Rheological Behavior of Self-Compacting Concrete Incorporating Crumb Rubber Particles As Fine Aggregate

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ABSTRACT

The utilization of the huge waste resulted from discarding end-of-life tires in the production of self-compacting concrete (SCC) is a decent and sustainable solution to mitigate serious environmental issues. The aim of this study is to evaluate the rheological properties and the density of SCC with different content of crumb rubber extracted from waste tires. Different rheological properties tests were conducted including: slump flow, J-ring, L-box, V-funnel and segregation resistance tests. Five SCC mixtures were prepared. The reference mix made with natural sand while the other four mixes were made with crumb rubber in which the natural sand was volumetrically replaced by crumb rubber at ratios of 10 %, 20 %, 30 % and 40 %, respectively. The results show that the addition of crumb rubber decreases the slump flow, decelerates the flow rate and increases the V-funnel time. In the case of L-box test, mixes with crumb rubber exhibited comparable results to that of the reference mix. The segregation resistance was higher for the mixes with crumb rubber than that of the reference mix. Adding crumb rubber to SCC decreases its density.

Keywords: Self-compacting concrete; Rheological properties; Density; Crumb rubber; Waste tires

1. INTRODUCTION

Studies conducted recently have pointed out that billions of tires are produced every year worldwide (1). In both developed and developing countries enormous numbers of tires are discarded every year. For example, 300 million of tires are discarded and became waste annually in the EU alone as per European Tire Recycling Association (2). The disposal of such huge number of waste tires has a large impact on the environment. Also, waste tires can cause serious issues to the human health and increase fire hazards in the case of burning or illegal dumping (3, 4). A decent and sustainable solution to mitigate these impacts and issues is by using such waste in the production of concrete (4).

Self-compacting concrete (SCC) has been deemed as one of the key advances in concrete technology in last few decades due to several advantages. Among these advantages are: the ease of placing, flowing and compacting under the effect of gravity with no vibration effort and saving time needed for construction (5).

The use of crumb rubber driven from processing waste tires as fine aggregate in the production of SCC can be a valuable solution for the aforementioned issues associated with the disposal of waste tires (6). This will also enhance the sustainability of SCC and make this type of concrete eco-friendly through eliminating the consumptions of limited areas of landfilling, reduce the hazards and health problems associated with tires disposal; and save the natural recourses of sand.

The characteristics of SCC in the fresh state are vital since SCC should have the ability to consolidate, pass the reinforcing rebars and fill all form's parts and corners with no segregation (5). The addition of crumb rubber as fine aggregate in the production of SCC affects its properties in fresh and hardened states (7, 8). According to previous studies (7-14), replacing sand with crumb rubber may have an adverse effect on the rheological properties of SCC. Crumb rubber can reduce the flowability, increase the viscosity (decrease the passing ability), increase the risk of segregation and decrease the density of the fresh SCC. Despite the general agreement on the negative influence of the crumb rubber on the rheological properties of SCC, reported results regarding satisfying the European guidelines of SCC (or EFNARC) (4) are contradicting. It seems that meeting these guidelines mainly depends on the content of the crumb rubber and the quantity of the superplasticizer used in the concrete mixture. Therefore, in the case of using crumb rubber in SCC for a specific application, it is recommended to conduct an experimental investigation to characterize its rheological properties (7,13).

This article is part of a research aims at assessing the properties of SCC with different content of crumb rubber. This article describes the experimental program, presents the experimental results and analyses the effect of different content of crumb rubber on the rheological and density of SCC.

2. EXPERIMENTAL WORK

2.1 MATERIALS

Ordinary Portland Cement (OPC) manufactured by AL-MAS cement factory (42.5 R – B.S) 12/96 in Kurdistan-Iraq was used in this study. The specific gravity and specific surface area of cement were 3.12 and 314 m^2/kg, respectively. The adopted cement conforms to the Iraqi specification No.5/1984 (15).

The coarse aggregate was natural rounded river aggregate with a maximum size of 14 mm. The size distribution of the coarse aggregate is shown in Figure 1 which shows the size distribution of all aggregates used in the study. The coarse aggregate has a specific gravity of 2.67. Two types of fine aggregates were used in this study, natural and rubber particles. The natural fine aggregate was river sand with a maximum size of 4.75 mm. Its specific gravity and fineness modulus are 2.66 and 2.79, respectively. It complies with the Iraqi specification, IQS No. 45/1984 (15) as can be seen in Figure 1.

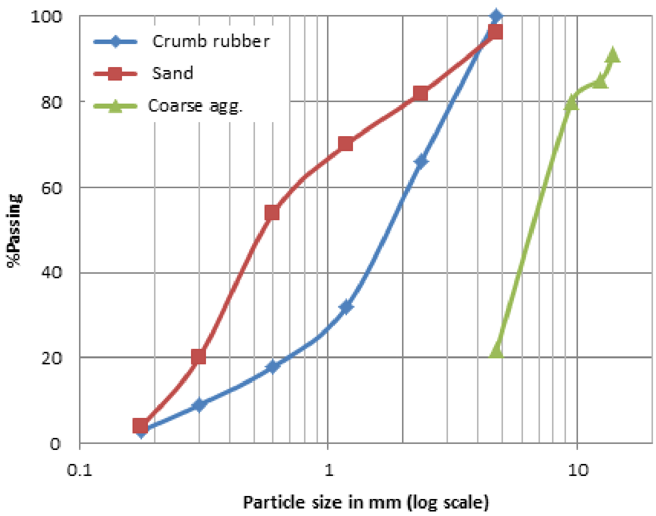


FIGURE 1. Particle size distribution of coarse and fine aggregates

In this study crumb rubber was also used as recycled fine aggregate. The rubber fine aggregates were obtained from the mechanical grinding of post-consumer tires, see Figure 2. The maximum size of rubber aggregate was 4 mm. The particle size distribution of the crumb rubber can be seen in Figure 1 .The crumb rubber aggregates were characterized by specific gravity of 1.15, bulk density of 489 kg/m^3 and negligible water absorption.

FIGURE 2. Crumb rubber used in current study.

A commercial silica fume (SF) called Sika Fume-HR was used in this study. The powder was characterized by a grey color, a specific gravity of 2.2 and a specific surface area of 20100 m^2/kg. The silica fume was incorporated in all mixes as a partial replacement (10% by weight) of cement content.

The superplasticizer used in this study was a polycarbxylic-ether type. The commercial name is Sika viscocrete super E4-S. It is a high-range water reducer that provides long workability and stability. It has a brown color and a specific gravity of 1.065 and conforms to the requirements of ASTM C494 –Type G.

2.2 MIX PROPORTIONS

Five SCC mixtures were prepared. These mixes had the same total binder content (cement + silica fume) of 495 kg/m^3 and water to binder ratio of 0.33. The code and the proportions of all mixes are presented in Table 1. The reference mix (M0) made with natural sand while the other mixes (M1, M2, M3 and M4) were made with crumb rubber. In mixes M1, M2, M3 and M4 the natural sand was volumetrically replaced by crumb rubber at ratios of 10 %, 20 %, 30 % and 40 %, respectively. The silica fume content was 10% by weight of cement. The superplasticizer (SP) was added to all mixes at constant ratio of 2.3% of cement weight.

TABLE 1.
Code of mixes and mix proportions in kg/m^3

Code of mix	Cement	Water	Silica fume	FA		CA	SP
				Sand	Crumb rubber		
M0	450	165	45	888	-	810	11.39
M1	450	165	45	799	39	810	11.39
M2	450	165	45	710	77	810	11.39
M3	450	165	45	622	116	810	11.39
M4	450	165	45	533	154	810	11.39

2.3 TEST METHODS

The rheological behavior (fresh properties) of the SCC mixes was assessed through conducting slump flow, T_{50} flow time, J-ring, L-box, BJ, TJ, V-funnel and segregation resistance tests following specifications and guidelines of European Federation of National Associations Representing producers and applicators of specialist building products for Concrete (EFNARC) for SCC (5). The sequence of performing the fresh concrete tests was the same with all mixes. The fresh properties were conducted immediately after the completion of concrete mixing. The density of the fresh concrete was quantified following the EN-12350-6 (15) without using vibration.

2.4 PRODUCTION OF CONCRETE AND CURING

The production of all SCC mixes was the same and undertaken following the European guidelines of SCC. A 0.04 m^3 mechanical rotary mixer was employed in the production of concrete mixtures. The dried ingredients (cement, silica fume, coarse and fine aggreagte) were first prepared and batched. After that, the dry coarse and fine aggregates were added to the mixer and mixed for half minute. Then, half of the water was added and mixing continued for another minute. Afterward, the cement and the silica fume were introduced to the mixer and the mixing resumed for 2 more minutes. Thereafter, the rest of the water and the SP were blended together before adding them gradually to the mixer and mixing continued for 3 and a half minutes. Finally, the mixture was left to rest for 1 minute before the commence of testing the fresh concrete. The mixtures were designed to achieve a slump flow of more than 700 mm and to satisfy or exceed the other SCC requirements (V-funnel, L-box and segregation resistance) based on EFNARC (5). Trial mixes were first prepared and tested to reach this desired slump flow (700 mm). The sequence of conducting the fresh properties of the concrete mixtures was: slump flow time and diameter, j- ring, V-funnel, L-box, segregation resistance and density.

3. ESULTS AND DISCUSSIONS

Aiming at evaluating the effect of adding crumb rubber as fine aggregate on the performance of SCC mixtures, the rheological behavior of all mixes was quantified by assessing: 1- flow, viscosity and filling ability of concrete by slump flow and V-funnel tests; 2- the passing ability of concrete by j-ring and L-box tests and 3- segregation resistance by sieve segregation test (see Figure 3). The results of all fresh concrete properties are presented in Table 2. According to the results, it seems that generally, the partial replacement of sand with crumb rubber causes a reduction in flow, passing ability of SCC and the density in a systematic way. The discussions on these results are reported herein:

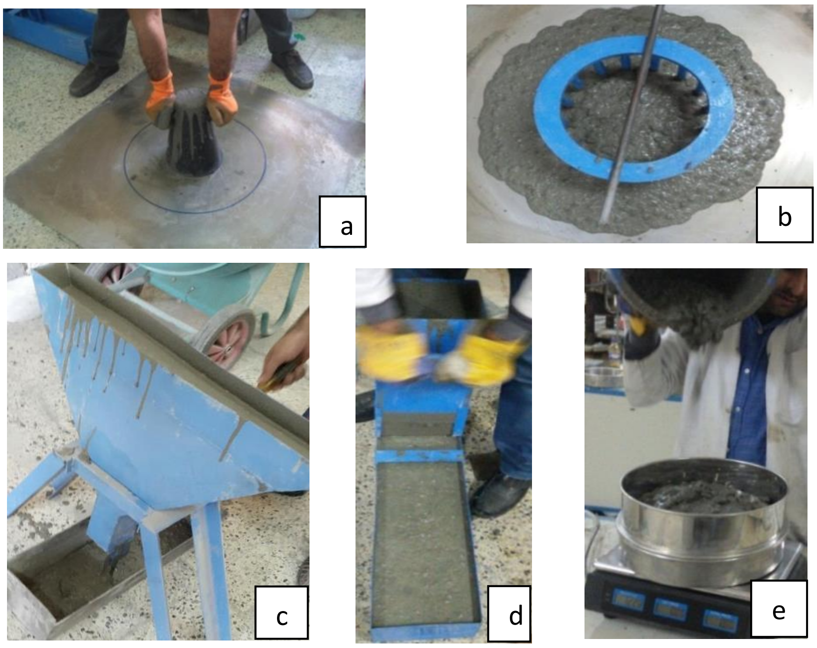


FIGURE 3. Rheological properties tests: (a) slump flow, (b) j-ring, (c)V-funnel, (d) L-box, d-Segregation resistance

TABLE 2.
Result of rheological properties.

Max Code	Flow mm	T_{50cm} sec	V-Funnel sec	J–ring mm	B j	T J-50 cm	L-box %	Segregation Resistance %	Density kg / m^3
M0	720	3.5	7.2	685	2.375	5	0.93	13.8	2378
M1	685	4	9.8	660	1.8	6	0.9	12.4	2292
M2	670	4.7	12.3	640	1.875	6.8	0.9	8	2258
M3	655	5.8	15.4	635	1.75	9.4	0.87	7.4	2197
M4	630	6.9	18.3	615	2.125	11.8	0.84	5.7	2150

3.1 SLUMP FLOW

The results of flow diameter and flow time using slump flow test are presented in Table 2. The reference mix M0 which includes no rubber showed a 720 mm slump flow and 3.5 sec flow time (T_{50cm}). These figures put this mix under the category (SF2) of good filling ability and moderate flow rate according to the categories proposed by EFNARC (see Figure 4a). The addition of crumb rubber (mixes M1 to M4) diminishes the slump flow and increases the flow time as can be seen in Figures 4a and 4b. The increase in the flow time is an indication of the high viscosity of the mixes with rubber aggregate.

Figure 4a shows the results of flow for all mixes and the limits of the guidelines of EFNARC. It can be seen that, the higher the replacement ratio of sand by crumb rubber, the higher the reduction in flow diameter and the slower the flow rate of the mix. However, the reduction in flow for mixes up to 20% (by volume) crumb rubber content (M1 and M2) is slight and represents only 5% and 7%, respectively, in comparison to that of the reference mix (M0).This is clear in Figure 4c which shows the normalized flow (flow of mix/flow mix M0) for all mixes. The slight decrease in the flow for mixes M1 and M2 keep these mixes within the category SF2 of EFNARC for flow diameter and flow rate maintaining good filling ability and moderate flow rate (same category for the reference mix M0). On the other hand, when the replacement ratio is more than 30% (M3 and M4), the reduction in the flow is doubled putting these mixes in a category (according to EFNARC) different from that of M0.

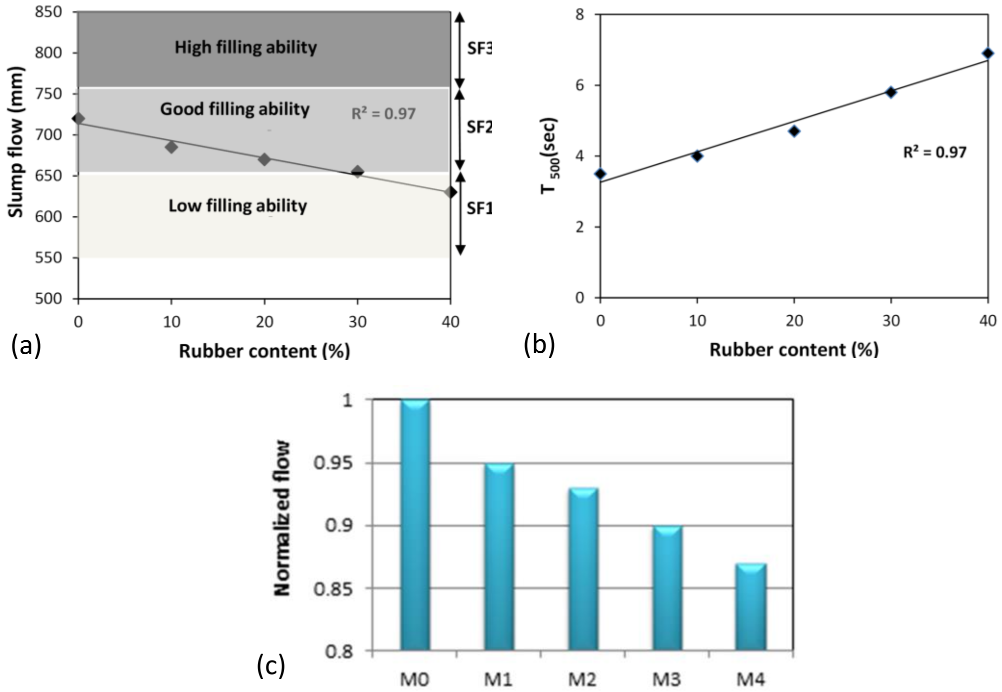


FIGURE 4. (a) Effect of crumb rubber on slump flow, (b) Normalized slump flow, (c) Effect of crumb rubber on the flow rate (T_{50} in sec)

Similar results were reported by (8-10,12) as they found that up to certain replacement ratio does not lead to a considerable change in the flow ability of SCC mixtures. The reduction in flow diameter and the increase in flow time for the mixes with rubber can be attributed to surface characteristics and the deformability of the rubber particles (6,8). The rough surface texture and elastic behavior of the rubber particles are the sources for a likely increase in inter-particle friction under the free flow (4,12) with a possible absorbing of the moving energy (17).

3.2 V-FUNNEL TEST

The results of the V-funnel test, which is a measure of the viscosity of SCC, are presented as time measured in seconds in Table 2. Table 2 shows that mix M0 has a V-funnel time of 7.2 sec; hence this mix can be categorized as VF1 with good filling ability and high flow rate as per EFNARC (5) for V-funnel categories. Just as the slump flow test, the addition of crumb rubber affected the results of the V-funnel test. The V-funnel time of mixes M1, M2, M3 and M4 was 9.8, 12.3, 15.4 and 18.3 sec, respectively. The V-funnel time increases with the increase of replacement ratio of crumb rubber as can be seen in Figure 5.This means that the mixes incorporating crumb rubber exhibited higher viscosity than that of mix M0. Unlike mix M0, the mixes with crumb rubber dose not fulfill the EFNARC requirement of the category (VF1) characterized with good filling ability and high flow rate. However, according to EFNARC, all mixes with rubber can be categorized as VF2 with moderate to low flow ability and low flow rate which means that these mixes still maintain the characteristics of SCC. These results are in line with other studies (8,17). The increase in V-funnel time for the mixes with rubber could be due to the angular shape and rough surface of the rubber particles which most probably can lead to high mechanical interlock hindering the flow of the mixture (4,12). Another reason could be the increase in air content associated with inclusion of rubber particles (18). Air content of concrete mixture with rubber may increase as rubber particles tend to entrap air in their rough surface during mixing as well as the non-polarity nature of crumb rubber particles (4,17). The increase in air content with the low unit weight of mixtures with rubber (see the density section) could hinder consolidation and the flow of the concrete through the opening of the funnel (17,12).

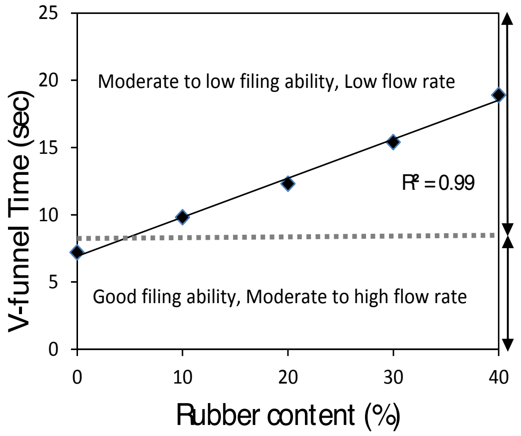
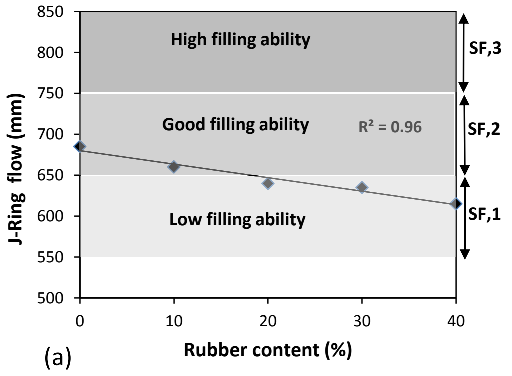


FIGURE 5. Effect of crumb rubber on V-funnel time (sec)

3.3 J-RING TEST

The j-ring flow (in mm) of all mixes obtained from the J-ring test is illustrated in Table 2. The results are also shown in Figure 6a. A similar trend to that of the slump flow test can be noticed**.** The J-ring flow for the M0 mix was 685 mm. According to EFNARC, this result puts M0 under the category SF,2 with good filling ability. The addition of the crumb rubber reduces the flow of SCC (see Figure 6a). The reduction in the flow increases with the increase of the content of crumb rubber. Figure 6b shows the normalized j-ring flow (flow of mix/flow of M0). The j-ring flow of the mixes with rubbers M1, M2, M3 and M4 is less than that of M0 and corresponds to 95%, 93%, 90% and 88% of that of the reference mix (M0), respectively. Comparable results were reported by (8,12,17).The reduction in the j-ring flow for the mixes with rubber can be attributed to the surface texture and deformability of rubbers particles as mentioned above. None of the mixes with rubber, except M1, can be characterized as SF,2 with good filling ability per EFNARC but can show the flow of SCC with low ability (category SF,3).

As far as the results of blocking step (Bj) are concerned, it is clear that both mixes with and without rubber exhibit no or low risk of blocking per EFNARC since the results of all mixes are less than 10 mm (see Table 4). This is also confirms that the addition of crumb rubber up to the contents used in this study does not lead to a significant change in the rheological behavior of SCC.



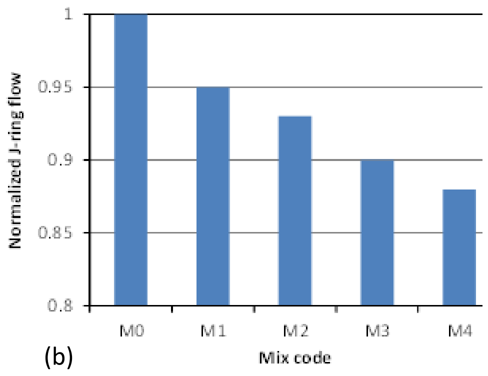


FIGURE 6. (a) Effect of crumb rubber on j-ring flow in (mm), (b) Normalized j-ring flow

3.4 L-BOX TEST

This test evaluates the passing ability (PA) of the SCC. The results of the L-box test are presented in Table 3. The results show that when sand is replaced with crumb rubber, the PA of SCC is not significantly changed. The PA of the reference mix (M0) was 0.9 and those of mixes M1, M2, M3 and M4 were 0.9, 0.9, 0.87 and 0.84 respectively (see Figure 7). The results of all mixes conform to the guidelines of the EFNARC which states that PA of SCC should be equal or less than 0.8. Similar behavior was observed by (12). It can be concluded that adding crumb rubber up to 40% by sand volume causes insignificant change in the passing ability of SCC without changing the water or the superplasticizer content.

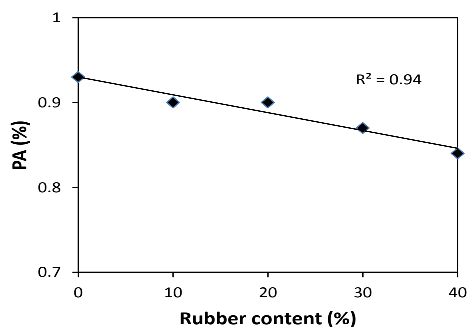


FIGURE 7. Effect of crumb rubber on passing ability ratio.

3.5 SEGREGATION RESISTANCE TEST

The results of segregation resistance (SR) ratio measured using the sieve method are shown in Table 2. It is clear that the addition of rubber aggregate improved the segregation resistance of SCC as with the increase of the rubber content the SR ratio decreased which in turn means better segregation resistance performance (see Figure 8a). Similar results were reported by (12,18). This behavior could be due to the high viscosity of the mixes with rubbers as confirmed by the results of T_{500} and V-funnel time (see figures 4b and 5). This is also clear in Figure 8b which demonstrates the relation between T_{500} and the SR ratio. It can be seen that with increase of the time (T_{500}) (increase in the viscosity), the SR ratio decreases. According to EFNARC (5), all mixes (with and without rubber) can be considered as appropriate since each mix meet the sieve segregation resistance category SR2 (SR ≤ 15%).

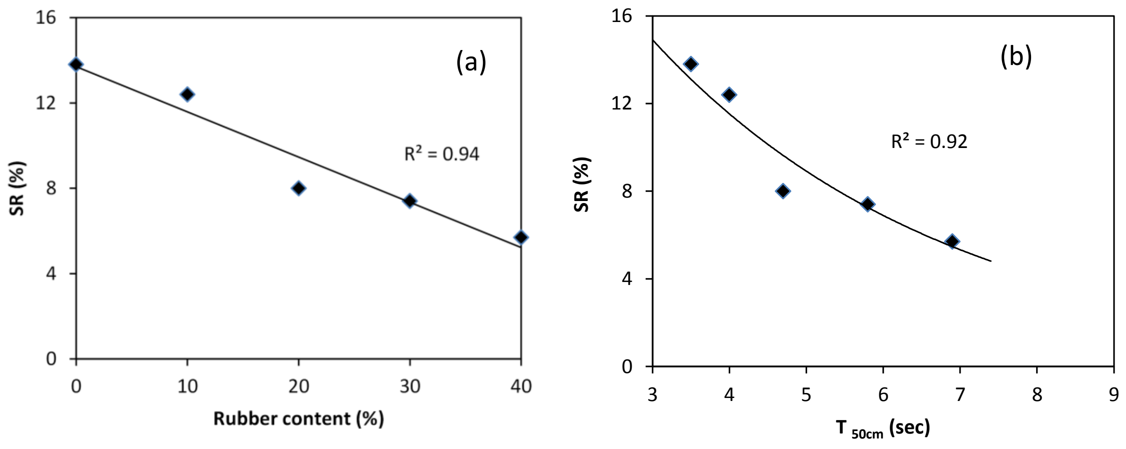


FIGURE 8. (a) Effect of crumb rubber on segregation ratio (SR), (b) relation between segregation ratio and flow rate (T_{500})

3.6 DENSITY TEST

Table 2 also shows the results of the density of the fresh concrete. The density of the fresh concrete decreased with the addition of the crumb rubber aggregate. The reduction in the density increases with the increase of the rubber content as can be seen in Figure 9 which shows the effect of the crumb rubber content on the density of the concrete. Similar observation was reports by (8,17,12).

This is expected as it is well documented that replacing natural aggregate with rubber aggregate reduces the density of concrete. This is mainly due to the lower specific gravity of rubber particles compared to that of sand (4). In addition, the non-polarity of the crumb rubber could entrap air during mixing which in turn causes a reduction in the density of SCC (4,17). Moreover, the tendency of the rubber particles to repel water is another factor that could attract air to the surface of the rubber particles leading to low density (4,19). Nevertheless, the decrease in the density is slight with a maximum ratio.

of 9 % (at 40% rubber content) of that of the reference mix and almost negligible at 10 % and 20 % rubber content. Despite this reduction in the density, all rubberized mixtures can be used in structural applications as concrete mixtures having a density larger than 2000 kg/m^3 is usually deemed as structural concrete and used in most civil engineering application (20).

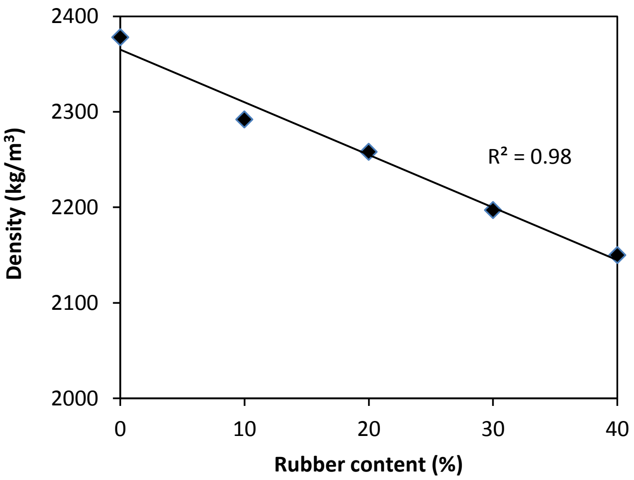


FIGURE 9. Effect of crumb rubber on fresh density of SCC

4. SUMMARY AND CONCLUSIONS

The effect of replacing sand with waste driven crumb rubber aggregate on the rheological behavior of SCC was experimentally quantified. Four replacement ratios (by volume of sand) were evaluated. In total, five concrete mixtures were prepared, one without rubber and four with rubber. The rheological characteristics of the concrete mixtures such as, flowability, filling capacity, passing ability and segregation resistance. The discussion of the results can lead to the following conclusions:

a. Adding crumb rubber decreases the slump flow and decelerates the flow rate (T_{500}) of SCC mainly due to the rough surface texture and elastic behavior of the rubber particles which may be due to the increase in inter-particle friction under the free flow. Maximum reduction observed in the slump flow was 14% of that of the reference mix at 40% rubber content. However, all mixes with rubber still maintain the requirement of slump flow and flow rate stated by EFNARC.
b. Mixes containing crumb rubber showed higher viscosity than that of plain SCC as the V-funnel time increases with the increase of replacement ratio of crumb rubber. This was attributed to the rough surface of the rubber particles and the increase in air content associated with inclusion of rubber particles. According to EFNARC, all mixes fulfill the requirement for v-funnel time.
c. Adding crumb rubber reduces the J-ring flow of SCC. Nevertheless, all rubberized mixes comply are in accordance with the guidelines of EFNARC for J-ring flow.
d. The passing ability (PA) of the rubberized SCC mixtures exhibited quite comparable results to that of the plain SCC and also conforms to the guidelines of the EFNARC.
e. The addition of rubber improved the segregation resistance (SR) of SCC as with the increase of the rubber content the SR ratio decreased. For all rubberized SCC mixtures, the SR ratio was lower than that of the plain SCC mixture. This behavior could be due to the high viscosity of the mixes with

rubbers as confirmed by the results of T_{500} and V-funnel time. According to EFNARC, all mixes (with and without rubber) can be considered as appropriate since each mix meet the sieve segregation resistance class SR2 (SR ≤ 15%).

f. The addition of the rubber aggregate led to a reduction in the density of the fresh SCC. The reduction in the density increases with the increase of the rubber content. Nevertheless, the decline in the density is slight with a maximum ratio of 9 % (at 40% rubber content) of that of the reference mix.

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