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Effect of Supplementary Cementing Materials on Fresh Properties and Stability of Self-Consolidating Rubberized Concrete

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***Abstract*:** *This study was conducted to investigate the effect of using different supplementary cementing materials on the fresh properties and stability of self-consolidating rubberized concrete. In total, sixteen mixtures with a water-to-binder ratio (0.4), a binder content 550 kg/m^3, varied percentages of crumb rubber (0-40% replacements by fine aggregate volume), and different supplementary cementing materials (SCMs) (fly ash, slag, and metakaolin) were tested. The performance of the developed SCRCs was evaluated based on the results of compressive strength, flowability, passing ability, high-range water-reducer admixture demand, coarse aggregate segregation, and the distribution of CR in the mixture. The results indicated that the fresh properties and strength of the tested mixtures generally decreased as the CR increased. Using 550 kg/m^3 binder content with no SCMs showed acceptable strength, fresh properties, and stability with up to 20% replacement of CR. The results also showed that compared to the other tested SCMs, the addition of metakaolin (MK) significantly improved the mixture viscosity and particle suspension/distribution, which allowed up to 30% CR to be used with acceptable compressive strength (40 MPa) and without any sign of segregation.*

Keywords: *self-consolidating concrete, crumb rubber, metakaolin, fresh properties*

1. Introduction

Owing to the large expansion in the automobile industry around the world, huge volumes of scrap tyres have become a potential waste management problem [1]. Based on 2002 UK statistics, the number of used tyres was estimated to be 37 million annually and this number continues to increase every year [2]. In the United States this number reached up to more than 275 million scrap tyres per year [3]. During the last two decades, intensive research has been carried out studying the properties and potential uses of rubber in engineering applications, especially in concrete as a replacement for fine and coarse aggregate. Reutilization of waste rubber (from scrap vehicle tyres) in the construction industry has a direct impact on limiting environmental pollution [4]. As well, the low density of rubber aggregate compared to a conventional aggregate can significantly contribute to developing semi-lightweight and lightweight concrete that can help to reach a more economical design of building [4].

Recently, researchers investigated the effect of adding crumb rubber on the fresh and hardened performance of self-consolidating concrete (SCC). The previous studies reported that rubberized SCC with a slump flow ≥ 600 mm, a reduction of J-ring ≤ 50 mm, and a $T_{50} \leq 5$ s requires a significant increase in super plasticizer dosage [5]. This finding agrees with that reported by Güneyisi [6] and Topçu and Bilir [7]. Güneyisi [6] stated that increasing the rubber content caused an increase in T_{50}, V-funnel flow times, and viscosity, but using rubber and fly ash together reduced the viscosity of the mixture. Topçu and Bilir [7] observed that increasing the rubber content increased the fluidity, but with an increased risk of segregation. Turatsinze and Garros [8] developed SCRC by using chipped rubber as a coarse aggregate, but the reduction of strength reached up to 33% and 73%

at 10% and 25% replacements of sand by rubber, respectively. In general, the losses in compressive strength of SCRC were found to be lower than in plain rubberized concrete [9] due to improvement in the microstructure of SCRC that enhances the ITZ.

Development of SCRC needs a high-viscous mixture to improve the particle suspension and reduce the risk of segregation. Increasing the particle suspension of SCRC mixtures can be achieved by incorporating rich binder content and/or supplementary cementing materials (SCMs). One of the most effective SCMs that proved to enhance the mixture viscosity is metakaolin (MK). Recent research [10] has shown that using MK in SCC improves the passing ability and increases the viscosity of the mixtures. The increased viscosity helps to improve the aggregates' suspension in the mixture, prevent coarse aggregate segregation, and keep the mixture homogeneous [11]. Hassan et al. [10] reported that including MK in SCC mixtures greatly improved the viscosity and mechanical properties of mixtures. Madandoust and Mousavi [12] found that using MK enhanced the stability of SCC mixtures; however, making highly flowable concrete cannot be practically achieved without adding large amounts of HRWRA.

There is a lack of information regarding the fresh properties and stability of SCRC, especially when using metakaolin to improve the stability of the mixture. The main objective of this research was to develop SCRC mixtures with maximum percentage of CR, and minimum segregation and strength reduction. The experimental test parameters included percentage of CR, binder content, coarse aggregate size, air entrained, and different SCMs. The fresh properties tests included slump flow, V-funnel, L-box, J-ring, air content, and sieve segregation tests, while the hardened properties tests included compressive strength and distribution of CR in hardened concrete samples.

2. Experimental Work

2.1. Materials

MK was delivered from eastern United States by Advanced Cement Technologies, conforming to ASTM C 618 Class N. The used slag (SG) and cement (type GU) were similar to that of ASTM Type I, and the used fly ash (FA) was similar to that of ASTM Type F. Natural crushed stones with a maximum size of 10 mm and natural sand were used for the coarse and fine aggregates, respectively. Each aggregate type had a specific gravity of 2.6 and absorption of 1%. A crumb rubber aggregate with a maximum size of 4.75 mm, specific gravity of 0.95, and negligible absorption was used as a partial replacement of the fine aggregate in SCRC mixtures. Glenium 7700 produced by BASF Construction Chemicals was used as an HRWRA to achieve the required slump flow of SCC mixtures. This admixture is similar to ASTM C 494 Type F with specific gravity, volatile weight, and pH of 1.2, 62%, and 9.5, respectively.

2.2. Scope of Work

Stage 1 – Optimizing the Percentage of CR in SCC Mixtures

The main objective of this stage was to obtain the maximum percentage of CR that can be safely used to develop SCRC mixtures with acceptable strength, fresh properties, and stability. In total, seven mixtures were tested in this stage. The percentage of CR varied from 0% to 40% replacement of sand (by volume). A constant coarse-to-fine aggregate (C/F) ratio of 0.7 was chosen for all tested mixtures in this stage. This percentage was chosen based on previous research work [13] carried out on SCC with different C/F ratios. A total binder content of 550 kg/m^3 and 0.4 w/b were used in all tested mixtures in stage 1 and 2. The amount of HRWRA was varied in all tested mixtures to obtain a slump flow diameter of 650 ± 50 mm. The slump flow diameter and J-ring slump diameter were used to evaluate the deformability and the flowability of fresh SCRC. The time to reach 500 mm slump flow diameter and the V-funnel time were used to evaluate the mixture viscosity. These times were accurately measured for all tested SCRC mixtures using videotape recording. L-box heights was measured for all tested mixtures to evaluate the passing ability of SCRC. The segregation resistance (SR) of SCRC mixtures was assessed using a sieve segregation resistance test. All of the aforementioned tests are detailed in the Self-Compacting Concrete Committee of EFNARC (2005). The percentage of the entrained air in the fresh SCRC mixtures was measured by following a procedure given in ASTM C231. The distribution of the rubber particles in the mixture was visually evaluated after splitting 100 mm diameter x 200 mm height concrete cylinder. The stability of rubber was classified into three cases; namely no segregation (NS), moderate segregation (MS), and heavy segregation (HS). The compressive strength was conducted according to ASTM C39. The mixture proportions of SCRC containing different percentages of CR are shown in Table 1.

Stage 2 – Effect of SCMs on the Fresh Properties, Stability, and Strength of SCRC Mixtures

Owing to the low density of the used rubber, the preliminary test results of stage 1 indicated a segregation problem in mixtures containing higher percentages of CR (more than 20%). Moreover, increasing the CR content generally decreased the fresh properties and strength of all tested mixtures. Therefore, stage 2 was designed to improve the fresh properties, stability, and strength of SCRC mixtures in order to allow higher percentages of CR to be used safely in SCRC. This stage investigated the effects of using different SCMs on enhancing the stability, fresh properties, and strength of SCRC in nine SCRC mixtures. The nine SCRC mixtures were detailed as follows: three mixtures containing MK, three mixtures containing slag, and three mixtures containing FA. The mixtures with SCMs contained 20% MK, 30% SG, and 20% FA. The percentages of MK and SG were chosen based on optimal values obtained from previous research [13, 14] carried out with these SCMs, while the 20% FA was used to obtain a reasonable compressive strength in SCRC mixtures [6]. Since the fresh properties were expected to be improved with higher total binder content and the addition of SCM, the CR replacement level in this stage began at 20% and was increased incrementally until either unacceptable SCC fresh properties or very low compressive strengths (less than 17 MPa) were obtained. The mixture proportions of SCRC in this stage are shown in Table 1.

TABLE 1: Mixture Design for SCRC Mixtures

Stage 1								
Mixture	Cement (kg/m^3)	SCM (Type)	SCM (kg/m^3)	C. A. (kg/m^3)	F. A. (kg/m^3)	CR (kg/m^3)	HRWRA (kg/m^3)	Density (kg/m^3)
550C-0CR	550	-	-	648.1	925.9	0.00	1.64	2344.0
550C-5CR	550	-	-	648.1	879.6	16.92	1.71	2314.6
550C-10CR	550	-	-	648.1	833.3	33.83	1.81	2285.3
550C-15CR	550	-	-	648.1	787.0	50.75	1.84	2255.9
550C-20CR	550	-	-	648.1	740.7	67.7	1.84	2226.5
550C-30CR	550	-	-	648.1	648.1	101.5	1.84	2167.8
550C-40CR	550	-	-	648.1	555.5	135.3	2.63	2109.0
550C-20CR-MK	440	MK	110	638.4	729.6	66.7	5.26	2204.7
550C-30CR-MK	440	MK	110	638.4	638.4	100.0	5.26	2146.8
550C-40CR-MK	440	MK	110	638.4	547.2	133.3	6.58	2088.9
550C-20CR-SG	385	SG	165	643.3	735.2	67.2	1.84	2215.7
550C-30CR-SG	385	SG	165	643.3	643.3	100.7	1.84	2157.3
550C-40CR-SG	385	SG	165	643.3	551.4	134.3	2.63	2099.0
550C-20CR-FA	440	FA	110	636.0	726.9	66.4	1.84	2199.3
550C-30CR-FA	440	FA	110	636.0	636.0	99.6	1.84	2141.7
550C-40CR-FA	440	FA	110	636.0	545.2	132.8	2.63	2084.0

Note: All mixtures have a 0.4 w/b ratio; C. A. = Coarse aggregates; F. A. = Fine aggregates; and CR = Crumb rubber

3. Discussion of Test Results

3.1. Effect of the Percentage of CR

3.1.1. HRWRA Demand

The demands of HRWRA for all tested mixtures are presented in Table 1. It can be seen that the addition of 30% CR increased the HRWRA demand by 14.3% (to achieve the target slump flow of 650 ± 50). Meanwhile, this dosage significantly increased when the percentage of CR exceeded 30%. For example, the addition of 40% CR in 550C-40CR showed 60.4% increase in the HRWRA demand compared to the control mixture with no CR.

The result of increasing the HRWRA demand with high percentages of CR agrees with that reported by other researchers [6, 7].

3.1.2. Viscosity and Flowability

The results of T_{50} and V-funnel time were used to evaluate the viscosity and flowability of SCRC mixtures. Increasing the percentage of CR appeared to increase the mixture viscosity and reduce its flowability. These findings are similar to what other researchers have found [6, 8]. Table 2 shows that the T_{50} increased from 0.99 to 2.31 seconds as the percentage of CR increased from 0% to 40%. V-funnel tests also showed the same effect in which the V-funnel time increased from 4.03 to 17.5 seconds as the percentage of CR increased from 0% to 40%. The European Guidelines for Self-Compacting Concrete (2005) specify two viscosity classes for each of T_{50} and V-funnel time: VS1 pertains to mixtures with a T_{50} of less than 2 seconds while VS2 pertains to mixtures with a T_{50} of more than 2 seconds. Meanwhile, VF1 pertains to mixtures with a V-funnel flow time of less than 8 seconds while VF2 pertains to mixtures with a V-funnel flow time ranging from 9 to 25 seconds. The characteristics of the produced SCRCs are specified to be appropriate for a given application. According to this, SCRC mixtures with up to 20% CR can be classified as VS1/VF1 which is recommended to be used in multiple applications such as floors, slabs, piles, and walls. Meanwhile, SCRC mixtures containing 30% to 40% CR can be classified as VS2/FV2, which is recommended to be used in certain applications such as ramps.

3.1.3. Passing Ability

The H2/H1 L-box ratio was used to evaluate the passing ability of all tested mixtures. As seen in Table 2, the addition of CR reduced the passing ability compared to the control mixture (CR = 0). Increasing the percentage of CR from 0% to 40% decreased the L-box by 58.24%. This result is similar to what other researchers have found [5, 6], in which the increased percentage of CR reduced the flowability and passing ability of SCC mixtures. The reduction of the passing ability with the increased percentage of CR could be attributed to the high friction and blocking between crushed stone aggregate and rubber particles. According to the European Guidelines for Self-Compacting Concrete (2005), the recommended value of H2/H1 in the L-box test is 0.75 or greater. A similar limit of the H2/H1 value is given by the Interim Guidelines for the Use of Self-Consolidating Concrete (2003), which indicates potential problems if the value of H2/H1 is less than 0.75 for mixtures used in members with a medium-to-high reinforcement level, medium-to-high element length, low wall thickness, and/or mixtures cast using low placement energy. The results of this stage indicated that the tested mixtures with up to 20% CR replacement showed H2/H1 results match that value recommended by the two guidelines.

3.1.4. Segregation Resistance

The sieve segregation resistance (SR) values were used to evaluate the coarse aggregate segregation of all tested mixtures.Also, as explained earlier, the stability of rubber particles was evaluated visually. As seen in Table 2, the results of SR indicated that the risk of segregation increased as the percentage of CR increased, as expected [7]. Increasing the CR replacement from 0% to 40% raised the SR from 2.1% to 7.1%. All tested mixtures gave values fell inside the acceptable range ($SR \leq 15\%$) for SCC mixtures, as stated in the European Guidelines for Self-Compacting Concrete (2005). Table 2 also shows that no sign of segregation was observed in the hardened splitted cylinders up to 20% CR replacement, but mixtures 30%, and 40% CR appeared to be medium segregated. This finding is attributed to the low density of the rubber (0.95), which makes it easy for the rubber to float toward the concrete surface during mixing.

3.1.5. Compressive Strength

The 28-day compressive strengths of the tested mixtures are shown in Table 2. As seen, increasing the percentage of CR reduced the 28-day compressive strengths. Adding 40% CR decreased the compressive strength by 60.56%. This result is similar to what other researchers have found [1, 15]. The reduction of the compressive strength with higher percentages of CR may be attributed to the poor strength of the ITZ between the rubber particles and surrounding mortar as well as the significant difference between the modulus of elasticity of the rubber and the aggregate. Moreover, increasing the percentage of CR increased the air content (Table 2), which may also have a negative effect on the compressive strength of the mixtures.

According to the results of the fresh properties, stability, and strength of the tested SCRC mixtures in stage 1, it can be concluded that using up to 20% CR with 550 kg/m^3 binder content can achieve reasonable fresh properties, stability, and strength according to the European Guidelines for Self-Compacting Concrete (2005) and the Interim Guidelines for the Use of Self-Consolidating Concrete (2003), as shown in Table 2.

3.2. Effect of SCMs

3.2.1. HRWRA Demand

Table 1 also shows the results of HRWRA demand for varying percentages of CR in SCRC mixtures incorporating SCMs (MK, SG, or FA). The addition of MK showed the greatest increase in the HRWRA demand (compared to the mixtures without SCMs) with an average of 274%, as expected [13]. The HRWRA demand in mixtures with MK ranged from 5.26 to 6.58 kg/m^3 as the percentage of CR varied from 20% to 40%. On the other hand, mixtures with FA or SG showed no difference in HRWRA demand (compared to 550C-20CR, 550C-30CR, and 550C-40CR) as the percentage of CR varied from 20% to 40%.

3.2.2. Viscosity and Flowability

The results also indicated that the viscosity of SCRC greatly increased by adding 20% MK. The T_{50} and the V-funnel times increased by an average of 46.5% and 19.6%, respectively, in MK mixtures compared to the reference mixtures (550C-20CR, 550C-30CR, and 550C-40CR), as shown in Table 2. These results are expected from the replacement of cement with MK [11, 10]. The results also indicated that adding 20% FA or 30% SG increased the flowability of SCRC mixtures compared to mixtures without SCMs (550C-20CR, 550C-30CR, and 550C-40CR). The T_{50} and the V-funnel times of FA mixtures decreased by an average of 27.18% and 10.74%, respectively. With 30% SG the times decreased by an average of 24.58% and 30.24%, respectively, compared to the reference mixtures (550C-20CR, 550C-30CR, and 550C-40CR). The behaviour of SCRC with FA agrees with that reported by Güneyisi [6].

3.2.3. Passing Ability

The addition of MK showed higher L-box values (see Table 2), indicating better passing ability. These results are similar to what other researchers have reported [16]. The H2/H1 ratio of the L-box increased by an average of 42.51% compared to the reference mixtures (550C-20CR, 550C-30CR, and 550C-40CR). In general, the addition of MK allowed the use of up to 30% CR in SCRC mixtures and maintained acceptable fresh properties according to the European Guidelines for Self-Compacting Concrete (2005) and/or the Interim Guidelines for the Use of Self-Consolidating Concrete (2003). The addition of FA and SG in SCRC mixtures also showed some improvement in the passing ability of the mixtures (Table 2). However, this improvement was relatively small compared to that achieved with MK mixtures.

3.2.4. Segregation Resistance

The addition of MK enhanced the stability of SCRC mixtures (Table 2). All mixtures had acceptable SR values based on the European Guidelines for Self-Compacting Concrete (2005). The percentage of SR ranged from 2.1% to 3.1% as the percentage of CR varied from 20% to 40% in MK mixtures. The addition of MK also showed no sign of segregation in the hardened splitted cylinders with up to 40% CR replacement. Although the values of SR for FA and SG mixtures fell inside the acceptable range ($\leq$ 15%), the visual observation of their hardened splitted cylinders showed unsatisfactory results in cases using 30%-40% CR with FA and 40% CR with SG.

3.2.5. Compressive Strength

A significant increase was observed in SCRC mixtures incorporating MK; the results indicated that the 28-day compressive strength increased by 43.4% (on average), compared to mixtures with no SCMs (reference mixtures). This finding agrees with several studies carried out on the effect of MK on SCC mixtures [12, 10]. Using 20% MK contributed to developing SCRC mixtures with up to 40% CR having strength more than 32.95 MPa. The results of SG and FA mixtures showed a slight increase in strength reaching up to 5.7% and 5.4% (on average), respectively.

TABLE 2: Fresh Properties for Tested SCRC Mixtures

Mixture	Slump flow		L-box	V-funnel	SR	Air	CR	f'_c
	D_s (mm)	T_{50} (sec)	H2/H1	T_0 (sec)	%	%	Stability	MPa
550C-0CR	690	0.99	0.91	4.03	2.1	1.4	-	53.50
550C-5CR	700	1.01	0.86	4.90	2.1	1.8	NS	47.07
550C-10CR	700	1.11	0.77	5.11	2.5	2.3	NS	43.39
550C-15CR	710	1.32	0.76	5.97	3.1	3.5	NS	38.45
550C-20CR	700	1.54	0.75	6.65	3.0	3.2	NS	32.81
550C-30CR	625	2.08	0.56	10.50	4.2	3.6	MS	27.05
550C-40CR	650	2.31	0.38	17.50	7.1	4.3	MS	21.10
550C-20CR-MK	680	2.57	0.86	8.25	2.1	3.4	NS	47.33
550C-30CR-MK	620	2.86	0.75	13.50	2.9	4.2	NS	39.83
550C-40CR-MK	660	3.12	0.68	18.60	3.1	4.8	NS	32.95
550C-20CR-SG	705	1.07	0.80	5.90	1.9	3.2	NS	34.59
550C-30CR-SG	670	1.37	0.70	6.30	2.9	5.5	MS	30.64
550C-40CR-SG	660	2.1	0.62	10.6	5.2	6.5	MS	20.75
550C-20CR-FA	700	0.99	0.76	5.90	3.1	3.1	NS	34.15
550C-30CR-FA	655	1.46	0.66	9.5	6.3	4.9	MS	31.02
550C-40CR-FA	650	1.94	0.54	15.5	7.3	5.5	MS	20.58

4. Conclusions

This study investigated the fresh properties and compressive strength of SCRC mixtures. The effect of CR content and different types of SCMs (MK, FA, SG) was studied. The following conclusions can be drawn based on the results described in this paper:

- Increasing the percentage of CR in SCRC mixtures reduced the flowability, passing ability, stability, and compressive strength, while the air content and HRWRA demand increased with higher percentages of CR in SCRC mixtures.
- It is possible to develop successful SCRC mixtures without SCMs with a maximum percentage of CR of 20%. Such mixtures can have a minimum binder content of 550 kg/m^3 and a minimum w/b ratio of 0.4. Using a percentage of CR higher than 20% will result in a significant decrease in the fresh properties and stability.
- Compared to SG and FA, the addition of MK improved the viscosity and particle suspension of SCRC mixtures, which resulted in increased passing ability. The addition of MK also increased the compressive strength and HRWRA demand, while the flowability of SCRC mixture decreased. SCRC mixtures with 550 kg/m^3 binder content and 20% MK showed acceptable fresh properties, stability, and strength of up to 30% CR.

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