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Research Article

Effect of particle size of the coated and un-coated crumb rubber on the mechanical properties and water absorption of rubberized concrete

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Abstract

To diminish the environmental impact of enormous waste tires and reduce the concrete cost, crumb rubber (CR) was utilized to replace concrete aggregates. The CR and sand sizes were sieved and separated. Moreover, the CR was pre-coated with silica fume slurry, having a water-to-cement ratio of 0.55. The coated and uncoated CR was used as a partial replacement of sand by five percentages (0, 5, 10, 20, and 25% by volume). Cubes and cylinders were cast and then cured in water tanks until the date of testing. The compressive strength of the control and rubberized concrete (RuC) samples was measured at 7, 28, and 56 days, the tensile strength was obtained at 28 days, and the water absorption was measured at 56 days. Replacing sand with a 2.36 mm particle size with the same CR size showed lower effects on the concrete compressive strength than replacing sand with 1.18 mm CR. Moreover, replacing sand with 5% pre-coated CR (particle size 1.18 mm) enhanced the compressive strength (f_{cu}) by 104.88, 100.44 and 101.9% at 7, 28, and 56 days, respectively, compared to the subsequent mixes with uncoated CR while at 10% pre-coated CR content, the f_{cu} enhancement was 118.3, 108.53, and 104.80%, respectively.

1. Introduction

The concrete mixture should include recycled and waste materials to achieve sustainability. These waste materials could replace the non-renewed natural aggregates with a lower quantity than required. For the previous reasons, the aggregate was classified as a necessary material after water importance for use worldwide [1–3]. The use of glass, crumb rubber (CR), and other waste materials in concrete instead of natural aggregate (NA) could reduce the environmental impact (EI) of these wastes and concrete costs. In addition, the storage area and excavation energy were also reduced (less than 25% of CR as NA replacement was recommended to reduce the EI of the CR production energy [4]). Owing to the high development of cars worldwide, the growth of damaged and old tires causes EI as CR decomposition is very slow and needs more time. An anticipated 1000 million tires end their valuable lives every year, and an additional 5,000 million will be disposed of in 2030. Due to the high durability and volume of old tires produced yearly, scrap tires are considered one of the most problematic waste resources of recent societies. Until now, some of these tires have been recycled while the rest are stored or buried [26]. Dumped tires cause various environmental problems; when such tire dumps capture fire, it is hard and expensive to destroy [5]. Recycling CR keeps beneficial natural resources and diminishes the area needed to store the CR [6]. To partially solve the EI of the CR, it was used to replace the concrete NA [7,8], producing the concrete denoted as crumb rubber

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concrete (CRC), green concrete, or rubberized concrete (RuC) [9–14]. The RuC is considered an advanced clean production material [15]. The resulting RuC possesses lower strengths than NA concrete [16–20] but enhanced its earthquake endurance, its impact, and its toughness [21]. The air spaces produced by the CR's lower water absorption than NA resulted in extra stresses in the bordering matrix and formed additional cracks [22–26]. The research on RuC and the effect of replacing NA with CR on reducing the concrete compressive strength up to 85% was studied [27–35]. Moreover, CRC's tensile strength and modulus of elasticity were also diminished [27–35]. The concrete strength reductions depend on the CR size and content [27]. The workability of CRC is less than the normal concrete (NC) [36], but it can be controlled by adding a superplasticizer by 1–3% of cement weight ASTM 494 standard [37]. In [11], as the aggregates were replaced by CR (1.18–2.36 mm sizes) up to 3.5% by volume, the concrete strength remained unchanged while increasing CR% up to 9.5% reduced the CRC compressive strength to 37%. A reduction in the reinforcing bars-CRC bond besides CRC strength was also noticed in [38].

Contrasting fine NA, the CR surface is smooth and non-porous due to its chemical nature and the authority of oil spots. So, chemical treatment is essential to enhance the CR properties [39]. In [11], as the NaOH solution was used to treat CR, the CRC compressive strength increased by 6% to 15% compared to those with non-treated CR depending on the curing time. Moreover, using FRP to confine the reinforced CRC columns reverses the decrease of concrete strength and enhances the structure ductility. The compressive strengths and microstructure of CRC were examined at several curing days (3, 7, 14, 28, and 56). The CRC curing products were the same as NC, while the CRC porosity increased in contrast to their pore spacing coefficient compared to NC. Moreover, the compressive strength increased, and the pore spacing coefficient decreased with the curing time [40]. The reduced CR-cement interface greatly affected the CR cement composite strength. So, several CR treatment and coating materials were used to enhance this interface. In [41], the CR was pre-coated with limestone powder (LP), and silica fume (SF) was added to the cement composite. The pre-coated CR replaced the fine NA at 0, 5, 10, and 15% by volume. An equivalent mortar compressive strength and higher flexural strength than the reference mixture was obtained for mixes including SF and up to 10% LP pre-coated CR, while the CR mortar sorptivity was reduced [41]. In [42], the effect of the same ratios of replacement for NA by LP pre-coated CR as in [41] was also discussed, but 15% SF replaced the cement. The CR and pre-coated CR enhanced the CRC mixes' surface resistivity and chloride permeability [42]. In [22], the sand was replaced by CR with 2, 8, 16, 24, and 40% CR (by weight) to study the CR effect on the concrete durability, while the NaOH, KM_nO_4, and cement were the CR treatment materials. In [22], the CRC durability was measured through the evaluation of its water absorption (WA), acid resistance (AR), electrical resistivity (EC), and chloride permeability (CP). The WA of the CRC decreased as the treated CR was used while the AR-enhanced for 8% NaOH-treated CRC compared to the untreated CRC. Conversely, the strength loss of KM_nO_4-treated CRC was higher than that of NaOH and cement-treated CRC, but its weight loss was lesser. Moreover, the cement-treated CRC with 40% CR showed the best AR. Consequently, in [43], the CR treated with NaOH, KM_nO_4, and cement was used to produce CRC with 2, 8, 16, 24, and 40% sand replacement by CR. For CRC with 16% treated CR, the compressive strength raised by dissimilar percentages depended on the treated materials (cement treatment is the best) and the concrete strength (the CRC with less than 30 MPa showed high enhancement values) [43]. In [39], NaOH with 0.1 mol, 0.5 mol, and 1 M as concentrated solutions were used in treated CR at 2 h and 24 h durations. The CRC hardened properties with CR% of 2, 5, 10, and 20% as fine NA replacement were obtained at 7 to 90 days of curing. The 7-day compressive strength of CRC with 2% CR treated by NaOH with 0.5 mol and 1 M solution for two hours was reduced by 3.07% compared to untreated CR. Conversely, increasing the NaOH dosage to

1M and the time to 24 h for CRC (20% CR) showed loss recovery of its strengths compared to those with untreated CR [39].

The fresh properties and strength of high-strength concrete (HSC) with 15% metakaolin (MK) and CR up to 30% as sand replacement were studied [44]. The CRC showed a loss in workability, strength, and Young's modulus at 20% CR replacement while its ductility and toughness index improved (the same observations were reported in [45]). The CRC with up to 20%MK and 20%CR achieved compressive strength of more than 60 MPa, but a reduction in strength was noticed with any further rise in CR%. Moreover, the characteristics of ultra-high-performance RuC (UHPRuC) with 2% steel fibers (by volume) and rubber powder (0-40%) were examined under quasi-static and dynamic loading [46]. The compressive strength of statically tested UHPRuC reduced from 136.1 MPa to 67.8 MPa as CR% increased from 0% to 40%, while the UHPRuC dynamic characteristics were sensitive to strain rate and this sensitivity raised as the CR% increased [46]. Rubberized engineered cementitious composites (RECC) showed extreme capabilities for various structural applications as the RECC compressive strength remains higher than 25 MPa with high ductility [8]. Moreover, the RuC compressive strength remained higher than 30 MPa for the self-compacting concrete containing 25% CR or tire chips [47]. The effect of CR particle size intervals on the RuC flexural properties and microstructure was investigated [20]. As the CR size interval was 4.75–2.36 mm, the RuC flexural strength was diminished. Moreover, reducing the CR size gaps to 1.18 to 0.6 mm and 1.18–0.3 mm reduced the flexural strength by 27.3% and 29.4%, respectively [20]. Conversely, many durability characteristics of RuC improved up to a certain CR content, while the RuC corrosion resistance remained as those with NC [23].

To enhance the bond between waste rubber tire aggregate (WRTA) and cement paste using double pre-coating using resin and micro-silica [48]. The young modulus and flexural and compressive strengths of the concrete with modified CR were enhanced by 28, 30, and 60%, respectively, while the concrete workability and specific gravities decreased. Similar results related to RuC mechanical properties were reported in [26] besides the cost-efficiency enhancement [23,48] In contrast, RuC mechanical properties and Young's modulus declined (f_{cu} by 20.9–71.9 % and ftu by 12.2–51.7 %) as the untreated WRTA content raised [26]. The use of waste quarry dust (WQD) to treat CR was discussed in [23]. The 20% sand replacement with treated CR enhanced the RuC strengths, while the 20% sand replacement with non-treated CR enhanced the ductility and toughness index of RuC compared to the corresponding RuC with treated CR [49]. The CR with sizes of 0.6–2.36 mm was utilized to replace the fine NA by (0, 10, 15, 20, 25, and 30%). At 15% CR, insignificant compressive strength loss was observed when CR was treated with H_2SO_4 solution, while there was no necessity to add more superplasticizers (SP) to obtain the same NA concrete workability [50]. The CR double pre-coating using resin and micro-silica enhanced the CR-cement paste in-between bond. The sand replacement by pre-coated CR ranged between 0% and 30% by volume. The resulting RuC properties were improved by using the double pre-coated CR at 5%CR content and 5% micro silica but reduced with increasing the CR content (coated or uncoated) [51].

The above review showed limited research studying the effect of CR size and coating on the RuC properties and WA. In this paper, the coated and uncoated CR content in the concrete mixes to replace sand was 0, 5, 10, 20 and 25%. The CR was coated using SF with the recommended content. The coated and uncoated CR replaced the two limited sand sizes in nature (1.18 and 2.36 mm) to discuss the CR effect on the RuC strengths and WA. The RuC compressive strength (f_{cu}) was obtained at 7, 28, and 56 curing days. Moreover, the RuC tensile strength (f_{tu}) and WA were obtained at 28 and 56 curing days, respectively. The obtained results were compared to verify the effect of the testing factors on the concrete strengths and WA.

2. Experimental Work

2.1 Material Properties

2.1.1. Aggregate and CR

The CR powder was taken from the OCTAL BET RESIN company in Oman. Fig. 1 shows the aggregates and CR grading curves in which the coarse aggregate (crushed basalt) and the fine aggregate (natural sand) agree with ASTM C33 limits [52]. The CR curve did not follow either the coarse aggregate or the fine aggregate limits, so it was sieved to replace specific sizes of sand. The sand fineness modulus and basalt maximum size were 3.0 and 12.5 mm, respectively. The physical properties of basalt (Fig. 2), sand (Fig. 2), and CR (Fig. 2) were obtained experimentally, and the average values are scheduled in Table 1. The sand and CR were sieved using sieves with opening sizes of 4.75, 2.36, 1.18, and 0.6 mm. The sand and CR remained on 4.75 mm sieve opening (denoted as 4.75 mm), passed the 4.75 mm sieve opening and remained on 2.36 sieve (denoted as 2.36 mm), those passed from the 2.36 mm sieve opening, and remained on 1.18 sieve (denoted as 1.18 mm), and those passed from 1.18 mm (denoted as < 1.18 mm) were collected in separate containers (Fig. 3). The previous sieved sand passed from sieve size 4.75 was used in the current mixes after adopting it to follow the ASTM C33 limits [52]. Consequently, the two CR sizes, 2.36 and 1.18 mm, were used to replace the corresponding sizes of sand partially. As the CR was obtained from car tires as in [53], the chemical composition of CR was taken from [53] (Table 2).

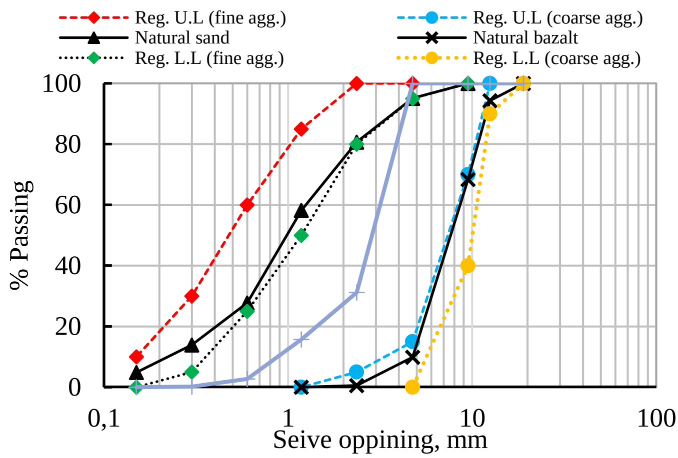


Fig. 1. Sieve analysis for the Sand, Basalt, and CR.

Basalt Sand CR

Fig. 2. The basalt, sand, and CR used in this study.

Table 1. The Physical properties of NA and CR.

Physical properties	Crushed Basalt	Natural sand	CR
Apparent specific gravity	2.92	2.62	1.26
Water absorption (%)	1.77	2.06	1.03
Moisture content (%)	0.93	1.04	-

2.36 mm (sand) | 1.18 mm (sand) | < 1.18 mm (sand)

2.36 mm (CR) | 1.18 mm (CR) | Not needed < 1.18 (CR)

Fig. 3. The classification of particle sizes for sand and CR.

2.1.2 Silica Fume and Cement

In this study, the silica fume (SF, from Saudi Silica Company) shown in Fig. 4a was utilized to coat the CR particles. Moreover, ordinary Portland cement (OPC from Al-Madinah company, KSA) was used for all mixtures. The compositions of both SF and OPC were experimentally obtained, as listed in Table 2.

Table 2. The chemical compositions of CR, OPC, and SF

Crumb rubber [53]		Cement and silica fume		
Test	Results	Item	OPC	SF
Ash content %	5.11	SiO_2	22.24	96.36
Carbon black content %	28.43	CaO	62.64	0.24
Acetone extract %	9.85	AL_2O_3	6.62	0.62
Volatile matter %	0.56	Fe_2O_3	2.33	0.81
Hydrocarbon content %	56.05	MgO	3.36	0.62
Polymer analysis	SBR	Na_2O	0.21	0.45
		K_2O	0.28	0.54
		SO_3	2.32	0.36
		L.O.I	0.58	1.4

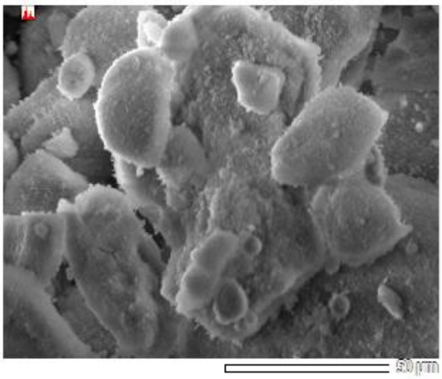
L.O.I= Loss on ignition

2.2 Coating of CR

The CR particles with sizes 2.36 and 1.18 were coated using SF slurry with a water/cement (W/C) ratio of 0.55. As reported in [54], the cement slurry with a W/C of 0.4 was used to coat the CR particles. The same quantity of cement slurry recommended in [54] for each CR particle size was also replaced by SF slurry to coat the CR particles used in this study. The SF, SF-coated CR, and the SEM of the SF are shown in Fig. 4.

Silica fume

CR coated with SF



SEM of CR.

Fig. 4. The SF, SF-coated CR, and the SEM of SF used in this study.

2.3 Mix Design and Testing Variables

The control mix (M0, Table 3) was designated according to [55] to integrate about 663, 1168, 180, and 430 kg of well-graded sand, basalt, water, and OPC, respectively. To keep the W/C constant (W/C= 0.5), the superplasticizer (Conplast SP430SA) with 2% of the cement (by weight) was used. The previous concrete components aimed to obtain the 28 days target compressive strength ($f_{cu,28}$) of 40 MPa with 60-100 mm slump. For mixes M1-M4 (G1), the uncoated 1.18 mm CR was used to partially replace sand by 5.0-25% (by volume) to study the CR effect on the concrete strengths and WA (Table 3). In G2 (mixes M5-M8), the uncoated 2.36 mm CR partially replaced sand by 5.0 and 10% (by volume, M5 and M6, respectively), while the combined uncoated CR of 1.18 and 2.36 mm partially replaced sand by 20 and 25% (by volume, M7 and M8, respectively). The mixes of G2 aimed to study the effect of uncoated CR content and size on the concrete strengths and WA (Table 3). Group G3 and G4 had the same mixes as G1 and G2, respectively, but the uncoated CR was replaced by coated CR with SF (Table 3). The mixes of G3 (M9-M12) aimed to study the effect of 1.18 mm CR coated with SF (1.18 CCR) on the concrete strengths and WA. Conversely, G4 (M13-M16) aimed to investigate the effect of 2.36 mm CCR and combined CCR (particle size =1.18 and 2.36 mm) on the concrete strengths and WA (Table 3).

Table 3. The weights and percentages of the components required for 1 m^3 of concrete.

Group		CR (%)	Sand (kg) (663.1)			Basalt (kg)	CR or CCR (kg)		Water (kg)	Cement (kg)	SP (%)
			2.36 mm	1.18 mm	< 1.18 mm		2.36 mm	1.18 mm			
Control	M0	0	99.5	165.8	397.8	1168	0	0	180	430	2.0
Uncoated crumb rubber											
G1	M1	5	99.5	132.65	397.8	1168	0	12.26	180	430	2.0
	M2	10	99.5	99.5	397.8	1168	0	24.53	180	430	2.0
	M3	20	99.5	33.2	397.8	1168	0	49.06	180	430	2.0
	M4	25	99.5	0	397.8	1168	0	61.33	180	430	2.0
G2	M5	5	66.35	165.8	397.8	1168	12.26	0	180	430	2.0
	M6	10	33.20	165.8	397.8	1168	24.53	0	180	430	2.0
	M7	20	33.20	99.5	397.8	1168	24.53	24.53	180	430	2.0
	M8	25	16.63	82.93	397.8	1168	30.66	30.66	180	430	2.0
Coated crumb rubber with silica fume											
G3	M9	5	99.5	132.65	397.8	1168	0	12.26	180	430	2.0
	M10	10	99.5	99.5	397.8	1168	0	24.53	180	430	2.0
	M11	20	99.5	33.2	397.8	1168	0	49.06	180	430	2.0
	M12	25	99.5	0	397.8	1168	0	61.33	180	430	2.0
G4	M13	5	66.35	165.8	397.8	1168	12.26	0	180	430	2.0
	M14	10	33.20	165.8	397.8	1168	24.53	0	180	430	2.0
	M15	20	33.20	99.5	397.8	1168	24.53	24.53	180	430	2.0
	M16	25	16.63	82.93	397.8	1168	30.66	30.66	180	430	2.0

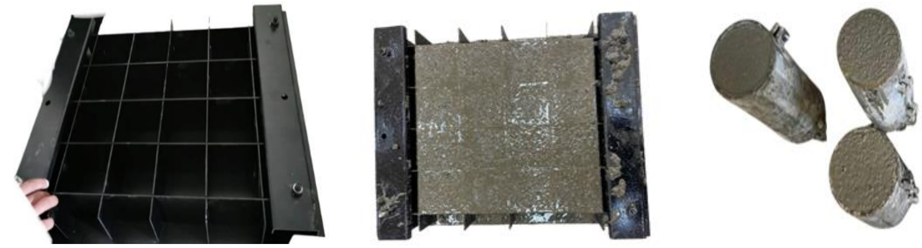
2.4. Mixing Procedures, Specimens, and Testing Methods

The sand, basalt, OPC, and CR or CCR (if they exist) were mechanically dry mixed for 1 min. Consequently, part of the mixing water was regularly added to the running concrete. Afterwards, the rest of the water mixed with the SP was added to the mixer, and then the concrete was mixed for 2 minutes after adding water. Sixteen steel cubes (100 mm x 100 mm x 100 mm x 100 mm x 100 mm) were prepared in one unit (designated by author, Fig. 5) to be cast for each mix to achieve the homogeneity of the cube's components. Moreover, the standard cylinders (150 mm in diameter and 300 mm in depth) were prepared from each mix for the Brazilian tensile test. The mechanical vibrator plate was used to compact the concrete for cubes and cylinders. The steel unit and cylinders were easily de-molded one day after casting without any vibration. The previously de-molded specimens were cured in water tanks until the testing date. The cubes were loaded in compression (Fig. 6) at 7, 28, and 56 days of curing (3 cubes for each case) and averaged to obtain the concrete compressive strength (fcu, [56]). The Brazilian tensile test (Fig. 6) was performed at only 28 days to get the 28-days tensile strength (ftu).

Conversely, the WA of the concrete mixes was measured at 56 days. Among the well-known method of WA measuring techniques ASTM C1585 [57], BS 1881 [58], and ASTM C642 [59], the simple and rapid technique reported in ASTM C642 [59] was used in which the WA was calculated using Eq. (1) [59].

$$WA\,\%_{\,(after\ immersion\ only)} = \left[\frac{(B-A)}{A}\right] \times 100 \tag{1}$$

Where A is the oven-dry mass (Temperature= 100 -110 ˚C and time ≥ 24 hours) and B is the surface-dried sample weight of the previous oven-dried cubes after immerging in water (time ≥ 48 hours and temperature ≈21˚ C).



Steel cube unit   Cubes Casting   Cylinder casting

Fig. 5 The prepared steel unit of cubes and casting process.

Compression Test   Tensile test

Fig. 6. The compressive and tensile tests of concrete.

3. Results and Discussions

3.1 Compressive Strength

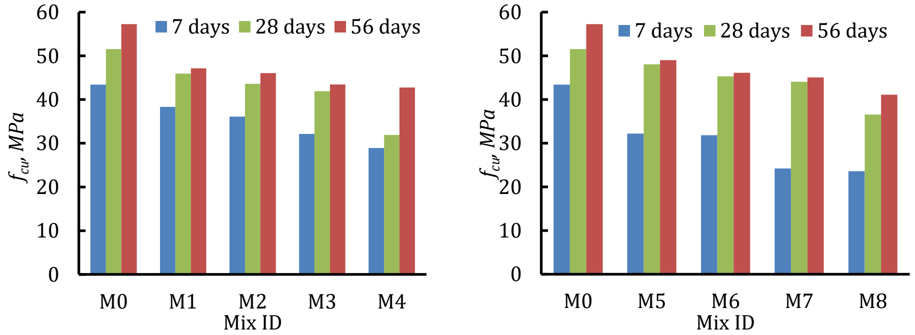
Table 4 summarizes the obtained RuC compressive strength at 7, 28, and 56 days of curing. Moreover, the reductions in the RuC compressive strength related to the NC strength (μ_7, μ_{28}, and μ_{56}) at the curing days (7, 28, and 56 days, respectively) are also reported in Table 4. Table 4 and Fig. 7 noted that the longer the curing period, the higher the concrete compressive strength, whatever the CR size and content. Moreover, increasing the CR content decreased the compressive strength of all concrete mixes at the three curing dates. For mixes M1-M4, in which the sand with grain size 1.18 mm was replaced by CR having the same particle size, the compressive strength decreased by 11.63-33.72% at 7 days of curing compared to M0. Consequently, increasing the curing date to 28 days reduces the compressive strength reduction for mixes M1-M4 to 10.89-22.12% compared to M0. In contrast, for the previous mixes (M1-M4), increasing the curing time to 56 days raises the compressive strength reduction to 17.67-25.32% compared to M0. For mixes M5 and M6, the sand with grain size 2.36 mm was replaced by CR having 2.36 mm particle size with similar percentages as in M1 and M2, respectively. For these mixes (M5 and M6), the compressive strength reductions were 25.12-26.66% at 7 days, 6.71-12.09% at 28 days, and 14.44-19.5% at 56 days compared to M0. Comparing M1 and M2 strengths with M5 and M6 strengths highlighted the effect of CR particle size on the concrete compressive strength. Replacing the sand with a high particle size by CR with the same particle size was more efficient than replacing the sand with a small particle size with the corresponding CR particle size. This means the mixes with high fine sand particles and course CR were more efficient than those with coarse sand and fine CR.

Table 4. Compressive strength of concrete with uncoated CR

Group	Mix ID	Specimen No.	$f_{cu,7}$ MPa	Mean MPa	μ_7 %	$f_{cu,28}$ MPa	Mean MPa	μ_{28} %	$f_{cu,56}$ MPa	Mean MPa	μ_{56} %
Control	M0	1	42.44	43.40	0.0	50.32	51.53	0.0	57.00	57.27	0
		2	44.14			50.27			56.20		
		3	43.62			54.00			58.60		
G1	M1	1	38.34	38.31	88.27	44.10	45.95	89.17	48.30	47.15	82.33
		2	34.13			47.74			46.00		
		3	38.27			46.00			43.20		
	M2	1	36.07	36.12	83.30	43.19	43.61	84.63	48.20	46.05	80.41
		2	36.14			43.64			43.90		
		3	36.16			44.00			46.00		
	M3	1	32.90	32.15	74.08	40.70	41.93	81.37	46.30	43.45	75.87
		2	31.40			43.10			40.60		
		3	26.40			42.00			44.00		
	M4	1	29.40	28.77	66.28	40.00	40.13	77.88	42.80	42.77	74.68
		2	24.30			39.90			42.30		
		3	28.00			40.50			43.22		
G2	M5	1	34.60	33.37	76.88	50.20	48.07	93.29	47.00	49.00	85.56
		2	31.80			46.80			49.60		
		3	33.70			47.20			50.40		
	M6	1	33.80	31.83	73.34	41.90	43.97	87.91	50.30	46.10	80.50
		2	31.70			46.90			43.00		
		3	30.00			43.10			45.00		
	M7	1	24.90	24.20	55.76	39.90	38.73	85.52	43.90	45.05	78.66
		2	23.50			38.80			46.20		
		3	24.20			37.50			45.30		
	M8	1	23.60	23.60	54.38	37.01	36.57	70.97	40.10	41.10	71.77
		2	23.90			36.80			42.10		
		3	23.30			35.90			41.60		

$f_{cu,7}$, $f_{cu,28}$, and $f_{cu,56}$= compressive strengths at 7, 28 and 56 days of curing.

Conversely, replacing the sand with combined particle sizes 2.36 and 1.18 mm by the corresponding ratio and particle sizes of CR (M7, 20% CR) follow the same trend as M5 and M6. In contrast, increasing the content of CR with combined particle sizes 2.36 and 1.18 mm to 25% decreased the compressive strength compared to M4 with 1.18 mm CR size (Table 4 and Fig. 7). Increasing the CR content with combined 2.36 and 1.18 mm particles in M8 decreased the concrete strength compared to M4 as the CR particles with big sizes compressed more than those with small sizes besides their weak bond with the surrounding paste. From the previous discussion, replacing sand with size 2.36 mm by the same CR size showed lower effects on the concrete compressive strength than replacing size 1.18 mm as the existing finer sand size may enhance the mix's cohesion than that with size 2.36 mm. Moreover, the smaller the sand size, the higher the area of cohesion in the mix, in contrast to CR, as CR surface affected the mortar cohesion with the surrounding aggregate.



Uncoated CR with 1.18 mm   Uncoated CR with 3.36 mm

Fig. 7. Effect of un-coated CR size and content on the concrete compressive strength

SF was used to coat the CR particles to enhance the bond between the CR particles and the surrounding concrete components. To show both the SF coating and CR particle size effects on the concrete strength, the mixes in group G3 (with SF pre-coated CR) were compared with the corresponding mixes in group G1 (with uncoated CR), see Table 5 (μ_1, μ_2 *and* μ_3 are the percentage of concrete strength with SF coated and uncoated CR at 7. 28 and 56 days, respectively).

Table 5. The compression strength of concrete with SF-coated CR

Group	Mix ID	Spec. No.	$f_{cu.7}$ MPa	Mean MPa	$f_{cu.28}$ MPa	Mean MPa	$f_{cu,56}$ MPa	Mean MPa	μ_1 %	μ_2 %	μ_3 %
		1	39.10		46.90		47.20				
	M9	2	38.90	40.18	45.40	46.15	48.90	48.05	104.88	100.44	101.91
		3	40.60		47.30		47.07				
		4	43.00		49.60		48.50				
	M10	1	42.40	42.73	45.10	47.33	48.02	48.26	118.30	108.53	104.80
G3		2	42.80		47.30		46.10				
		1	23.51		28.12		33.40				
	M11	2	23.90	23.80	27.24	26.88	31.20	32.3	74.03	64.11	74.34
		3	24.00		25.28		33.00				
		1	23.51		25.30		26.00				
	M12	2	22.30	22.50	24.00	24.50	25.00	25.6	78.02	92.43	59.86
		3	21.70		24.20		25.80				
		1	38.11		46.80		47.25				
	M13	2	38.42	38.28	40.91	44.43	48.3	47.20	114.71	92.42	96.82
		3	38.30		45.30		46.2				
		1	29.12		35.73		41.7				
	M14	2	28.54	29.03	36.62	35.46	38.9	40.30	91.20	80.65	87.42
G4		3	29.43		34.02		37.2				
		1	27.24		31.63		35.6				
	M15	2	28.60	27.98	29.91	31.89	33.9	36.00	115.62	82.34	79.91
		3	28.10		34.14		36.5				
		1	25.80		25.30		32.4				
	M16	2	24.09	25.33	27.95	27.74	33.9	34.03	107.33	75.85	82.80
		3	25.30		29.98		35.8				

Besides, comparing the results in G2 with the corresponding mixes in G3 and G4. In G3, for the mixes M9-M12, the sand with a grain size of 1.18 mm was replaced by 1.18 mm CR particles pre-coated with SF. The compressive strength of M9 and M10 enhanced by 104.88 and 118.3% (at 7 days), 100.44 and 108.53% (at 28 days), and 101.91 and 104.80 (at 56 days) compared to M1 and M2, respectively, at the same curing days (Table 4). In contrast, increasing the content of CCR with 1.18 mm size to 20 and 25% decreased the concrete compressive strength compared to the corresponding specimens with uncoated CR. The extra amount of SF in the mix may affect the cement hydration and reduce the concrete strength. Conversely, using the CCR with a 2.36 mm size to replace the sand with a 2.36 mm size decreased the concrete strength compared to the corresponding mixes with uncoated CR. The higher the CR particle size, the easier CR was compressed and the lower the effect of the coating. Moreover, increasing the pre-coated CR content increased the SF in the mix and thus decreased the concrete compressive strength. The same trend was also noticed for RuC mixes (M15 and M16) compared to M7 and M8, respectively (Table 5 and Fig. 8). Among all the tested mixes, M10 showed the highest compressive strength value compared to M0 (93.65% at 28 days, Table 5). A sample of the tested cubes for mixes with coated and uncoated CR is shown in Fig. 9.

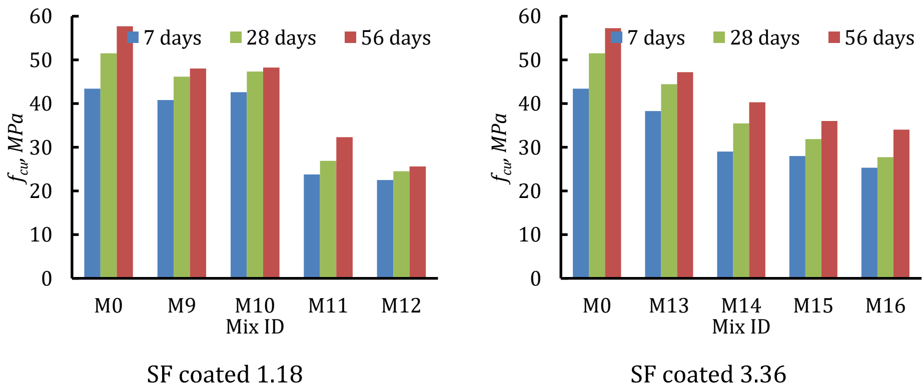


Fig. 8. Effect of SF-coated CR size and content on the concrete compressive strength.

3.2 Concrete Tensile Strength

The tensile strength at 28 days of curing for the tested RuC mixes decreased or increased depending on the CR content and particle size (Fig. 10, M refers to the mixes containing combined sizes of CR with 2.36 and 1.18 mm particle sizes). The tensile strength for the mixes with 1.18 mm uncoated CR was lower than that of M0. The RuC tensile strength reduction decreased as the replacement ratio of 1.18 mm CR increased from 10 to 25 %. The mix M2 had the best tensile strength among the mixes cast with the 1.18 mm uncoated CR. Replacing sand with 2.36 mm uncoated CR decreased the RuC tensile strength. The reduction increased as the CR content increased. Increasing the CR size increased the RuC tensile strength reduction. Conversely, coating the CR with SF reduced the tensile strength compared to those with uncoated CR except for M6 (1.18 mm CCR%= 10%). In contrast, the mixes with 2.36 mm coated CR showed higher tensile strength than those with uncoated CR.

M1

M2

M5

M6

M9

M10

M13

M14

Fig. 9. Photos of the specimens with pre-coated and un-coated CR tested at 28 days of curing

The mix M5 (CCR with 2.36 mm) showed higher RuC tensile strength than M0. From the above, it was assured that replacing the fine sand with 1.18 mm uncoated CR increased the RuC tensile strength than replacing the 2.36 mm sand with 2.36 mm uncoated CR. Conversely, replacing the sand with combined particle sizes by the corresponding CR (1.18 and 2.36 mm CCR) was more efficient than using the 1.18 mm CCR. The uncoated 1.18 mm CR may act as a crack closer with more efficiency than the uncoated 2.36 mm CR. Consequently, in the case of CCR, replacing the 1.18 mm sand with 1.18 mm CCR might increase the SF surface area and disturb the cement hydration than in the case of coarser CR with low SF surface area.

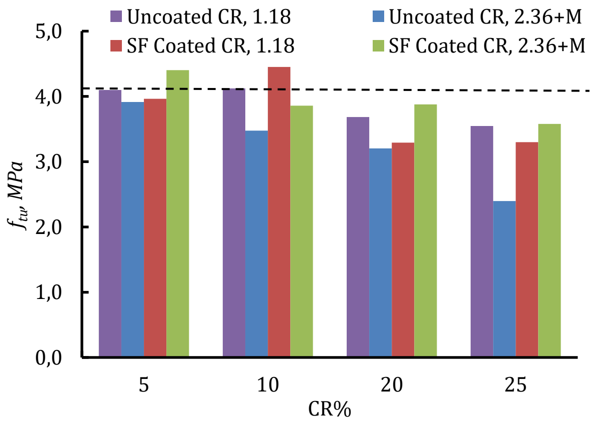


Fig. 10. The tensile strength of RuC mixes at 28 days. The dash line= M0 tensile strength (4.16 MPa).

3.3 Water Absorption of Concrete

Water absorption of concrete for all the prepared mixes tested at 56 days is presented in Fig. 11. WA was found to be concerned with the surface porosity and structural pores, and the existence of pores in geopolymer concrete specimens is also connected to WA [60,61]. Moreover, the finer the fly ash, the higher the surface area of its particles, which enhances the fly ash reactivity and the concrete properties [62]. From Fig. 11, it was observed that the WA of the RuC was higher than the WA of M0 except for M13 (with 2.36 mm CCR) as the porosity of the concrete increased with adding CR. The WA for mixes M1-M4 in which the 1.18 mm uncoated CR was partially replaced by the 1.18 mm sand had nearly the same values. Coating the 1.18 mm CR with SF significantly increased the WA, revealing the effect of SF on increasing the WA except for M10 (with 10% of 1.18 mm CCR). Conversely, increasing the uncoated CR size increased the WA of RuC as the concrete porosity increased as the CR particle size increased. Conversely, coating the 2.36 CR with SF decreased the WA of RuC, which reveals that the lower the coated CR area, the lower the WA, as the SF could decrease the decreased voids generated by the CR in the concrete mixes [41,60,61].

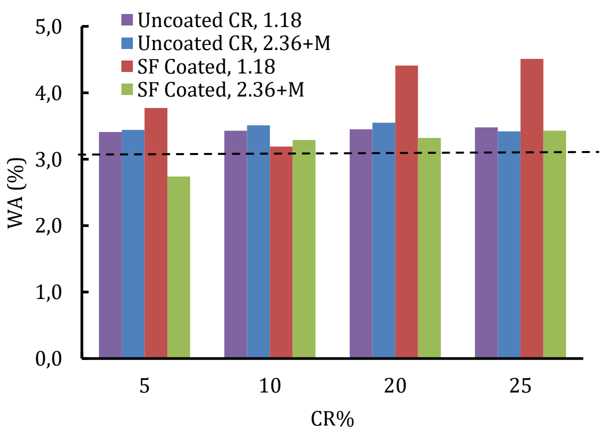


Fig. 11 The WA of RuC mixes at 28 days. The dash line= WA% of M0 (3.07).

4. Conclusion

- The higher the fine sand in the RuC mix, the higher the area of cohesion in the mix compared to those with uncoated CR, as the surface of rubber affected the mortar cohesion with the surrounding aggregate.
- Replacing sand with a particle size of 2.36 mm by 5 and 10% of 2.36 mm CCR showed higher RuC compressive strength than replacing sand with 1.18 mm particle size by the corresponding 1.18 mm CCR at all testing ages (7, 28, and 56 days).
- Increasing the content of CCR with 1.18 mm particle size to 20 and 25% decreased the concrete compressive strength compared to the corresponding specimens with uncoated CR. Also, using the CCR with a 2.36 mm particle size to replace the same content of sand with a 2.36 mm particle size reduced the concrete strength compared to the corresponding mixes with uncoated CR.
- Replacing the fine sand (particle size=1.18 mm) with uncoated CR (particle size=1.18 mm) increased the RuC tensile strength than replacing the sand with 2.36 mm particle size with the corresponding uncoated CR. Conversely, replacing the sand with combined particle sizes (1.18 and 2.36 mm) with the corresponding CCR was more efficient than replacing the sand with a 1.18 mm size particle with the 1.18 mm CCR.
- In the case of CCR, replacing the sand with a 1.18 mm particle size by the corresponding CCR might increase the SF surface area and disturb the cement hydration than in the case of coarser CCR, which had a lower SF surface area.
- As the 1.18 mm sand was partially replaced by 1.18 mm uncoated CR, the RuC mixes had nearly the same WA values. Using the 1.18 mm CCR instead of sand significantly increased the WA of the RuC, revealing the effect of SF on increasing the WA except for M10 (with 10% of 1.18 mm CCR). In contrast, Increasing the particle size of uncoated CR increased the WA of the RuC. Conversely, using the 2.36 CCR to replace sand decreased the WA of the RuC than for the 1.18 mm CCR.

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