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Comprehensive Study on Rubber Particle Size and Replacement Ratio on Fresh and Hardened Properties of Rubberized Concrete: A Review

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Abstract: The black pollution caused by the accumulation of Waste Tire Rubber (WTR) has engendered significant environmental and social consequences throughout the world by emphasizing the requirement of introducing a new approach to recycling WTR effectively. The recent research findings towards the utilization of End-of-Life Tires (ELT) to replace the Natural Aggregate (NA) in concrete have facilitated a promising way to handle the WTR while reducing the consumption of natural raw materials in the construction industry. However, the weak Interfacial Transition Zone (ITZ) between rubber aggregate and cement paste reduces the properties of Rubberized Concrete (RuC) and hinders its commercial usage. Among the many factors, the rubber particle size, shape, and Replacement Ratio (RR) significantly influence the performance of RuC. This paper reviews previous research findings relevant to the effect of the rubber particle size, shape, and percentage replaced in the concrete mix to pinpoint the further research gaps to be investigated. Overall, the previous findings indicate that the tire aggregate inclusion at a low level of replacement in the form of crumb rubber resulted in improved ductility and toughness with marginal impacts on workability, strength, and other mechanical properties of concrete compared to the control mix without WTR.

Keywords: Waste tire, Rubberized concrete, Particle size, Replacement ratio, Properties of concrete

1. Introduction

The rapid growth of the world's population and economic development has evolved waste generation, which will double in 2025 compared to the waste accumulation in the year 2000 [1,2]. Meanwhile, the massive generation of waste has provoked detrimental consequences on the environmental, economic, and public health sectors while emphasizing that the make, use, and throw model is not sustainable to any further extent, which has highlighted the significance of recycling all forms of waste materials while supporting a closed-loop circular economy [1,3]. Among the various sources which are responsible for generating tons of waste, End-of-Life Tires (ELT) are playing an enormous role due to their large volume of production and non-biodegradable properties since nearly 80% of automotive tires are produced by incorporating highly durable vulcanized rubber, which cannot be recycled easily [3-5]. The composition of tire rubber is shown in Table 1. Moreover, the previous statistics proved that the global annual production of tires is about 1.5 billion, and almost 1 billion tires are discarded as ELT annually. Meanwhile, more than 50% of ELT are stockpiled, or landfilled while creating detrimental impacts such as the leaching of toxic substances into the soil, accidental fires, and acting as breeding grounds for disease-carrying pets [3-7]. In addition, several researchers have confirmed that current disposal methods are wasteful and costly as they require either consumption of landfill space or regular costly maintenance [8].

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Table 1 - General Composition of Tires [9]

Material	Approx. Weight %
Rubber hydrocarbon composition (RHC)	48
Carbon black and silica	22
Metal reinforcements	15
Oil, antidegradants, wax, stearic acid, etc.	8
Fabric	5
Zinc oxide (ZnO)	1
Curing agents	1
Total	**100**

Consequently, recognizing the feasible methods to recycle ELT is crucial before they develop a catastrophe in the environmental, economic, and public health sectors. Meanwhile, demand for concrete has increased while consuming and depleting enormous quantities of natural construction materials since NA utilize nearly 70% volume of concrete mixture [7,10]. Whilst discovering a feasible solution for these emerging matters, recycling WTR to produce rubber aggregate (RA) has generated a renewed interest worldwide since rubber is a valuable material with high strength, durability, and elasticity properties, which can engender a beneficial impact to ameliorate the fresh and hardened properties of RuC. In addition, including such waste as an alternative material for replacing the NA in the concrete mix improves the sustainability of the building construction materials [11].

However, as stated in the literature, it is evident that the applications associated with RuC are mainly bounded to the non-structural components and low-strength structural elements [7,8]. Although WTR provides considerable potential to replace fine and coarse aggregate in the concrete mixture, the inclusion of RA conduces to alter the fresh and hardened properties of concrete significantly [3]. On the other hand, recycling waste tires into rubber granules is an energy-intensive and time-consuming process, which incurs a high cost [7,12] that keeps people away from this contemporary approach. In addition, many scholars have reported that the poor bond performance between rubber particles and the cement paste matrix causes a significant reduction in the mechanical and durability properties of RuC [7,8,13].

Although the RuC shows a decreasing trend in fresh and hardened properties, the controversy in the previous research findings still emphasizes the requirement of executing further investigations on this topic [14]. Consequently, this review paper debates the effect of the rubber replacement percentage, the shape & size, and the source of WTR on the properties of the RuC, and the notable matters are highlighted for future investigation.

2. Waste Tire Rubber Aggregate (WTRA)

The recycling process of WTR consists of several stages, which include shredding tires into different sizes in several phases while separating contaminants like textile and steel fibres [3]. The WTRA is mainly classified into three different categories based on their sizes (Figure 1) as stated below.

1. Rubber Chips (CH) for replacing coarse aggregate (13 -76 mm) [3,6,13]
2. Crumb rubber particles (CR) that replaces the fine aggregate (0.075 – 4.75 mm) [3,6,13]
3. Fine ground rubber (FG) for replacing cementitious material (0.075 – 0.5 mm) [3,6,13]

The process for manufacturing each type of rubber granules is subjected to a specific mechanism. The chipped rubber is produced by shredding the waste tires in two stages. Initially, waste tires are shredded into pieces that are generally 300-430 mm in length and 100-300 mm in width. Subsequently, the dimensions are lessened to 100-150 mm by cutting WTR pieces and if further reduction is required, particles are cut into 13-76 mm sizes, which is called chipped or shredded rubber [6,13]. The crumb rubber is manufactured by reducing the size of chipped rubber further down to sizes ranging from 0.075 to 4.75 mm by removing 99 per cent or more of the steel and fabric from the waste tires [6]. Past literature reveals that several techniques are available for manufacturing crumb rubber such as ambient grinding, cryogenic processing, and crack mill process [15-17]. Micro-milling process or wet grinding is used to produce fine ground rubber particles ranging from 0.075–0.475 mm by allowing particles to pass through two stages, which are magnetic separation and screening [13,15].

Figure 1 - Different Types of WTRA [17]

Table 2 - Physical Properties of Aggregates

Properties	Gravel	Sand	CH	CR	FG	Reference
Density (kg/m^3)	2690-2880	2400-2910	1010-1120	900-1180	950-1050	5,6,7,10,18,19,21,23,24,27,53
Bulk Density (kg/m^3)	1422-1610	1410-1770	359-497	590-650	650	19,18,23,51
Water Absorption (%)	0.3-1.32	0.3-0.8	1.6-5.1	2.97-5.1	-	5,7,19,18,45
Fineness Modules	5.57-7.31	2.0-2.9	-	1.91-2.83	1.56-2.17	4,10,19,22,21,23,27,53

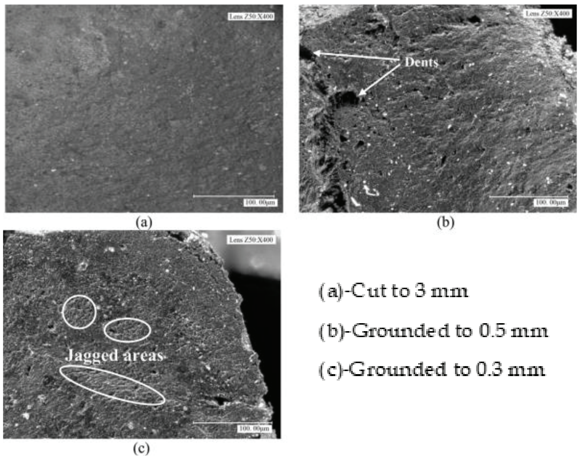

Figure 2 - SEM Images of Different Sizes of WTR Particles [14]

However, the mechanism used to grind the WTR significantly influences the fresh and hardened properties of the concrete [7]. The observation made by Bravo et al. [18] confirmed that mechanically ground rubber shows lower workability than cryogenic ground rubber due to the rough surface of the RA processed mechanically. Moreover, Su et al. [14] used three different sizes of WTRA (3 mm, 0.5 mm, and 0.3 mm) to identify the size effect of RA on the properties of RuC. In this experiment, the images processed from a Scanning Electron Microscope (SEM) clearly exhibited the presence of some dents and jagged areas on the surface of the fine rubber particles compared to the coarse rubber particles (Figure 2) and observed that roughness of the crumb rubber results in increasing the frictional resistance to the flowing movement of concrete. Hence, exploring the influence made by the shape and size of RA on the properties of concrete is imperative for improving the performance of RuC.

The physical properties of WTRA exhibit significant divergence compared to the NA as summarized in Table 2. Due to the specific properties of WTRA compared to NA, RuC experiences a significant reduction in compressive strength and certain durability properties compared to conventional concrete mixture [3,7,18]. However, the inclusion of WTRA in the concrete mix evolves several beneficial attributes compared to the conventional concrete mix [6] such as enhanced ductility [7,8,19], reduced density [8,10,20], improved energy absorption capacity [8,19,20] & impact resistance [3,20], reduced drying shrinkage [21], improved resistance to crack propagation without catastrophic failure [7,19,22], etc. Considering these advanced properties, many scientists have suggested promoting the usage of RuC towards light-weight structures [4,8], railway sleepers [19], crash barriers around bridges [3,8,20], low-strength concrete applications [8,10,20], noise barriers [20], etc.

3. Properties of Rubberized Concrete

3.1 Workability

Workability is defined by the ease of mixing, placing, and consolidating fresh concrete whilst maintaining adequate concrete homogeneity without segregation and bleeding effects [5]. Moreover, workability is a predominant property of fresh concrete, which make a significant influence on the hardened properties of concrete. However, it largely depends on the properties of raw materials used in the concrete mix [3]. Generally, the workability of RuC decreases with the increase in rubber content [3,7,8,14,23,24]. Nevertheless, previous research findings on RuC with different particle sizes exhibit conflicting results. Reda Taha et al. [24] reported that increasing the size of RA results in lower workability due to the rough surface of rubber particles, which generates high friction between fresh concrete ingredients. Eldin et al. [8] also recorded the same observation and reported that tire chips form interlocking structures under their own weight, which resist normal flow while reducing workability.

Interestingly, Karunarathna et al. [7], & Su et al. [14], observed an Abbas et al. [23] entirely contrasting result that reducing particle size lowers the workability of RuC due to the higher surface area of finer RA in unit volume than coarser RA, which generates more friction in the concrete mix while reducing the workability [7,22]. Moreover, the surface of the fine RA is much rougher than coarse RA due to the presence of dents and jagged areas (Figure 2), which further increases the frictional resistance to the flowing concrete [7,14]. Furthermore, Rashid et al. [22] & Khatib et al. [25] also reported the same observation while pinpointing the above phenomenon. Hence, it is obvious that there is a general reduction in slump values regardless of rubber particle sizes due to the presence of a rough surface.

Despite the previous findings demonstrating the contradictory results on the workability with the different sizes of RA, the validity of the general practice of using well-graded particles to produce the most workable and economical mix [26] requires to be checked for the RuC. Su et al. [14] examined the workability of RuC separately for both uniform and graded particles at 20% RR with fine aggregate and observed that graded rubber particles exhibit better performance in workability due to the improved packing density, which lessens the presence of voids in the RuC [14]. The same observation was reported by Raffoul et al. [5] by confirming that the combined replacement of fine and coarse RA helps to minimize the negative influence on strength and workability even for the higher rubber contents. Based on the literature review, it is evidenced that RuC gives acceptable workability at lower RRs (15-20%). However, Khatib et al. [25] reported that when rubber content exceeds 40% by total aggregate volume, the slump was near zero and the mix was not workable. Hence, recognizing the optimal RR and size of RA is highly recommended for achieving the desired workability.

Even though adding rubber aggregate decreases workability, RuC shows acceptable workability in terms of handling, placing, and finishing [14,27]. Numerous studies emphasized that the ordinary way of measuring slump does not support the actual state of the RuC workability [28] since adding more water to RuC mixes did not appear to change the slump significantly [8]. Anyhow, the workability of RuC can be improved by producing surface-treated rubber aggregates [3] and controlling the water cement ratio (w/c) of the concrete mixture [10]. In addition, Stalling et al. [29] and Tiwari et al. [30] reported that the workability of RuC can be improved by adding water-reducing admixtures.

3.2 Density

The density of the concrete mixture decreases with increasing percentage of rubber particles due to the lower specific gravity of RA compared to NA [8,10,18,19,25], increased air content [5,24,25], and lower packing density of rubber particles [5]. The previous experimental results obtained from the past research papers are summarized in Table 3, which clearly represents the decreasing trend of density over increasing rubber content. Interestingly, Eldin et al. [8], Topcu [19] & Khatib et al. [25] observed that the relationship between the unit weight of the RuC and rubber content linearly declines when increasing rubber RR under proper batching and good quality controlling conditions.

Table 3-Effect of WTRA sizes and replacement ratio on the density of RuC (28 Days)

Size (mm)	w/c	Density (kg/m^3)	Replacement Ratio (%) / Unit Weight Reduction Factor (%)																	Ref.
			2.5	5	7.5	10	12.5	15	17.5	20	25	30	40	45	50	60	75	80	100	
Coarse Waste Tire Rubber																				
4-10	0.40	2296				-11		-13		-14	-16.1									47
	0.45	2483	-1.6	-2.2	-2.5															41
5-19	0.60	2385				-6.8				-9.1		-14.3								19
8-20	0.52	2372									-2.9				-5.8		-8.8			39
		Mean	-2.1		-6.6		-11.9				-15.2									
		± S.D	0.4		4.1		2.5				7.2									
Fine Waste Tire Rubber																				
0.3	0.37	2400								-3.8										14
0.5	0.37	2400								-4.0										14
0.3-3	0.37	2400								-3.5										14
1-4	0.62	2300						-3.5				-7		-13						18
1-4	0.48	2087				-2.8				-6.4		-13	-17		-22					51
2	0.31	2459		-1.4		-3.4		-5.2												40
3	0.37	2400								-3.1										14
<4	0.60	2385				-0				-7.0		-9.6								18
<4.75	0.44	2471		-4.3		-6.8		-11		-14										30
<4.75	0.56	2399								-7.6			-14			-17		-24	-27	31
<5	0.40	2367		-1.3		-2.6		-4		-5.3	-6.57	-7.9	-11							44
		Mean	-2.4		-3.1		-6.0				-8.9		-15.2			-17.2		-25.57		
		± S.D	1.7		2.4		3.3				2.8		4.6					2.7		

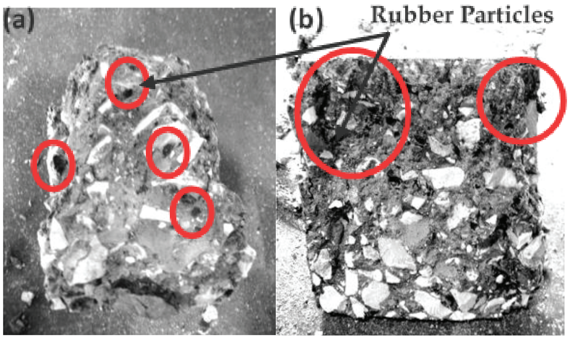

Figure 3-(a)15 s Vibration (b)30s Vibration [18]

Considering the effect of the rubber particle size, Eldin et al. [8] & Su et al. [14] measured the density and observed a decreasing trend when decreasing the particle size. Siddique et al. [16] also noted the same behaviour and reported that the non-polar nature of rubber particles repels water and increases the entrapped air on the rubber surface while expanding the number of air voids, which causes to lessen the density of RuC. However, the mean values in Table 3 show that density reduction in crumb rubber is lower than that of chipped rubber. Moreover, the density of RuC purely depends on the properties of rubber particles and the percentage of steel fibres remaining inside. Generally, previous research findings exhibit nearly 25% of unit weight reduction at 100% coarse aggregate replacement [8,31]. Nevertheless, it has been reported that the rubber content should not exceed 20% of the aggregate volume for maintaining unit weight within an acceptable range [31].

The effect of the vibration during concrete compaction plays a significant role in both fresh and hardened properties of concrete since RA tend to float top upon vibration due to the lower specific gravity of RA compared to other ingredients in the concrete [18]. Moreover, Bravo et al. [18] checked the required vibration time to mix every component homogeneously by vibrating RuC specimens separately for 15s and 30s and observed that the specimen with 30s vibration shows distinct segregation (Figure 3). Moreover, Zhu et al. [32] conducted a similar kind of experiment and reported that the floating and segregation consequences of rubber particles are more sensitive to the vibration time and can be controlled by optimizing the fines content in the concrete mix. Hence, great care should be taken while compacting RuC in the fresh stage to avoid unnecessary segregation upon over-compaction.

3.3 Air Content


Figure 4 - Trapped Air Bubbles on the WTR [7]

Concrete mixtures with higher rubber content typically produce high air content due to the non-polar nature of rubber particles [16] and the rough texture of WTRA [24, 29], which eventually increases the porosity of the concrete mixture. The observation made by Karunarathna et al. [7] by submerging tire shreds in the water clearly exhibits the entrapped air bubble on the rubber surface (Figure 4).

Moreover, it is noted that the percentage of voids inside the concrete is higher for chipped rubber than that for crumb rubber [7,18]. This can be attributed to the filler effect of crumb rubber particles although the texture of crumb rubber is rougher than coarse rubber [7]. Moreover, previous findings exhibit an approximately linear relationship between air content and rubber content when increasing RR [24]. Controlling the void inside the concrete matrix is highly essential since increased voids prevent the formation of strong bonds between rubber particles and cement paste, which leads to altering the properties of RuC detrimentally [33]. Pelisser et al. [34] reported that adding silica fumes (SF) conduces to reduce the air content due to the improved packing density.

3.4 Abrasion Resistance

Thomas et al. [10] reported that RuC exhibits better resistance to abrasion than the control specimen due to the resistance made by the rubber particles projected beyond the concrete surface, which is acting like a brush. Moreover, Kang et al. [35] reported that increasing rubber content with SF further increases the abrasion resistance of RuC. However, conflicting results were also found on the abrasion resistance of RuC. Sukontasukkul et al. [36] reported that increasing rubber content reduces abrasion resistance. The same observation was reported by Gupta et al. [37] when increasing rubber ash content in the concrete mixture. Nevertheless, when rubber ash is mixed with rubber fibres, the depth of wear was reduced with improved abrasion resistance [37], which emphasizes the rubber particle's size effect on the abrasion resistance. Moreover, Gupta et al. [37] reported that abrasion resistance could be improved by reducing the w/c of the concrete mixture. However, many scholars believe RuC shows better abrasion resistance than conventional concrete [3]. Nevertheless, further investigations are imperative to cognize the authentic behaviour against abrasion due to the lack of studies and controversial results.

3.5 Compressive Strength

Results of previous studies exhibit that the size, RR, and surface texture of rubber particles significantly affect the compressive strength of RuC. Although WTRA has been identified as an alternative material to replace NA in the concrete mixture, the addition of rubber changes the properties of RuC mix significantly compared to reference concrete [3,11,38].

Generally, the strength of the RuC decreases when increasing rubber RR [8,18,19,25,27] due to the poor adhesion between RA and cement paste [6,7,8,14,19]. In addition, low stiffness and poor surface texture of rubber particles make an inconsistency in the concrete mix [7]. Eldin et al. [8], Li et al. [12] & Topcu [19] found that the decrease in compressive strength is lower for crumb rubber due to the packing effect of the smaller rubber particles and better bonding between fine rubber particles and cement paste compared to the rubber chips. The SEM images (Figure 5-a,b) show a clear discontinuity along the rubber chip and cement paste (Lines I & II) compared to the crumb rubber and cement paste (Figure 5-c,d) by confirming the adhesion between cement paste and chip rubber is poorer than that of the crumb rubber [7]. Hence, it has been examined that the weak interfacial bond facilitates the appropriate condition for propagating cracks that lead to the failure of concrete under increasing compressive loads [22]. In addition, Rashid et al. [22] reported that well-developed smooth ITZ between fine rubber and cement matrix ameliorates the compressive strength of RuC. Another possible reason for the higher strength reduction of chipped rubber concrete is the replacement of natural aggregate with relatively low-stiff material since the strength of concrete greatly depends on the coarse aggregates [14].

Eldin et al. [8] reported 85% and 65% of strength reduction when coarse and fine aggregates are totally replaced with chip and crumb rubber, respectively. In addition, when rubber content exceeds 80% of the aggregate volume, the gap between 7 and 28 days of strength results is significantly reduced [25]. Despite some scholars confirming that crumb rubber concrete gives higher strength than chipped rubber concrete [7,12,19,39], interestingly Bravo et al. [18] observed higher compressive strength for coarse rubber than fine rubber. But, in his investigation, coarse aggregates were replaced in the range of 4 mm to 11.2 mm. Moreover, Su et al. [14] reported that a mix of well-graded rubber particles shows better performance in RuC strength than singly sized particles. Nevertheless, Stalling et al. [29] observed that replacing crumb rubber gives better performance in compressive strength than coarse rubber or a combination of coarse and fine rubber. Referring to these observations, it is evidenced that the particle size effect on the strength of RuC is still questionable and a detailed investigation is required for further clarification.

Consequently, in this review paper, the previous studies relevant to the untreated crumb and chipped rubber particles are studied and analysed deeply to cognize the real effect of rubber particle size and RR on the compressive strength of the RuC. A summary of the findings extracted from the previous research is listed in Table 4 separately for crumb and chip rubber. The strength reduction factor (%) compared to the strength of the control specimen is calculated separately for each RR (2.5% to 100%). The negative sign denotes the reduction of strength compared to the control specimen.

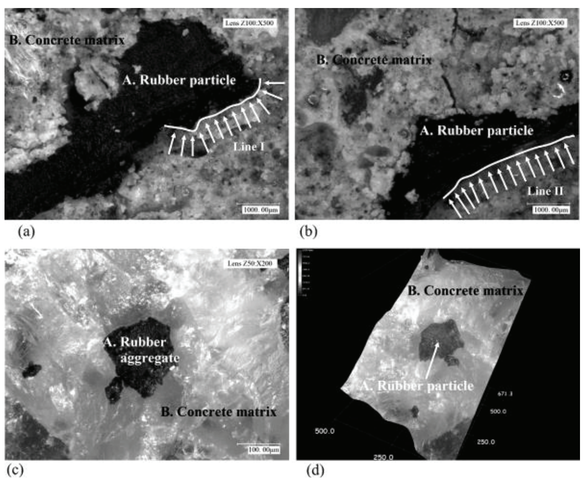

Figure 5 - ITZ between Rubber and Cement Matrix; Chipped RA (a,b), Crumb RA (c,d) [14]

Table 4-Effect of WTR sizes and replacement ratio on the 28 days compressive strength of RuC

Size (mm)	w/c	CSC[6] (Mpa)	2.5	5	7.5	10	12.5	15	17.5	20	25	30	40	45	50	60	75	80	100	Ref.
			Replacement Ratio (%) — 28 Days Compressive Strength Reduction Factor (%)																	
Coarse Waste Tire Rubber																				
6.25 [1]	0.5	33.6									-31.3				-43.5		-56.7		-63.5	8
4-10 [3]	0.4	43.5				-33		-54		-65	-73									47
4-11.2 [2]	0.5	55.5				-14.8			-32		-48.7									38
<12.7	0.5	31.9									-38.6				-56.7		-69.0		-76.5	27
15 [2]	0.4	41.3			-21.4				-29											7
<19 [5]	0.4	35				-28.6				-48.6		-66	-74		-85.7					29
5-19	0.6	22.3				-39.5				-57.4		-74.0								22
5-20	0.4	61.7				-25.6				-47.0			-59.0			-74.4		-76.8	-85.9	5
5-20	0.6	26.5									-40				-48		-73		-78	24
8-20 [4]	0.5	45.8									-47.8				-54.4		-62.0			39
10-40	0.4	54		-12.0		-18.5		-29.6		-37.6	-43.0	-49								60
19-37.5	0.5	33.6									-43.5				-65.8		-76.0		-82.7	8
		Mean		-12	-25.9		-44.5				-50.4		-60.9			-68.5		-77.2		
		± S.D			8.6		13.1				14.2		13.9			7.9		7.7		
Fine Waste Tire Rubber																				
<0.3 [3,4,5]	0.4	32.1		-3.5		-26.6		-27.0		-31.7										56
0-0.3 [3]	0.4	43										-46.1								61
<0.6 [3,4,5]	0.4	32.1		-9.7		-22.4		-16.1		-28.9										56
0.3	0.4	61.1								-9.5										14
0.5	0.4	61.1								-9.7										14
0-1	0.6	23.5						3.15				-16.0		-37						19
1	0.5	37.2		-5.4		-14.5				-20.2										57
1-1.32	0.5	32.3						-22.8				-46								53
2 [5]	0.3	57.8		-12		-21.6		-34.8												40
0.05-2 [2]	0.5	33								-25.2		-39								58
1-2 [3]	0.4	43				-15.4				-24.0		-33								61
0.3-3	0.4	61.1								-9.82										14
1-4	0.6	23.5						-31.1				-46		-58						19
1-4	0.5	33.6				-20.8				-24.4		-43	-65		-79.2					51
0.15-4.75	0.6	25.3								-25.2			-52			-68.1		-82.4	-90.1	31
0.8-4	0.4	42.5	-4	-12	-12.9	-21.2	-29.4	-41.2	-45	-52.9										10
	0.5	39	-3	-15	-21.8	-29.5	-35.9	-44.9	-45	-48.7										10
	0.5	36.5	-8	-16	-19.7	-34.3	-41.6	-49.9	-52	-53.4										10
2-4 [2]	0.4	41.3			-19.2				-21											7
2-4 [3]	0.4	43										-35								61
1-5	0.6	26.5									-15				-25		-50		-67	24
3	0.4	61.1								-10.6										14
<4.75	0.6	22.3				0.45				-43.1		-57								22
<4 [2]	0.5	55.5					-19.8				-35.1		-52							38
<4 [1,2]	0.5	55.5					-19.3				-33.3		-52							38
<4	0.4	54		-7.4		-17.6		-24.4		-35.2	-36.1	-44								60
<2.38 [5]	0.4	35.0				28.6				2.86		-20.0	-31							29
<4.75	0.4	54.0		-30		-49.9		-51.9		-71.1										30
<5	0.4	61.7				-13.5				-30.0			-49			-66.6		-76.2	-84.4	5
<5 [3,5]	0.4	73.1		-19				-37.1			-62.2									59
<5	0.4	53.0		-16		-20.5		-29.5		-42.0	-45.6	-53	-67							44
		Mean	-11.4		-18.5		-31.2				-39.2		-51.5			-61.6		-80.02		
		± S.D	7.4		15.1		15.9				12.9		15.9			10.1		8.8		
Coarse and Fine Waste Tire Rubber																				
0--11.2	0.5	55.5		-16		-32.6		-46.5												38
0-19	0.4	35						2.86				-37								29
<13 [5]	0.5	9.4								-58.5			-66.0			-76.6		-89.4	-94.7	46
<5-20	-0.4	-61.7								-48.1			-83			-88.5				5

1.Aggregates are manufactured using a cryogenic grinding process.
2.Actual replacement ratio is slightly different than the tabulated value and refer to the original article for more information
3.Compressive values for self-compacting concrete (SCC)
4.Steel fibers are not totaly removed from the rubber particles
5.Admixtures were incorporated
6.CSC-Compressive Strength of Control Specimen

The reduction factors depicted in Table 4 clearly exhibit that increasing rubber content decreases the compressive strength of RuC. However, a lower strength reduction was recorded for crumb rubber concrete compared to the coarse rubber concrete. Moreover, the mean values show that the strength of RuC is reduced by 25% and 18.5 % for chipped and crumb rubber concrete, respectively, at 10% RR, which exhibits the possibility of using RuC in the low-strength application with low-level rubber replacement.

3.6 Flexural and Splitting Tensile Strength

The inclusion of rubber particles decreases both flexural and splitting tensile strength [4,10,14,40,41] as depicted in Table 5. However, Khatib et al. [25] observed higher depletion for specimens cast by RuC during the flexural test compared to that of control specimens without RA. Toutanji [27] reported that it was observed a 7.9% decrease in flexural strength at 25% replacement. Moreover, Thomas et al. [10] & Su et al. [14] reported that the flexural strength reduction of RuC is significantly smaller compared to compressive strength reduction. The reduction factor depicted in Table 4 and Table 5 clearly exhibits this phenomenon. Nevertheless, the initial rate of strength reduction is steeper than that of the compressive strength due to the weak ITZ between cement paste and rubber particles [25,41]. Moreover, smaller size particles showed less strength reduction [39] similar to the compressive strength since the smaller particle may have a filler effect to increase the compactness of the concrete [14]. Based on the previous research findings, it is found that the weak interfacial bond between rubber particles and cement paste significantly affects strength reduction [4].

In the splitting tensile strength test, Eldin et al. [8] & Topcu [19] found that the RuC specimen shows an improved ability to absorb energy with a partially removable displacement at post-failure loads due to the elastic deformation of RA before the failure. Moreover, Elchalakani [42] reported that lower w/c and the addition of SF improved the flexural strength of RuC due to the improved bond strength. The use of RA in the form of fibre further improved the flexural strength capacity due to the energy dissipation capacity of RA [43]. Eventually, the flexural strength capacity of RuC could be further ameliorated by performing desired treatment to the RA [3].

3.7 Failure Mode

Raghvan et al. [20], Khaloo et al. [28] & Starlling et al. [29] reported that reference concrete separated into pieces (Figure 6-a) in the failure state whilst RuC was not accompanied by any detachment (Figure 6-b) due to the bridging of crack by RA. In addition, considerable lateral deformations were observed during the loading process in RuC compared to the control concrete due to the low elastic modulus and high Poisson's ratio of RA, which produce high internal tensile strength perpendicular to the direction of applied load [19].

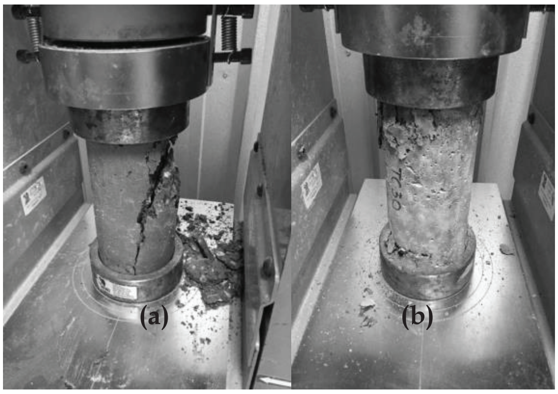

Figure 6 - Failure Mode of Specimens [29]

Moreover, several scholars reported that plain concrete shows a brittle behaviour at failure whilst RuC exhibits a ductile behaviour [16,19,40,44] since the ability to absorb a large amount of energy under compressive and tensile loads [16]. In addition, Toutanji et al. [27] observed that although the specimen is highly cracked, it was able to withstand some of the ultimate load with significant displacement since the RA can undergo large elastic deformation before failure. Moreover, Raghvan et al. [20] reported that RA acts as a spring while delaying the crack widening and preventing catastrophic failure (Figure-7), which is usually experienced in plain concrete specimens [39].

Figure 7 - Behaviour of Rubber Particle at the Failure [39]

Table 5-Effect of WTR sizes and replacement ratio on the 28 days splitting tensile strength of RuC

<table>
<tr><th rowspan="3">Size (mm)</th><th rowspan="3">w/c</th><th rowspan="3">STC[3] (Mpa)</th><th colspan="17">Replacement Ratio (%)</th><th rowspan="3">Ref.</th></tr>
<tr><th>2.5</th><th>5</th><th>7.5</th><th>10</th><th>12.5</th><th>15</th><th>17.5</th><th>20</th><th>25</th><th>30</th><th>40</th><th>45</th><th>50</th><th>60</th><th>75</th><th>80</th><th>100</th></tr>
<tr><th colspan="17">28 Days Tensile Strength Reduction Factor (%)</th></tr>
<tr><td colspan="21">Coarse Waste Tire Rubber</td></tr>
<tr><td>6.25 [1]</td><td>0.5</td><td>3.44</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>-18.6</td><td></td><td></td><td></td><td>-32</td><td></td><td>-41.6</td><td></td><td>-52.6</td><td>8</td></tr>
<tr><td>4-11.2 [2]</td><td>0.5</td><td>3.4</td><td></td><td></td><td></td><td>-12</td><td></td><td></td><td>-26</td><td></td><td>-32.4</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>38</td></tr>
<tr><td>19-37.5</td><td>0.5</td><td>3.44</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>-37.8</td><td></td><td></td><td></td><td>-57.0</td><td></td><td>-66.4</td><td></td><td>-75.8</td><td>8</td></tr>
<tr><td colspan="3">**Mean**</td><td colspan="2"></td><td colspan="2">-11.8</td><td colspan="4">-26.5</td><td colspan="2">-29.6</td><td colspan="3">-44.3</td><td colspan="2">-54.0</td><td colspan="2">-64.2</td><td></td></tr>
<tr><td colspan="3">**± S.D**</td><td colspan="2"></td><td colspan="2"></td><td colspan="4"></td><td colspan="2">9.9</td><td colspan="3">18.0</td><td colspan="2">17.5</td><td colspan="2">16.4</td><td></td></tr>
<tr><td colspan="21">Fine Waste Tire Rubber</td></tr>
<tr><td>0.3</td><td>0.4</td><td>3.6</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>-6.9</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>14</td></tr>
<tr><td>0.5</td><td>0.4</td><td>3.6</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>-8.3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>14</td></tr>
<tr><td>0-1</td><td>0.6</td><td>3.21</td><td></td><td></td><td></td><td></td><td></td><td>-32.4</td><td></td><td></td><td></td><td>-52</td><td></td><td>-64.8</td><td></td><td></td><td></td><td></td><td></td><td>19</td></tr>
<tr><td>1</td><td>0.5</td><td>3.36</td><td></td><td>-11</td><td></td><td>-14</td><td></td><td></td><td></td><td>-17</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>38</td></tr>
<tr><td>0.3-3</td><td>0.4</td><td>3.6</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>-7.8</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>14</td></tr>
<tr><td>1-4</td><td>0.6</td><td>3.21</td><td></td><td></td><td></td><td></td><td></td><td>-53.3</td><td></td><td></td><td></td><td>-67.0</td><td></td><td>-74.5</td><td></td><td></td><td></td><td></td><td></td><td>19</td></tr>
<tr><td>0.15-4.75</td><td>0.6</td><td>2.82</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>-35</td><td></td><td></td><td>-47.9</td><td></td><td></td><td>-67</td><td></td><td>-81.1</td><td>-92.2</td><td>31</td></tr>
<tr><td>3</td><td>0.4</td><td>3.6</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>-11</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>14</td></tr>
<tr><td><4 [2]</td><td>0.5</td><td>3.4</td><td></td><td></td><td></td><td></td><td>-23.5</td><td></td><td></td><td></td><td>-38.2</td><td></td><td>-44.1</td><td></td><td></td><td></td><td></td><td></td><td></td><td>38</td></tr>
<tr><td><4 [1,2]</td><td>0.5</td><td>3.4</td><td></td><td></td><td></td><td></td><td>-23.5</td><td></td><td></td><td></td><td>-26.5</td><td></td><td>-47.1</td><td></td><td></td><td></td><td></td><td></td><td></td><td>38</td></tr>
<tr><td><5</td><td>0.4</td><td>4.19</td><td></td><td>-0.72</td><td></td><td>-8.4</td><td></td><td>-19.8</td><td></td><td>-31.0</td><td>-37.7</td><td>-42</td><td>-56.6</td><td></td><td></td><td></td><td></td><td></td><td></td><td>44</td></tr>
<tr><td colspan="3">**Mean**</td><td colspan="2">-5.9</td><td colspan="2">-11.0</td><td colspan="4">-22.4</td><td colspan="2">-43.9</td><td colspan="3">-55.8</td><td colspan="2">-66.7</td><td colspan="2">-86.65</td><td></td></tr>
<tr><td colspan="3">**± S.D**</td><td colspan="2">7.3</td><td colspan="2">3.8</td><td colspan="4">13.8</td><td colspan="2">14.0</td><td colspan="3">11.9</td><td colspan="2"></td><td colspan="2">7.8</td><td></td></tr>
<tr><td colspan="21">Coarse and Fine Waste Tire Rubber</td></tr>
<tr><td>0--11.2</td><td>0.5</td><td>3.4</td><td></td><td>-29.4</td><td></td><td>-27</td><td></td><td>-44.1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>38</td></tr>
</table>

1.Aggregates are manufactured using a cryogenic grinding process.
2.Actual replacement ratio is slightly different than the tabulated value and refer to the original article for more information
3.STC - Splitting Tensile Strength of Control Specimen

3.8 Stress-Strain Relationship

Generally, increasing rubber content in the concrete mix results in lower peak stress with higher strain [19]. This phenomenon was checked by Kristina et al. [45] who plotted the stress-strain variation at different RRs varying from 0 % to 40% as depicted in Figure-8. The stress-strain behaviour of RuC is more non-linear, which experiences large deformation compared to the conventional concrete specimen [28]. In addition, Topcu [19] reported that RuC with 15% replacement of coarse aggregate reaches the ultimate strain of around 0.002, which is similar to the reference concrete without rubber particles. However, it was reported that when the replacement ratio varies, maximum strain changes between 0.003 and 0.005 since more energy is absorbed by RA in RuC, which conduces more strain at fracture [19]. Nevertheless, according to the results in previous investigations, inconsistency in maximum strain values was observed and detailed investigation is required for identifying authentic stress-strain behaviour of RuC at different RRs.

Moreover, the addition of rubber decreases the elastic energy capacity and increases the plastic energy capacity [8,19], which leads to improving the toughness properties of RuC compared to the control specimen [16,28]. Eldin et al. [8] discussed the improved ductility property of RuC by comparing areas under the stress-strain curve. Reda Taha et al. [24] reported that rubber particles absorb part of the energy while increasing the energy absorption capacity of RuC. However, Khaloo et al. [28] reported that the toughness of RuC increases up to 25% of total aggregate replacement and beyond that toughness properties are subjected to a decreasing trend due to the systematic reduction in strength (Figure-8). Nevertheless, higher impact resistance was recorded even in high replacement ratios compared to the control specimen [24].

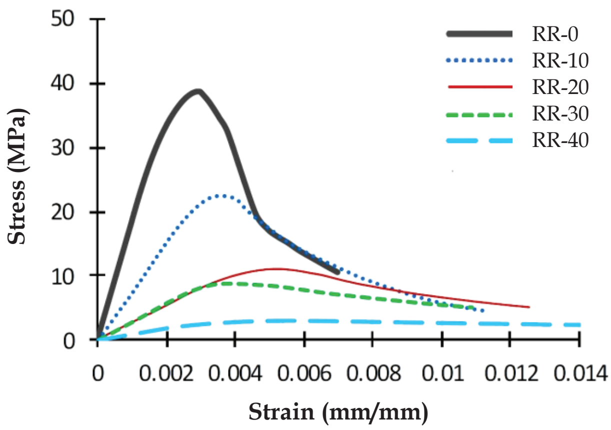

Figure 8 - Stress-Strain Diagram for RuC at Different RRs [45]

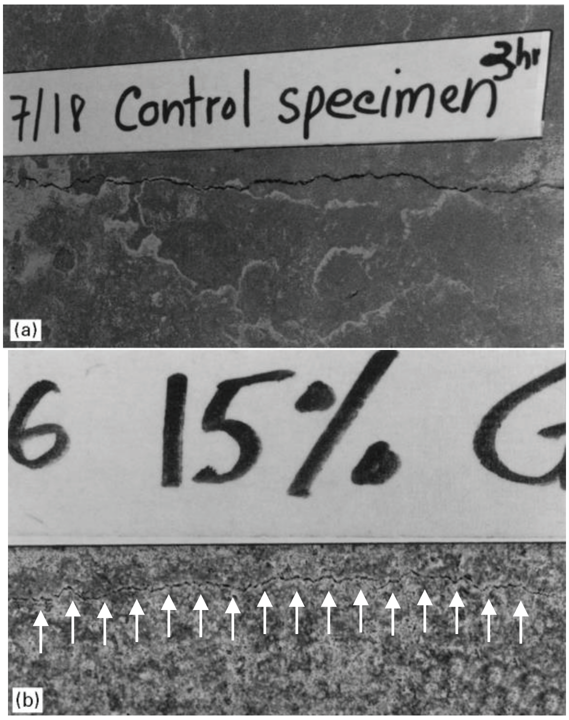

Figure 9 - Plastic Shrinkage Crack on (a) Control Specimen (b) 15% Rubber Shred [20]

The elastic modulus of the RuC decreases with the increased rubber content [46,47]. Karunarathna et al. [7] reported that the decrease in modules of elasticity is higher for chipped rubber than crumb rubber. Moreover, Zheng et al. [48] reported that RuC shows higher dynamic elastic modules than static elastic modules. Nevertheless, both static and dynamic elastic modulus decreases with the increasing rubber content (Figure-8).

3.9 Shrinkage

Limited literature was found on the investigation related to shrinkage effect of RuC. Raghawan et al. [20] observed that the addition of rubber shreds reduces the severity of plastic shrinkage cracking compared to the control specimen (Figure-9) since the rubber shreds bridge the crack and provide the resistance for crack widening (Figure-7). Moreover, the inclusion of rubber chips in the concrete mix delays crack propagation by arresting the micro cracks [20]. Mohammadi et al. [49] reported that there is an optimal rubber content where plastic shrinkage of RuC is minimal. Interestingly, Bravo et al. [18] & Sukontasukkul et al. [50] reported that RuC showed higher shrinkage than reference concrete. Moreover, increasing rubber content increased the drying shrinkage due to the decrease of internal restraints since RA is weak and highly flexible [50]. Due to the presence of contradictory results and limited investigation, there is a research gap to cognize the authentic behaviour of shrinkage properties of RuC.

3.10 Water Absorption

Replacing NA with WTRA increases the water absorption of RuC (Figure-10) due to the presence of voids between RA and cement paste [18,41]. Turki et al. [51] conducted an image-processing experiment to cognize the porosity of RuC and reported that porosity increases with rubber content. In addition, low vibration on rubberized concrete to avoid floating and segregation of RA during the initial compaction ends up in higher voids content with increased water absorption [18]. However, adding silica fume to the rubberized concrete reduces the water absorption to a certain level [52] due to the reduction in void content.
Considering the size effect of RA on water absorption of RuC (Figure 10), it was found that decreasing the size of the RA lessens the water permeability and absorption due to the grading effect on dense structure [14,41]. Moreover, Rezaifar et al. [53] reported that replacing cement with Metakaolin (a form of clay mineral) in a desirable RR can reduce water absorption effectively. However, suitably low permeability RuC can be produced by managing the cement content with a low water–cement ratio and proper concrete compaction with adequate curing [10].

3.11 Chloride Penetration Resistance

Chloride penetration resistance decreases with the increased size of the rubber aggregate due to the existence of permeable voids in the concrete mix. However, cryogenic fine rubber exhibits better resistance to chloride attacks than mechanical fine rubber since the better adherence between rubber particles and the cement paste [18].

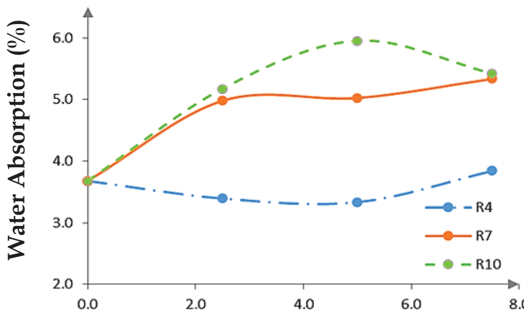

Figure 10 - Variation of Water Absorption with Replacement Ratio [41]

Interestingly, Gesoğlu et al. [52] reported that mixing fly ash with rubberized concrete under a long curing period (90 Days) reduces the chloride iron penetration drastically due to the long-term reaction of fly ash, which refines the pore structures. Moreover, according to the water absorption variation of RuC as depicted in Figure-10, it is evidenced that increasing RR and size of RA conduce to increasing the chloride iron penetration due to the high void content [41].

3.12 Resistance to Acidic Attack and Effect of Elevated Temperature on RuC

When RuC and reference specimens were immersed in the sulphuric acid, the maximum weight loss was recorded by the reference concrete [54]. Moreover, Yasser et al. [54] reported that the compressive strength reduction in RuC specimens were significantly low compared to control specimen by exhibiting greater resistance to sulphuric acid attack. This can be attributed to the fact that Calcium Sulphate ($Ca(SO)_4$) is formed when Sulphuric Acid (H_2SO_4) reacts with Calcium Hydroxide ($Ca(OH)_2$), which generates significant pressure on the concrete matrix with mass losses. Due to the presence of voids in RuC specimens, they have ability to absorb pressure without damaging the internal concrete matrix [54,55].

Yasser et al. [54] reported that increasing rubber content increased mass loss at elevated temperatures. Even though RuC was exposed to elevated temperature, it showed more ductile performance than reference concrete [54]. According to the literature, RuC shows better performance in durability properties than mechanical properties.

4. Discussion

Previous literature evidenced that the inclusion of WTR in concrete lessens the fresh and hardened properties of concrete. However, RuC shows improved performance in ductility and energy absorption capacity compared to the conventional mixture. Moreover, it is reported that RuC exhibits better performance at elevated temperatures and acidic environments in terms of durability concerns compared to traditional concrete. Consequently, optimizing the performance of RuC up to an acceptable level without escalating costs associated with WTRA production would evolve the usage of RuC in the construction industry. Any kind of application with RuC should be performed with an optimized size of RA and RR since it has been found that the crumb rubber particle performance at low RRs is high compared to chip rubber (Table 4). Consequently, small particle sizes ranging from 0-5 mm can be used in several applications like railway sleepers, crash barriers, light-weight structures, architectural elements, etc., which will support building an environmentally friendly construction practice in a sustainable platform.

Subsequently, a significant attention should be given to emphasize the possibility of using RuC in certain applications worldwide since it has not been accepted by the construction industry yet. This phenomenon is common for any product associated with recycled materials due to reduced properties compared to conventional specimens. The literature review shows a clear gap in identifying authentic material properties of RA with an effective method for treating the texture of RA. Consequently, as a novel approach, finding material properties of RA and improving the surface texture of RA with a desired treatment method would make a promising way to improve the properties of RuC. Even in surface treatment methods, physical improvement would be better instead of chemical treatment since the applicability of complex methods is limited in the industry. Moreover, the inclusion of waste tire steel fibre (WTSF) together with RA would be beneficial to reduce the strength reduction since steel fibres improve the ductile performance of the concrete.

Eventually, the use of WTRA in concrete has been recognized as a promising way to reduce the detrimental impacts created by the ELT. However, the alteration of the properties of concrete and the associated cost of producing WTRA [7] cause to lessen the commercial usage of RuC. As a suggestion, establishing a strong link between government organizations, research institutes and industrial partners will make a promising way for implementing and promoting the use of RuC in the industry. For instance, facilitating tax reduction/VAT exemption for the users who use RA in their construction activities will help to make RuC much more prominent in the industry than what is experienced currently. However, the use of rubber aggregate in concrete mix will have to be executed as a compulsory practice in future since limited NA is available for future consumption.

5. Conclusion

Based on the previous research findings discussed in this review paper, the following conclusions are made.

1. The workability of RuC reduces with the increasing percentage of rubber particles irrespective of particle size.

2. The density of RuC decreases with the increasing amount of RA due to the entrapped air inside the concrete mix and the lower density of rubber particles.

3. The substitution of RA results in reducing both the compressive and tensile strength of RuC. However, the decline in tensile strength is notably lower in contrast to the decrease in compressive strength.

4. RuC exhibits improved ductility behaviour with lower peak stress and higher strain instead of the brittle fracture that appeared in the control specimen.

5. RuC has improved toughness properties compared to the conventional concrete mix due to the higher energy absorption capacity of rubber aggregates.

6. Chloride penetration and water absorption of the RuC increases with the inclusion of WTRA due to the presence of increased voids inside the concrete matrix.

7. Even after deterioration from sulphuric acid and high temperatures, RuC showed more ductile performance than traditional concrete.

Although several scholars have evaluated the properties of RuC, further studies are required to be performed to cognize the actual behaviour of RuC under dynamic and static loading conditions. Moreover, the hypothesis of improving the strength of RuC by adding WTSF with surface-treated RA is required to investigate in future research as a novel approach to improving the performance of RuC.

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