured to further show the physical effects of the abrasion on the concrete. The results from this data collection during testing can be seen in Tables 2 and 3. Figure 2 presents the average weight loss plotted against time after each minute for all tested samples. The average weight loss was calculated by taking the average results of the three replicated samples of each mixture. It appears from Figure 2 that the weight loss followed a linear relationship over time. The tested samples lost more weight as the time increased up to six minutes. This linear relationship could be related to that the increase in the depth of wear was more associated with a wear in the fine materials rather than the coarse aggregate particles.

Table 2: Percent loss due to abrasion during testing

Mixture Name	Sample Number	Percent Loss (%)						Average Percent Loss (%)	Standard Deviation of Average Percent Loss (%)
		1 min	2 min	3 min	4 min	5 min	6 min		
NC	S1	0.21	0.35	0.46	0.53	0.64	0.7		
	S2	0.18	0.35	0.43	0.5	0.58	0.63	0.64	0.04
	S3	0.18	0.31	0.41	0.47	0.53	0.6		
SCC	S1	0.17	0.33	0.46	0.59	0.66	0.76		
	S2	0.09	0.14	0.22	0.27	0.35	0.4	0.59	0.15
	S3	0.16	0.32	0.41	0.5	0.54	0.6		
FA	S1	0.11	0.19	0.27	0.36	0.45	0.53		
	S2	0.17	0.32	0.48	0.61	0.72	0.8	0.68	0.11
	S3	0.13	0.26	0.38	0.5	0.61	0.7		
MK	S1	0.08	0.15	0.21	0.27	0.31	0.38		
	S2	0.09	0.18	0.26	0.34	0.42	0.46	0.43	0.04
	S3	0.11	0.18	0.33	0.36	0.39	0.46		
SF	S1	0.11	0.22	0.31	0.38	0.44	0.5		
	S2	0.11	0.19	0.28	0.35	0.41	0.47	0.50	0.02
	S3	0.13	0.24	0.34	0.4	0.47	0.52		
SG	S1	0.12	0.24	0.32	0.4	0.44	0.48		
	S2	0.13	0.31	0.36	0.46	0.51	0.56	0.55	0.05
	S3	0.17	0.31	0.4	0.48	0.52	0.6		

Table 3: Wear depth and compressive strength

Mixture Name	Sample Number	Wear Depth (mm)	Average Wear Depth (mm)	Standard Deviation of Average Wear Depth (mm)	Compressive Strength (MPa)	Average Compressive Strength (MPa)	Standard Deviation of Average Compressive Strength (MPa)
	S1	1.08			52.1		
NC	S2	0.97	0.99	0.07	51.5	52.5	0.97
	S3	0.92			53.8		
	S1	0.80			54.7		
SCC	S2	0.84	0.93	0.16	53.8	54.4	0.40
	S3	1.15			54.6		
	S1	0.77			50.7		
FA	S2	1.44	1.18	0.29	52.3	51.5	0.65
	S3	1.34			51.4		
	S1	0.61			73.2		
MK	S2	0.70	0.60	0.08	72.5	72.6	0.31
	S3	0.50			72.6		
	S1	0.31			69.8		
SF	S2	0.78	0.66	0.25	67.9	68.7	0.80
	S3	0.88			68.4		
	S1	0.94			60.9		
SG	S2	0.83	0.86	0.06	57.3	58.6	1.59
	S3	0.81			57.8		

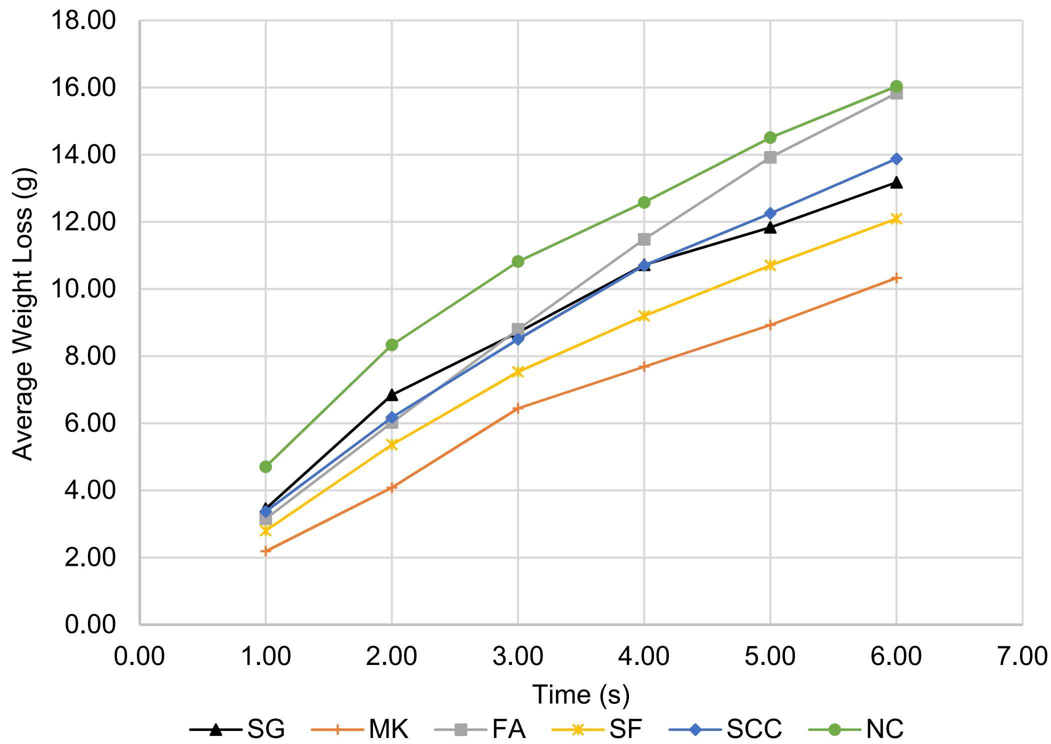

Figure 2: Average weight loss (g) versus time (s)

3.1 Effect of Concrete Type on Abrasion Resistance

Two types of concrete were evaluated in this study: SCC and NC (with a higher C/F ratio). The NC mixture showed an average wear depth of 0.99 mm and average percent loss of 0.64%. Also, the average compressive strength of the NC mixture at 28 days was 52.4 MPa. In comparison, the SCC mixture (without SCMs) had improved results with an average wear depth and percent loss of 0.93 mm and 0.59%, respectively, and an average compressive strength of 54.3 MPa. As seen in Figure 2, above the trend in the SCC mixture line is much lower than the NC mixture line. It should be noted that the percentage of C/F ratio in the mixture plays an important role in concrete abrasion. In this investigation, both SCC and NC mixtures had relatively high cement content (500 kg/m^3) and relatively low W/B ratio (0.4), creating a stronger paste to resist abrasion. And because SCC had higher mortar content (less coarse aggregate), it showed higher resistance to abrasion compared to NC mixtures. This reasoning would only be valid in the case that the strength of the mortar is higher than that of the coarse aggregates. In addition, studies show that optimum compaction is valuable for good abrasion resistance (Papenfus 2003). SCC is inherently more compactable than NC, giving it that added advantage (improved abrasion resistance). It is worth noting that, the increase in the compressive strength of SCC compared to NC mixture could also be another reason of the higher abrasion resistance of SCC over the NC counterpart.

3.2 Effect of SCMs on Abrasion Resistance

Figure 2 shows the average weight loss over time due to abrasion in all tested mixtures. Significant variations in the abrasion damage were observed from this figure among the tested SCC mixtures with different SCMs. The MK mixture proved to have the highest abrasion resistance of all tested mixtures, with a total average percent loss of 0.43% (Table 2). This result was anticipated as the compressive strength is correlated to the abrasion resistance (Scott and Safiuddin 2015); this mixture also had the highest average compressive strength at 28 days (seen in Table 3). Moreover, MK has a very high pozzolanic reactivity, which makes the paste of this mixture much stronger and leads to a higher abrasion resistance. NC and FA mixtures had the least abrasion resistance as they also had the lowest values for average compressive strength. The results of surface wear depth also showed a similar trend of variation as the variation in wear loss. MK samples had the least amount of wear depth (0.60 mm) and FA samples had the most (1.18 mm). The SCC mixtures with SCMs are ranked from the lowest to highest abrasion resistance as follows: FA, SG, SF, and MK. The average percent loss and wear depth due to abrasion of these SCMs mixtures, in that order, were 0.68%, 0.55%, 0.50% and 0.43%, and 1.18, 0.86, 0.66, and 0.6 mm, respectively. In general, the results of SCC with SCMs were significantly better than the NC and SCC control mixtures. These results matched the outcomes of a previous study, which indicated that the addition of silica fume as an SCM to NC and SCC significantly improved its abrasion resistance (Ghafoori and Diawara 1999, Turk and Karatas 2011). The only exception to this rule is the FA mixture, which had higher percentage of weight loss and larger wear depth compared to the NC mixture. However, the compressive strength of FA mixture was slightly lower than NC mixture, which can directly affect the abrasion resistance of a mixture.

4 CONCLUSIONS

The rotating cutter method of abrasion was used to test the abrasion resistance of various concrete mixtures. The types of these tested mixtures were: NC, SCC, and SCC with various SCMs. An extensive analysis of the collected abrasion data was completed post-testing, which determined the effect of concrete type and SCMs on the abrasion resistance. This analysis gave the following conclusions:

- Regarding the effect of concrete type on the materials resistance to abrasion, the control SCC mixture (without SCMs) had a lower average percentage of abrasion mass loss and wear depth as well as an increased compressive strength compared to its NC counterpart.
- Varying the SCM type in the SCC mixtures yielded evident changes in the abrasion resistance as obtained from the tests performed herein. The abrasion resistance of the SCC mixtures containing SCMs can be ranked in order from highest to lowest as MK, SF, SG, and FA.
- The mixture with the highest abrasion resistance overall was the SCC mixture containing 20% MK. This mixture showed the lowest percent loss, wear depth, and highest compressive strength. On the other hand, the SCC mixture with 30% FA exhibited the least performance with respect to the average percent loss and compressive strength.
- This study proved that the usage of SCMs in self-consolidating concrete was beneficial in being capable of resisting abrasion when compared to NC and plain SCC. SCC is an excellent high performing concrete which would be sufficient for use in areas where abrasion damage is a concern.

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