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Detection of Abrasion Damage in Self-Consolidating Concrete Using Acoustic Emission Monitoring

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Abstract**:** *This paper utilizes the acoustic emission (AE) analysis to detect and assess the abrasion damage in self-consolidating concrete (SCC). SCC with variable 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. In conjunction with the abrasion testing, AE monitoring was simultaneously conducted on all mixtures using AE attached sensors. AE parameters such as signal amplitude, signal strength, number of hits, duration, and cumulative signal strength (CSS) were collected during the abrasion tests. The studied AE parameters including CSS and number of hits were well correlated to the extent of abrasion damage in all tested specimens. The progression of abrasion damage was associated with increased AE activities indicated by ever-increasing values of CSS and number of hits.*

Keywords: *abrasion, self-consolidating concrete, acoustic emission, damage detection*.

1. Introduction

Self-consolidating concrete (SCC) is a highly workable concrete intended for use in heavily reinforced or hard-to-reach areas [1-5]. 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 [6-10]. 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 surface.

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 [11]. Abrasion can also occur in areas with heavy ice flow when concrete is used in Arctic environments [11]. Resistance to abrasion depends on the hardness of the concrete (aggregate and paste hardness combined) and the aggregate/paste bond [12]. Aggregate hardness is a very important aspect as it makes up the majority of the mix proportions [12]. In the case of SCC, less coarse aggregate is used, putting more dependence for the abrasion resistance on the paste.

Acoustic emission (AE) is a method of non-destructive testing (NDT) and structural health monitoring (SHM) of civil infrastructure. It can be useful when visual inspection cannot be carried out and/or when regular site visits for physical monitoring are not feasible. AE occurs when transient waves are generated from a localized area due to any damage within a solid material [13]. AE sensors gather these waves and the data can

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then be analyzed to quantify and characterize the types of damage that may have occurred and identify the source location of this damage [13]. AE technique has a wide variety of uses in NDT and SHM for concrete materials/structures. For example, AE monitoring has been used to detect and quantify various damage mechanisms in concrete, including corrosion of steel in concrete [13-16], assessment of concrete-to-steel bond behaviour [17-20], detection of bond failure in the anchorage zone of reinforced concrete beams [21-22], and many other structural applications.

AE has yet to be used to monitor damage due to abrasion, thus warranting further investigation. AE technique can be used to remotely monitor concrete abrasion or surface wear in areas difficult to access or inspect. For instance, offshore structures, which may be exposed to ice abrasion, could be monitored using AE sensors. The main objective of this study is to utilize AE monitoring to detect the damage due to abrasion in variable SCC (with different SCMs) and normal-vibrated concrete mixtures. The study attempts, in particular, to relate the damage from the abrasion to the recorded AE activity during the abrasion test. This relation will then lead to being able to diagnose the damage from the abrasion by evaluating the signals given off by the AE phenomenon and gathered by the sensors..

2. Experimental Program

2.1. Materials

Five 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 tested mixture was plain SCC chosen to act as a control mixture. 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 [7] conducted to evaluate the optimum percentage of each of these SCMs in concrete. All tested mixtures had a total cementitious content of 500 kg/m3. 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 all mixtures. 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 [23]. Each of the tested mixtures used type GU Canadian Portland cement conformed to ASTM Type I [24] with a specific gravity of 3.15. 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 [25], with a specific gravity of 1.2 and pH of 9.5. Table 1 shows the details of all mixtures developed in this study.

TABLE I: Mixture Proportions

Mixture type	Cement (kg/m^3)	SCM (kg/m^3)	C.A. (kg/m^3)	F.A. (kg/m^3)	Water (kg/m^3)	HRWRA (l/m^3)
SCC	500	0	686.5	980.8	200	2.37
FA	350	150	670.0	957.2	200	2.08
MK	400	100	677.7	968.1	200	5.42
SF	460	40	681.3	973.2	200	4.17
SG	350	150	682.1	974.5	200	2.25

2.2. Test Setup

For each mixture, three prism specimens were cast. All specimens were cured at 25°C in a moist-curing room for a period of 28 days before testing. The prism samples were cut into three 100-mm cubes for the preparation of the ASTM C 944 [26] abrasion test. 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 (Fig. 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 tests to estimate the average result. Piezoelectric AE sensors with integral preamplifier (model R6I-AST) were attached to the cube samples and connected to a data acquisition system to record the signals being emitted during the test. The system has a set amplitude threshold of 40 dB and a full list of the other parameters can be found elsewhere [13]. The amplitude, signal strength, duration, energy and absolute energy, counts, rise time, average frequency, and peak frequency were detected and recorded during the test. Full descriptions of these parameters and more information on AE terminology can be found in the ASTM E 1316 [27].

Fig. 1: Test setup.

3. Results and Discussion

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 Table 2. Fig. 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 Fig. 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 II: Abrasion Percent Loss

Mixture name	Sample number	Percent loss (%)						Average percent loss (%)	Wear depth (mm)	Average wear depth (mm)
		1 min	2 min	3 min	4 min	5 min	6 min			
SCC	S1	0.17	0.33	0.46	0.59	0.66	0.76	0.59	0.80	0.93
	S2	0.09	0.14	0.22	0.27	0.35	0.40		0.84	
	S3	0.16	0.32	0.41	0.50	0.54	0.60		1.15	
FA	S1	0.11	0.19	0.27	0.36	0.45	0.53	0.68	0.77	1.18
	S2	0.17	0.32	0.48	0.61	0.72	0.80		1.44	
	S3	0.13	0.26	0.38	0.50	0.61	0.70		1.34	
MK	S1	0.08	0.15	0.21	0.27	0.31	0.38	0.43	0.61	0.60
	S2	0.09	0.18	0.26	0.34	0.42	0.46		0.70	
	S3	0.11	0.18	0.33	0.36	0.39	0.46		0.50	
SF	S1	0.11	0.22	0.31	0.38	0.44	0.50	0.50	0.31	0.66
	S2	0.11	0.19	0.28	0.35	0.41	0.47		0.78	
	S3	0.13	0.24	0.34	0.40	0.47	0.52		0.88	
SG	S1	0.12	0.24	0.32	0.40	0.44	0.48	0.55	0.94	0.86
	S2	0.13	0.31	0.36	0.46	0.51	0.56		0.83	
	S3	0.17	0.31	0.40	0.48	0.52	0.60		0.81	

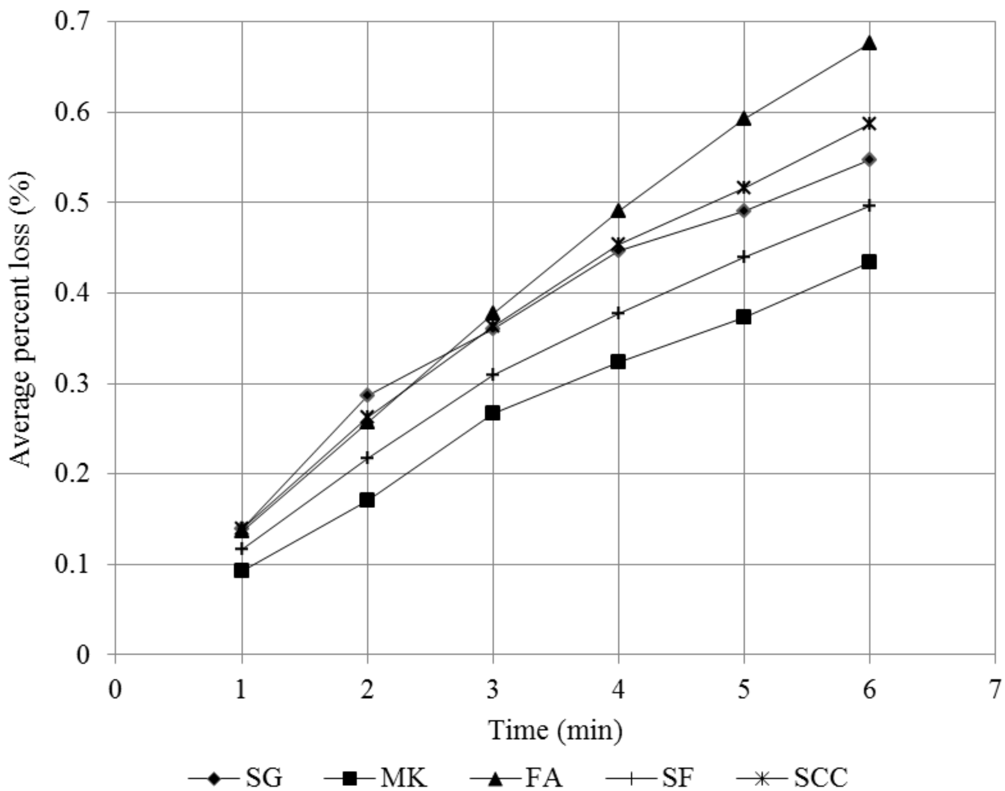

Fig. 1: Percent loss versus time.

3.1. Impact of Abrasion Damage on AE Data

The graphs in Figs. 3 and 4 represent the results of one of the tested samples from this study, as an example. The solid curves in Figs. 3 and 4 show the variations in the cumulative signal strength (CSS) and number of hits, respectively, throughout the abrasion test. The dotted curve in each figure shows the percentage of loss due to abrasion of the same sample over the course of the testing period. The selected sample illustrated was the FA sample number one (FA S1). This sample is used as a representation of results from this test as the rest of the mixtures and each of their samples all followed similar trends. The results of these AE parameters from the rest of the tested samples obtained at one and six minutes can be seen in Table 3. The CSS versus time curve (Fig. 3) showed a continual increase during the test period (reaching a maximum value of 1810 mV.s), matching that of the changes in weight loss due to abrasion. The number of hits versus time (Fig. 4) follows the same patterns as the CSS graph: gradual increase over time. Across the many samples tested, a direct correlation was observed between the abrasion damage and the studied AE parameters (Table 3). More specifically, the values of CSS and number of hits will increase as the amount of weight loss increases due to abrasion over time.

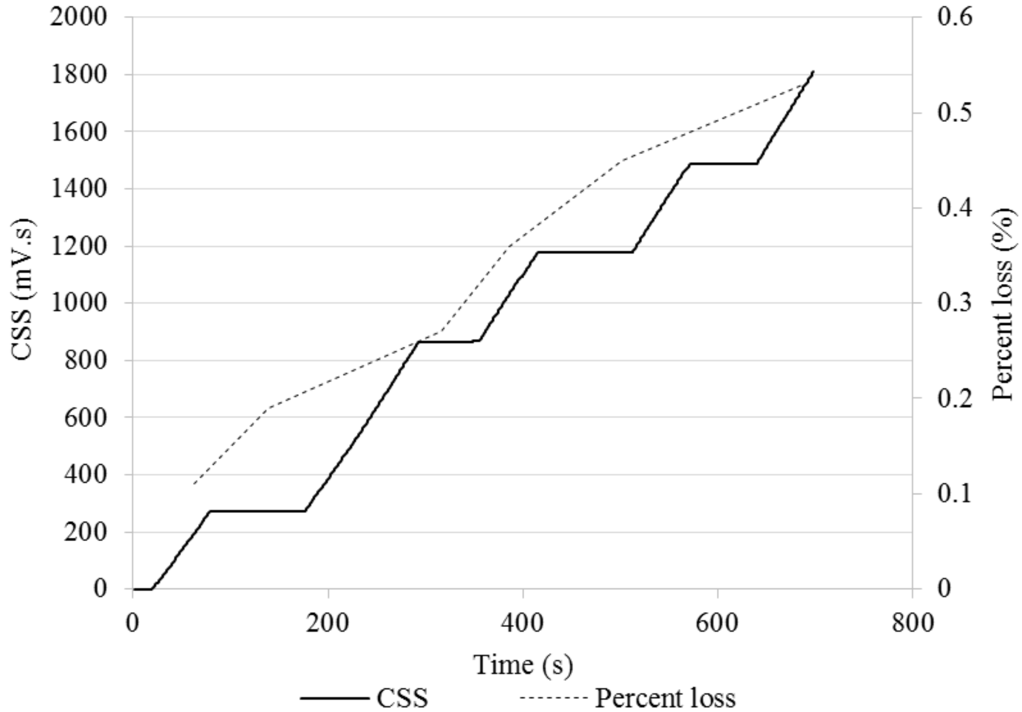

Fig. 2: CSS versus time of FA S1.

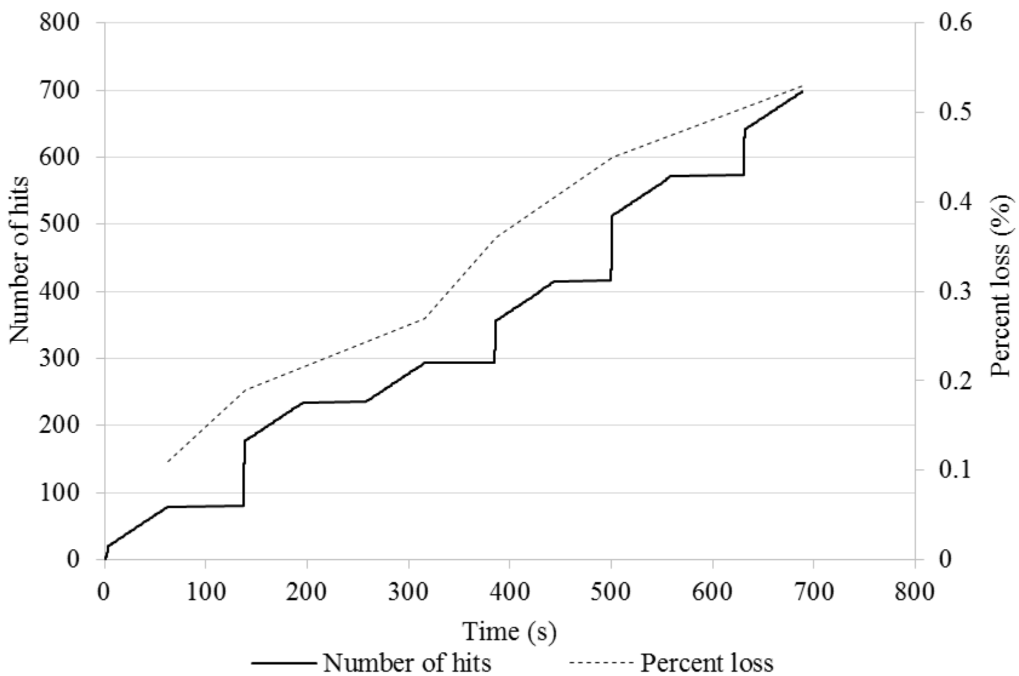

Fig. 3: Number of hits versus time of FA S1.

TABLE III: Number of Hits and CSS for all Mixtures

Mixture name	Sample number	Number of hits		CSS x 10^3 (mV.s)	
		1 min	6 min	1 min	6 min
SCC	S1	115	461	0.36	2.23
	S2	112	391	0.40	2.34
	S3	103	1143	0.37	2.41
FA	S1	79	698	0.27	1.81
	S2	97	1138	0.27	2.75
	S3	103	1026	0.32	2.67
MK	S1	60	407	0.19	2.00
	S2	66	395	0.28	2.14
	S3	65	560	0.29	1.77
SF	S1	77	395	0.26	2.12
	S2	68	604	0.29	2.14
	S3	69	447	0.34	2.24
SG	S1	122	493	0.29	2.15
	S2	120	493	0.31	2.20
	S3	118	559	0.32	2.20

3.2. Impact of SCMs on Abrasion Damage and AE Data

Fig. 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). MK has a very high pozzolanic reactivity, which makes the paste of this mixture much stronger and leads to a higher abrasion resistance. FA mixture had the least abrasion resistance. 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 SCC control mixture. Regarding the AE data, the AE parameters including the number of hits and CSS showed different values for each mixture according to its abrasion performance. For example, the SCC control mixture had an average number of hits of 665 and CSS of 2320 mV.s at the end of the test. The average values of these AE parameters for the MK mixture, in the same order, were 563 and 1970 mV.s indicating improved abrasion resistance (Table 3). This result further confirms the correlation between the increased abrasion resistance and decreased number of hits and CSS magnitudes, indicating a strong correlation between the abrasion resistance and the studied AE parameters in all mixtures.

4. Conclusions

AE monitoring was used while testing the abrasion resistance of various SCC mixtures: SCC control, and SCC with various SCMs. The rotating cutter method of abrasion was used to test the abrasion resistance of the samples, and the samples were monitored with attached AE sensors to collect the AE data emitted during testing. The analysis of the collected AE data was completed post-testing compared with the abrasion results. The analysis and comparisons led to the following conclusions:

- The CSS and number of hits generally increased with test time as the abrasion increased gradually throughout the testing period in all tested samples. These findings reflect the sensitivity of the AE monitoring technique to the abrasion damage in concrete, regardless of SCM type.
- Changing the SCM type in the SCC mixtures had a significant impact on both their abrasion resistance and the studied AE parameters including CSS and number of hits.

• The mixture with the highest abrasion resistance overall was the SCC mixture containing 20% MK. This mixture showed the lowest percent loss and wear depth. On the other hand, the SCC mixture with 30% FA exhibited the least performance with respect to the average percent loss.

• 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 AE parameters studied (CSS and number of hits) also indicated this performance order.

• This study proved the effectiveness of the AE analysis presented in this paper to detect and characterize abrasion damage in concrete based on laboratory tests. Potential uses for this study include offshore structures and areas where typical visual inspection techniques cannot be carried out on-site or in person for extended periods of time.

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