ISBN 978-93-84468-19-4
Proceedings of International Conference on Transportation and Civil Engineering (ICTCE'15)
London, March 21-22, 2015, pp. 68-75

Mechanical Properties of Self-Consolidating Rubberized Concrete with Different Supplementary Cementing Materials

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Abstract**:** *This research presents the results of an experimental investigation to study the effect of using different supplementary cementing materials (SCMs) on the mechanical properties of self-consolidating rubberized concrete (SCRC) mixtures. Totally, 16 mixtures with different percentages of CR (0-40% by volume of sand) and different types of SCMs (fly ash, slag, and metakaolin) were investigated. The mechanical properties of the tested mixtures were evaluated based on their compressive strength, flexural strength (FS), splitting tensile strength (STS), and modulus of elasticity (ME). The results indicated that using CR generally has a negative effect on the 28-day compressive strength, STS, FS, and ME. However, structural grade SCRC (fc> 17 MPa) can be achieved with up to 40% CR replacement. The results also showed that using MK has the most significant effect on improving the mixture stability and particle suspension, which facilitated the development of SCRC mixtures with a high percentage of CR (30%) and with acceptable stability/strength and with a density of less than 2100 kg/m^3.*

Keywords: *self-consolidating concrete, crumb rubber, supplementary cementing materials, mechanical properties*

1. Introduction

Many recent studies show a growing need to enhance the ductility of concrete in attempting to improve the behaviour of structures, especially those exposed to dynamic loads and seismic activities [1]. Reutilization of waste rubber (from scrap vehicle tyres) as an aggregate replacement is one of the potential alternatives to develop concrete with larger strain capacity (ductility), energy dissipation, damping ratio, impact resistance, and toughness compared to normal concrete using conventional aggregate [2-4]. Using recycled rubber in the construction industry also has a direct impact on reducing environmental pollution [5]. As well, the low density of rubber aggregate compared to a conventional aggregate can significantly contribute to the development of semi-lightweight and lightweight concrete [3] that can help to reach a more economical design [5].

Previous studies carried out on use of waste rubber in concrete found that increasing the rubber content has a negative effect on the compressive strength, tensile strength, flexural strength, and modulus of elasticity [6, 7]. This reduction is attributed to two reasons: firstly, the significant difference between the modulus of elasticity of rubber aggregate and mortar; and secondly, the poor strength of the interfacial transition zone (ITZ) between the rubber particles and surrounding mortar [5]. However, a study performed by Najim and Hall [2] reported that using rubber aggregate greatly enhances the strain capacity of concrete, which in turn decreases the crack mouth opening displacement. In addition, increasing the rubber content showed a significant improvement in the flexural toughness, which had a direct impact on enhancing the concrete's ductility and energy absorption. Najim and Hall [2] also found an improvement in the damping performance of concrete when using CR. They found that the damping coefficient of the rubberized concrete at 15% CR increased by 230% compared to the traditional concrete. Another study by Ganesan et al. [8] indicated that the fatigue strength of concrete can be enhanced by adding scrap rubber to the mixture.

Recent studies [9] reported that the porosity and the width of the ITZ were highly affected by the compaction of fresh concrete. Therefore, the porosity of the ITZ of normal vibrated concrete is expected to be higher than that of self-consolidating concrete (SCC). This finding potentially indicated that the losses in the mechanical properties of rubberized concrete can be minimized when using self-consolidating rubberized concrete (SCRC) compared to a vibrated rubberized concrete (VRC). However, the development of SCC containing rubber involves significant problems, such as a decrease in fresh properties and stability of SCC mixtures with increased rubber content.

Using supplementary cementing materials (SCMs) is one of the potential ways to enhance the fresh and mechanical properties of SCRC. Metakaolin (MK) is one of the most effective SCMs that can be used in SCRC and is proven to enhance mixture viscosity, which has a direct impact on improving the particle suspension and reducing the coarse aggregate and crumb rubber segregation. In addition, MK has a high pozzolanic reactivity, which modifies the concrete microstructure and enhances its overall mechanical and durability performance. Rahmat et al. [10] reported that the compressive strength and tensile strength of SCC containing MK were significantly improved by 27% and 11.1%, respectively, compared to the control mixtures of SCC. Hassan and Mayo [11] also observed that the inclusion of 20% MK increased the 28-day compressive strength by 30%.

There is a lack of information regarding the mechanical properties and stability of SCRC, especially when developing SCRC with a high percentage of crumb rubber using metakaolin. The main objective of this research was to study the mechanical properties of a number of developed SCRC mixtures with high percentages of CR and minimum strength. The research particularly highlights the effect of MK compared to other SCMs on enhancing the mechanical properties and stability of SCRC mixtures. The experimental test parameters included different percentage of CR and different SCMs. The mechanical properties tests included compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity.

2. Experimental Work

2.1.1. 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.

2.1.2. Scope of Work

A total of 16 rubberized concrete mixtures were tested in this investigation. The experimental investigation aimed to develop a number of SCRC mixtures having maximum percentages of CR (by volume of fine aggregate) and a minimum reduction in strength and stability. The main objective of developing SCRC mixtures with maximum percentages of CR was to present some optimized SCRC mixtures with a reduced self-weight and a high potential use in applications involving high impact resistance and energy dissipation.

The tested mixtures are detailed as follows: a) seven SCRC mixtures with varied CR percentage from 0% to 40% and binder content of 550 kg/m^3; b) nine SCRC mixtures with different SCMs (MK, SG, and FA) (Table I). The effects of the CR percentage, and MK compared to other SCMs on the mechanical properties and stability of SCRC mixtures were investigated and discussed. The first set of mixtures (mixtures 1–7) was designed to investigate the effect of the percentage of CR in SCRC mixtures without SCMs. The second set (mixtures 8–16) was designed to investigate the effect of MK compared to other SCMs on enhancing the mixture stability and mechanical properties.

The percentages of MK (20%) and SG (30%) were chosen based on optimal values obtained from previous research [11, 12] carried out with these SCMs, while the percentage of FA (20%) was used to obtain a reasonable compressive strength in SCRC mixtures [13]. A constant coarse-to-fine aggregate (C/F) ratio of 0.7 was chosen for all tested mixtures. This ratio was chosen based on previous research [11] carried out on SCC with different C/F ratios. The tested mixtures were designated by total binder content, percentage of CR, and type of SCM used. For example, a mixture using a 550 kg/m3 binder, 40% CR, and MK would be labelled as 550C-40CR-MK.

TABLE I: Mixture Design for SCRC Mixtures

Mixture #	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)
1	550C-0CR	550	-	-	648.1	925.9	0.00	1.06	2344.0
2	550C-5CR	550	-	-	648.1	879.6	16.9	1.71	2314.6
3	550C-10CR	550	-	-	648.1	833.3	33.8	1.81	2285.3
4	550C-15CR	550	-	-	648.1	787.0	50.7	1.84	2255.9
5	550C-20CR	550	-	-	648.1	740.7	67.7	1.84	2226.5
6	550C-30CR	550	-	-	648.1	648.1	101.5	1.84	2167.8
7	550C-40CR	550	-	-	648.1	555.5	135.3	2.63	2109.0
8	550C-20CR-MK	440	MK	110	638.4	729.6	66.7	5.26	2204.7
9	550C-30CR-MK	440	MK	110	638.4	638.4	100.0	5.26	2146.8
10	550C-40CR-MK	440	MK	110	638.4	547.2	133.3	6.58	2088.9
11	550C-20CR-SG	385	SG	165	643.3	735.2	67.2	1.84	2215.7
12	550C-30CR-SG	385	SG	165	643.3	643.3	100.7	1.84	2157.3
13	550C-40CR-SG	385	SG	165	643.3	551.4	134.3	2.63	2099.0
14	550C-20CR-FA	440	FA	110	636.0	726.9	66.4	1.84	2199.3
15	550C-30CR-FA	440	FA	110	636.0	636.0	99.6	1.84	2141.7
16	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

2.1.3. Testing of Samples

The fresh properties of all tested mixtures were conducted as per the European Guidelines for Self-Compacting Concrete. The fresh properties tests included slump flow, V-Funnel, L-Box, and sieve segregation tests. The percentage of entrained air in the fresh SCC mixtures was measured by following a procedure given in ASTM C231. A detailed description of the fresh properties of the tested mixtures is presented in Table II. The compressive strength and splitting tensile strength (STS) tests were conducted using 100 mm diameter x 200 mm high concrete cylinders, according to ASTM C39 and C496. The splitting tensile strength test was also used to evaluate the distribution of CR in the mixture using visual inspection of the fractured surface. This investigation classified the stability of rubber particles into three cases based on CR segregation; namely, no segregation (NS), moderate segregation (MS), and heavy segregation (HS) (see Table II). The flexural strength (FS) of 100 mm x 100 mm x 400 mm prisms was measured for all SCRC mixtures according to ASTM C78. Also, the modulus of elasticity (ME) of all mixtures was tested using 100 mm diameter x 200 mm long cylinders with an attached 25 mm strain gauge. The mechanical properties tests were implemented after the sample had been moist-cured for 7 and 28 days, based on the test age.

3. Discussion of Test Results

3.1.1. Effect of the Percentage of CR

3.1.2. Compressive Strength

The 7- and 28-day compressive strengths of the tested mixtures are shown in Table III. As seen from mixtures 1–7, increasing the percentage of CR decreased the 7- and 28-day compressive strengths. Varying the CR from 0% to 40% reduced the 7- and 28-day compressive strength by around 59.25%. This finding agreed with what other researchers have found [3, 4, 14]. 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 observed by many researchers. For example, Emiroglu et al. [15] investigated the microstructure of the ITZ of rubberized concrete using Scanning Electron Microscopy (SEM) and found that the poor bonding between the rubber particles and mortar led to generate micro cracks started from and around the ITZ and affected negatively the mechanical properties. Also Najim and Hall [16] reported in their SEM investigation that a significant interfacial de-bonding and micro cracks were observed between the rubber particles and cement paste. The reduction of the compressive strength with higher percentages of CR may also be attributed to the significant difference between the modulus of elasticity of the rubber and the aggregate, as mentioned earlier [5]. Moreover, increasing the percentage of CR increased the air content (Table II), which may also have had a negative effect on the compressive strength of the mixtures. However, all tested SCRC mixtures exceeded the minimum compressive strength for structural concrete (17 MPa) [17], and the mixture with 20% CR (which is the maximum percentage that can be used with 550 kg/m^3 of binder content and no SCMs according to the results of rubber stability and passing ability, Table II) showed a good 28-day compressive strength (32.81 MPa).

3.1.3. Splitting Tensile Strength

The STS results for mixtures 1–7 are presented in Table III. It can be observed that the STS decreased as a function of the increase in the CR replacement. Increasing the percentage of CR from 0% to 40% reduced the 7- and 28-day STS by 43.17% and 52.41%, respectively. SCRC mixtures with 20% CR, which contained the maximum percentage of CR for mixtures without SCMs, showed reductions of 20% and 31.5% in the 7- and 28-day STS, respectively. This reduction may be attributed to the same reasons for the reduction of compressive strength with increased percentage of CR. These results are similar to previous studies finding [18, 19], in which the mechanical properties of structural and non-structural VRC with a 100% maximum percentage of CR (by volume of fine aggregate) were investigated.

3.1.4. Flexural Strength

Table III shows the four-point flexural strength test results for mixtures 1–7. The results showed a decreasing trend in the ultimate flexural load as the percentage of CR increased. The addition of 40% CR decreased the 7- and 28-day FS by 43.2% and 35%, respectively. Also, the addition of 20% CR in 550C-20CR (the most successful SCRC with a maximum percentage of CR in mixtures without SCMs) reduced the 7- and 28-day FS by 24.51% and 15.54%, respectively. These results agree with those found by other researchers [2], in which SCRC mixtures with a 15% maximum percentage of CR (by weight of fine aggregate) were investigated. The reduction of the ultimate flexural load with increasing the percentage of CR can be explained by the same reasons related to the reduction of the compressive strength and STS, as mentioned above.

3.1.5. Modulus of Elasticity

As seen in Table III (mixtures 1–7), the ME decreased as the percentage of CR increased in SCRC mixtures. The ME decreased by 3.7% at 5% CR, while at 40% CR the reduction was as much as 46.1%. Ganjian et al. [20] found similar behaviour in their investigation studying VRC mixtures with a maximum of 10% CR. Mixture 550C-20CR which is considered the most successful SCRC mixture (with no SCMs) with the highest percentage of CR (20%) showed 28.3% reduction in the ME compared to the control mixture (0% CR). Generally, the ME of SCRC as a composite material is directly related to the stiffness of the coarse aggregates, mortar (including the CR), and their bond structure [21]. Therefore, increasing the proportion of a low-stiffness component such as CR decreases the stiffness of the mortar, and hence reduces the overall ME. Moreover, the poor strength of the ITZ in mixtures with CR may have encouraged precocious cracking under loading, which could also have reduced the ME.

3.1.6. Effect of MK on the Mechanical Properties of SCRC

3.1.7. Compressive Strength

The results of mixtures 8–10 indicate that using MK can significantly increase the compressive strength of SCRC mixtures. The 7- and 28-day compressive strengths of mixtures 8–10 increased by an average of 64% and 49.2%, respectively, compared to mixtures 5–7 (with no SCMs). The addition of MK also greatly improved the 28-day compressive strength of the most successful SCRC mixture incorporating SCMs (550C-30CR-MK) according to the results of the passing ability (Table II), increasing it from 27.05 MPa (550C-30CR) to 39.83 MPa (550C-30CR-MK). On the other hand, the results of SG and FA mixtures (mixtures 11-16) showed a slight increase in the 28-day compressive strengths, reaching an average of 5.7% and 5.4%, respectively.

3.1.8. Splitting Tensile Strength

Adding 20% MK in mixtures 8–10 increased the 7- and 28-day STS by an average of 19% and 17%, respectively, compared to the reference mixtures (5, 6, and 7) (see Table III). On the other hand, using SG and FA (mixtures 11-16) showed a slight increase in the 28-day STS of around 5.4% and 3% (on average), respectively, compared to the reference mixtures (mixtures 5-7) (see Table III). SCRC mixtures with 30% CR, which contained the maximum percentage of CR that can be used successfully with MK, showed an increase of 14.75% and 13% in the 7- and 28-day STS, respectively, compared to the mixture with no SCMs (mixture 6).

3.1.9. Flexural Strength

The results of the MK mixtures (mixtures 8–10) showed an enhancement in the 7- and 28-day FS of 20.94% and 14.6% (on average), respectively, compared to the reference mixtures (mixtures 5–7). Using 30% SG (mixtures 11-13) showed a slight increase in the 28-day FS of around 5.1% (on average) compared to the reference mixtures 5-7 (see Table III). On the other hand, incorporating 20% FA (mixtures 14-16) showed similar results to those of the reference mixtures (5-7) at 28 days. Table III also shows that SCRC mixtures with 30% CR (the most successful SCRC with the maximum CR percentage in MK mixtures) had higher values for the 7- and 28-day FS of around 15% compared to mixture 6 (550C-30CR).

3.1.10. Modulus of Elasticity

As shown in table III, the addition of MK increased the 28-day ME by an average of 24.9%, while the inclusion of SG and FA increased the 28-day ME by an average of 5.3% compared to the reference mixtures (5-7). Mixture 550C-30CR-MK, which had the maximum CR percentage when using MK in SCRC mixtures, showed an increase of 19.15% in the 28-day ME compared to the mixture with no SCMs (mixture 6).

TABLE II: Fresh Properties for Tested SCRC Mixtures

Mixture #	Mixture	Slump flow		L-Box	V-Funnel	SR	Air	CR
		D_s mm	T_{50} sec	H2/H1	T_0 sec	%	%	Stability
1	550C-0CR	670	0.99	0.91	3.03	2.1	1.4	NS
2	550C-5CR	700	1.01	0.86	4.90	2.1	1.8	NS
3	550C-10CR	700	1.11	0.77	5.11	2.5	2.3	NS
4	550C-15CR	710	1.32	0.76	5.97	3.1	3.5	NS
5	550C-20CR	700	1.54	0.75	6.65	3.0	3.2	NS
6	550C-30CR	625	2.08	0.56	10.5	4.2	3.6	MS
7	550C-40CR	650	2.31	0.38	17.5	7.1	4.3	MS
8	550C-20CR-MK	680	2.57	0.86	8.25	2.1	3.4	NS
9	550C-30CR-MK	620	2.86	0.75	13.5	2.9	4.2	NS
10	550C-40CR-MK	660	3.12	0.68	18.6	3.1	4.8	NS
11	550C-20CR-SG	705	1.07	0.80	5.90	1.9	3.2	NS
12	550C-30CR-SG	670	1.37	0.70	6.30	2.9	5.5	NS
13	550C-40CR-SG	660	2.10	0.62	10.6	5.2	6.5	MS
14	550C-20CR-FA	700	0.99	0.76	5.90	3.1	3.1	NS
15	550C-30CR-FA	655	1.46	0.66	9.50	6.3	4.9	MS
16	550C-40CR-FA	650	1.94	0.54	15.5	7.3	5.5	MS

TABLE III: Mechanical Properties for Tested SCRC Mixtures

Mixture #	Mixture	7-day			28-day			
		f'_c MPa	STS MPa	FS MPa	f'_c MPa	STS MPa	FS MPa	ME GPa
1	550C-0CR	45.44	3.15	5.14	53.50	4.35	5.92	33.59
2	550C-5CR	42.34	3.06	5.04	47.07	4.28	5.60	32.36
3	550C-10CR	35.50	2.83	4.85	43.39	3.92	5.52	30.86
4	550C-15CR	29.90	2.70	4.57	38.45	3.37	5.19	27.23
5	550C-20CR	26.53	2.52	3.88	32.81	2.98	5.00	24.10
6	550C-30CR	22.92	2.17	3.65	27.05	2.54	4.25	22.03
7	550C-40CR	19.14	1.79	2.92	21.10	2.07	3.85	18.10
8	550C-20CR-MK	45.93	2.84	4.71	47.33	3.32	5.88	30.42
9	550C-30CR-MK	36.83	2.49	4.20	39.83	2.87	4.88	26.25
10	550C-40CR-MK	30.25	2.32	3.69	32.95	2.62	4.29	23.42
11	550C-20CR-SG	26.36	2.34	3.78	34.59	3.12	5.21	26.36
12	550C-30CR-SG	25.39	2.15	3.52	30.64	2.66	4.43	23.12
13	550C-40CR-SG	18.21	1.88	3.04	20.75	2.21	4.12	18.71
14	550C-20CR-FA	26.90	2.18	3.47	34.15	2.99	4.90	25.61
15	550C-30CR-FA	20.90	2.10	3.12	31.02	2.55	4.34	24.61
16	550C-40CR-FA	17.01	1.72	2.74	20.58	2.24	3.83	17.37

4. Conclusions

In this investigation, the mechanical properties of SCRC were studied. The parametric study investigated the effect of crumb rubber content and different types of SCMs (MK, FA, and SG). The results indicated that increasing the CR replacement from 0% to 40% decreased the 28-day compressive strength, STS, FS, and ME by 59.25%, 52.41%, 35%, and 46.1%. However, all developed mixtures exceeded the minimum strength for structural applications (17 MPa). MK proved to be the most effective SCM at enhancing the fresh properties and stability of SCRC mixtures. MK was found to improve mixture viscosity and particle suspension, which allowed up to 30% CR to be used safely in SCRC mixtures compared to a maximum of 20% CR in SCRC mixtures without SCMs. Using MK in SCRC mixtures alleviated the reduction in the mechanical properties with higher percentages of CR, as it improved the compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity by an average of 49.2%, 17%, 14.6%, and 24.9% when the CR increased from 20% to 40%.

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