INVESTIGATION MECHANICAL & DURABILITY PROPERTIES OF CRUMBED RUBBER CONCRETE CONTAINING RECYCLED CONCRETE AGGREGATE

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ABSTRACT

The concrete construction industry requires huge amount of natural resources. Currently natural resources are depleting while demand for concrete is increasing. Several studies are focused to solve this issue. The waste rubber has become a huge environmental issue worldwide. Researchers identified a sustainable way of reusing waste rubber by recycling it to Crumbed Rubber and partially replacing that for fine aggregate in concrete. However, with introduction of this crumbed rubber to concrete, the compressive strength of developed concrete was decreased. Therefore, the main aim of this research is to improve compressive strength in Crumbed Rubber Concrete using recycle concrete aggregate. Other than that, some fresh properties, mechanical & durability properties were investigated. 15 percent of replacement of fine aggregate by rubber has been identified as an optimum replacement level by other studies. Therefore, this study was conducted for 15% volume based fine aggregate replacement. As recycle aggregate act as a cementitious binder, it was added in 10,15,20,30 percent of weight basis for cement. The w/c ratio was kept constant at 0.57. Maximum 10 mm aggregate was used in the study. The crumbed rubber replacement resulted in 60 percent decrement in compressive strength and recycled aggregate in all levels resulted in a higher compressive strength than rubber-only concrete but got optimum increment in 20 percent and starts to decrease. Same as compressive strength, splitting tensile, flexural strength increased to optimum values with 20 percent of recycled aggregate. The available design codes were used to calculate theoretical values using experimental values to investigate adequacy of these mixes. The investigate revealed that available standard guidelines cannot be used to predict the behavior of crumbed rubber concrete containing recycled concrete aggregate. This study proves that addition of recycle aggregate to crumbed rubber concrete improves its strength. However, the durability and dynamic properties of this developed concrete needs to be investigated.

KEYWORDS: *crumbed rubber concrete, recycled concrete aggregate, mechanical properties*

1 INTRODUCTION

The increase of discarded rubber products has turned into a global problem for the environment currently. The poor waste management is the main reason for this observation. Waste tire Rubber is one of such waste which challenge the environment. Every year, a huge number of tires go to disposal, but only about 50% of them get recycled, and the remaining go to landfills. Therefore, there is an urgent need to address this issue. One sustainable solution to waste tires is to use them as an alternative to conventional aggregate in concrete.

However, countries like Sri Lanka are facing difficulties when it comes to maintaining and reusing or recycling this rubber to maintain a green environment and keep the industry pollution free. On the other hand, along with the accelerated development activities, demand for concrete is increasing worldwide, and the concrete industry is already facing huge difficulties when it comes to finding a

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satisfactory amount of material. The natural fine aggregate (NFA) used for concrete is river sand. Which is a nonrenewable natural, depleting resource. As we know, waste rubber disposal has become a big environmental problem worldwide. Treatment processes also face many difficulties due to the huge amount of rubber material disposed of. These tires pose an economic, health, and environmental risk by releasing toxic waste into water, air, and soil. Rubber tires act as long-term storage for water due to their specific shape and nature of resistance to water. Hence, they provide a breeding ground for mosquitoes and various other pests as well. The easiest way of disposing of rubber tires is tire burning, but it causes serious fire hazards to the environment. It has been found that, overall, 1000 million tires reach their end of life every year. By 2030, the amount of waste tires from motor vehicles is expected to be 1200 million, on behalf of nearly 5000 million tires that will be disposed of on a regular basis (Sofi, 2016). Therefore, there is an urgent need to address this issue (Roychand et al., 2019). Countries like Sri Lanka are facing difficulties when it comes to maintaining and reusing or recycling this rubber to promote a green environment and keep the country pollution free. Nowadays, researchers have found a sustainable solution to waste tires. That is using waste rubber tires as an alternative to aggregates in conventional concrete. Also, for the investigation, rubber can be used in three forms, which can be listed as rubber chips, molded rubber, and rubber powder. Generally, rubber chips are larger than 6 mm and crumbed rubber is less than 6 mm. The cost of shredding increases with the reduction of particle size, and the particles influence the strength of concrete. Larger particles would decrease the compressive strength and small particles would increase it relative to large particles (Mendis, Deen, & Ashraf, 2016).

Crumbed rubber (CR) concrete is a good solution to the overuse of river sand. So far, rubber concrete has only been used for non-structural applications because it has several disadvantages. Research studies have shown that crumbed rubber can be used as a partial replacement for both natural coarse aggregate (NCA) and natural fine aggregates (NFA). However, it was shown that mechanical and durability properties had changed, and hence, it would not be suitable for direct use in construction work. With the addition of rubber into concrete, the following disadvantages occurred: relatively low compressive strength, low tensile strength, low workability, low stiffness, early cracking, and low young's modulus of elasticity, found by these researchers (Jokar, Khorram, Karimi, & Hataf, 2018), (Bisht & Ramana, 2017). However, as advantages, replacement for natural materials, as a good method of reusing rubber tires, increased ductility, increased energy dissipation, higher damping ratio, non-biodegradable material, and reduced concrete density can be highlighted (Mendis et al, 2016). According to Mousavimehr and Nematzaded (2019),It was found that by replacing 15% and 30% of the rubber with fine aggregate, the CS decreased by 35% and 52%, respectively. (Xie et al, 2019) found that by replacing rubber with fine aggregate 10% and 20% with 1.5% of steel fiber, compressive strength decreased relatively by 8% and 19% in concrete cubes, but in cylindrical concrete, it decreased the compressive strength by 7% and 15% compared to control concrete (CC).

To overcome the above-mentioned decrement in compressive strength, many researchers have found various materials and various methods of treatment. Studies have found that 25–50% of RCA on concrete does not show a big difference in the mechanical properties of concrete compared to CC (Hossain, Shahjalal, Islam, Tiznobaik, & Alam, 2019). As mentioned in rubber, researchers have found RCA has higher absorption capacity and low density. However, the RCA can be used as a replacement or additional material for both natural fine aggregates, NCA. Ali, Zidan & Ahmed (2020) state The mechanical properties of concrete were investigated using 0%, 25%, 50%, and 100% RCA as a replacement for natural aggregate. The results have shown that replacing up to 50% will not have a huge effect on mechanical properties. However, when RCA is increased by up to 100%, there will be higher compressive strength and a tensile strength decrease. Evangelistaa & Brito (2005) state that using 30% of RCA does not have a considerable effect on the mechanical behavior of concrete. Etxeberria, Vazquez, & Barra (2005) state that it was also found that the rough texture of RCA and proper bonding of cement paste could result in good compressive strength in concrete. Ali et al (2020) state In conclusion, it can be decided that RCA can be used up to 30% of its replacement efficiently. Boudali, Kerdal, Ayed, Abdulsalam, & Soliman (2015) state that the incorporation of RCA in the mixture will give a better performance than pozzolan in CC. According to Hossain et al. (2019), it was noticed that there was an increase in compressive strength when replacing 10% of RCA. Compressive strength decreases with each increment of RCA and crumbed rubber. The addition of polypropylene fiber has increased compressive strength, but the maximum 27% of compressive strength increment was achieved in 30% of RCA and 2% of fiber without crumbed rubber. Xie et al (2018) state that replacing 100% of

RCA with a partial percentage of crumbed rubber showed a result of strength decrement due to the addition of RCA and a further strength decrease due to the addition of crumbed rubber. Similarly, Xie et al (2014) state that a decrement of strength occurred due to the addition and increment of crumbed rubber and the addition of constant RCA. In his 5th edition of the Properties of Concrete book, A. M. Neville mentioned the following things: Which means the strength of concrete will depend on the cohesion of the mixture of cement and the bond it carries with aggregates and the strength of the aggregate carried itself. By increasing aggregate size, strength can be increased. Due to the contribution of old mortar in RCA unit weight, concrete made with RCA will have a lower value. Similarly, higher absorption and porosity can be expected. The absorption can be reduced by saturated RCA before use. The strength of concrete mainly depends on the W/C ratio and the degree of compaction. And the penetration depth is negatively proportional to the strength of the concrete.

Therefore, considering the above facts, this study investigates the possibility of using crumbed rubber as a substitute for fine aggregates in concrete and alleviates the inherent adverse effects of crumbed rubber on concrete's compressive and tensile strength, workability, low stiffness, etc. by adding recycled concrete aggregates. An experimental study was conducted to investigate the mechanical, durability, and fresh properties of each concrete mix. Basic tests like compressive strength (CS), splitting tensile strength (STS), and modulus of rupture (MR), density, water absorption (WA), and volume of voids (VV) are performed.

Considering the above facts, the potential research area in this sector was identified. In the research, it would be investigated whether crumbed rubber concrete has RCA. Usually, with the addition of rubber, the compressive strength of concrete decreases. However, in concrete cast, using RCA, higher mechanical properties have been shown by some researchers. But in this research, RCA was added as an additional material, and it won't be replaced with any material. Here, RCA is assumed to be a cementitious material, and by increasing cementitious materials, it is aimed to improve the strength of concrete. This study will use a maximum size of 10 mm NCA, a maximum size of 4 mm natural fine aggregate, a constant 15% crumbed rubber replacement, and a 0–30% RCA replacement. Hence, in this research, experiments will be conducted to find a solution to this compressive strength decrement and ways of improving it by changing mixed proportions in concrete like RCA. Basic tests like compressive strength tests, tensile strength tests, workability, water absorption, volume of voids, etc. will be initially carried out, and as the research goes on, more tests will be conducted to obtain proper results and meet the ultimate objectives of this study.

1.1 Materials and methodology

A. Materials and mixtures

A detailed description of all the ingredients used in this study to prepare concrete mixtures is provided below. Mainly Crumbed rubber was used as a replacement for natural fine aggregate content by 15% of its volume. Recycled concrete aggregate was used in various percentages to increase cement content in this concrete production.

Portland Limestone Cement (PLC) of grade 42.5 was used in this concrete production. Concrete industry tends to use PLC over OPC due to the environmental benefits of PLC. PLC can be directly used in the same mix designs as OPC. Locally available, well-graded natural river sand with a nominal maximum grain size of 4.75 mm, Locally available, well-graded natural gravel with a maximum of 10 mm, crumbed rubber with a maximum of 2 mm, and recycled concrete aggregate, which was collected from a demolished building and crushed manually with a maximum aggregate size of 10 mm, were used in this study. The sieve analysis and gradation of recycled concrete aggregate were done using ASTM C136–19 standards. The figures depict the gradation curves of all aggregates and demonstrate that the aggregates were within the ASTM upper and lower bound ranges. The material characterization of the recycled concrete aggregate was performed using the same procedure as for natural coarse aggregate. In order to achieve a similar distribution as fine aggregate, the final crumbed rubber mixture contained 70% of rubber passing through # 30 mesh and 30% of rubber passing through # 10 mesh. In order to achieve the required workability of concrete, a locally available high-range water-reducing admixture (MasterRheobuild 1000) was used. The natural fine aggregate and crumbed rubber density are 1700 and 532.5 kg/m3 respectively.

Figure 1 shows the particle distribution of natural fine aggregate (NFA), natural coarse aggregate (NCA), crumbed rubber (CR), and recycled concrete aggregate (RCA).

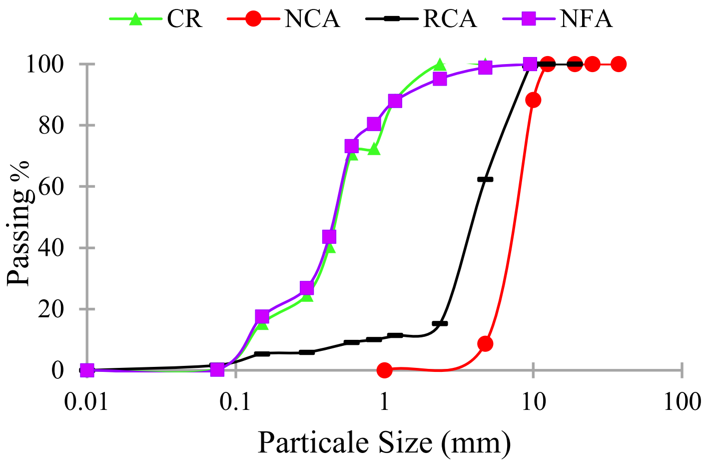

Figure 1. Particle distribution of aggregates

B. Mixture proportions

Six different concrete mixes were prepared for this study to support proportional analysis. A target compressive strength of 25–35 MPa in 28 days is commonly used in designing reinforced concrete structures in Sri Lanka, depending on the construction. The total Portland limestone cement content and the effective water cement ratio were kept constant at 405 kg/m3 and 0.57, respectively. It was assumed that coarse and fine aggregate used in this study were in saturated surface dry conditions. The percentage of crumbed rubber replacement was kept at a constant value of 15 throughout the study. Crumbed rubber was replaced by a volume of fine aggregate. Therefore, crumbed rubber was replaced by 15% by volume of sand and recycled concrete aggregate was added additional by weight of cement up to 30% as addition cementations material. To improve workability, the high water reducing admixture "MasterRheobuild 1000" was used. With the introduction of admixture, 20% of water content was reduced as a standard. The remaining 80% of water was divided into 4 parts. At first, 3 parts of water were added to the concrete, and finally the remaining part was added after properly mixing it with the admixture. 1 L of admixture was added for every 100 kg of cement (1% of admixture). The specimen identification description is shown in Table 1. For illustration, ($C_{15}R_{20}A_1$) describes 15% crumbed rubber replacement, 20% recycled concrete aggregate added along with 1% admixture (MasterRheobuild 1000).

Table 1. Concrete mixture proportions per meter cube.

Refer No	w/c ratio	Cement Kg/m^3	Water Kg/m^3	Sand Kg/m^3	Metal Kg/m^3	CR Kg/m^3	RCA Kg/m^3	Admixture L
$C_0R_0A_0$	0.58	405.8	233.3	761.59	969.29	0	0	0
$C_{15}R_0A_0$	0.58	405.8	233.3	647.35	969.29	5.76	0	0
$C_{15}R_{10}A_0$	0.58	405.8	233.3	647.35	969.29	5.76	40.58	0
$C_{15}R_{15}A_1$	0.58	405.8	186.7	647.35	969.29	5.76	60.87	4.06
$C_{15}R_{20}A_1$	0.58	405.8	186.7	647.35	969.29	5.76	81.16	4.06
$C_{15}R_{30}A_1$	0.58	405.8	233.3	647.35	962.29	5.76	121.74	4.06

C. Experimental program

In order to evaluate the fresh, mechanical, and durability properties of concrete, the following standard experiments were conducted, and the results were compared with control concrete. Standard ASTM C143 was used to measure slum value. Frustum of a cone was used for the slum test, which has a 300 mm height and 100 mm and 200 mm diameter openings. The apparatus was placed on a smooth surface with a smaller opening at the top and was filled with concrete in three layers. Each layer was tamped 25 times with a standard 16 mm diameter steel rod. Immediately after filling, the cone was slowly lifted, and unsupported concrete slumped. The decrement in the height was measured to the nearest 5 mm. The uniaxial compressive strength test was conducted according to ASTM C39. A constant load of 0.25 ± 0.05 Mpa/sec was applied. The splitting tensile strength test was conducted according to ASTM C496 & a constant load of 0.011 to 0.023 Mpa/sec was applied. The flexural strength test of concrete prims was conducted according to ASTM C78 & BS EN 12390–5: 2000, which suggests a prism size of 100 mm × 100 mm × 500 mm for concrete that uses less than 25 mm of aggregates. To investigate water absorption capacity, density, and volume of voids, the standard ASTM C642 test was conducted.

D. Comparison with standard code of practice

Various design guidelines and standards exist for predicting the mechanical and durability of concrete using various properties like compressive strength and flexural strength. In this study, present design guidelines and standards from Eurocodes (EC2), fib, ACI, and CSA were used to predict the different response parameters of the concrete specimens. Then predicted behaviors were compared with experimental values. A ratio (ξ) between experimental and predicted values was calculated for comparison, where a ξ value greater than 1 indicates an over-prediction, while a value less than 1 indicates an under prediction of the result.

fib2010 & EC2 recommend using Eqs (1) & (2), and taking respective measures. AS3600 is also used, but there is another relation between Eqs (3). ACI 318-14, ACI 363-92 provide direct reflection between Eqs. (4) and (5). Where, is splitting tensile, tensile, mean compressive strength, respectively. Guidelines by fib2010, AS3600, ACI 318-14, and ACI 362-92 have proposed a relationship between CS and modulus of rupture by Eqs (6)–(9) respectively. Where, modulus of rupture, compressive strength & depth of prism.

$$f_{ctm,sp} = f_{ctm}/\alpha_{sp} = 0.3\left(f_{cm}\right)^{\frac{2}{3}}/\alpha_{sp} \quad (1)$$

$$f_{ctm} = \alpha_{sp} f_{ct,sp} \quad (2)$$

$$f_{ctm,sp} = f_{ctm}/\alpha_{sp} = 1.4 \times 0.36\sqrt{f_c^{'}}/\alpha_{sp} \quad (3)$$

$$f_{ctm,sp} = 0.556\sqrt{f_c^{'}} \quad (4)$$

$$f_{ctm,sp} = 0.59\sqrt{f_c^{'}} \quad (5)$$

$$f_r^{'} = \frac{0.3(f_c^{'})^{\frac{2}{3}}}{\alpha_{fl}} \; where, \alpha_{fl} = \frac{0.06h_b^{0.7}}{1+0.06h_b^{0.7}} \quad (6)$$

$$f_r^{'} = 0.6\sqrt{f_c^{'}} \quad (7)$$

$$f_r^{'} = 0.62\sqrt{f_c^{'}} \quad (8)$$

$$f_r^{'} = 0.94\sqrt{f_c^{'}} \quad (9)$$

1.2 Results and Discussion

A. Workability

The average slump value recorded for each of the six mixes is shown in Table 2. The addition of 15% crumbed rubber resulted in a lower slump value. Recycled concrete aggregate also decreased the slump value.

Due to the very low workability of 15%, admixture was introduced to the remaining mixes. But in 15% and 20% recycled concrete aggregate mixes, there was enough workability without 20% required water. But 30% recycled concrete aggregate mix requires 100% water. The slump value highly depends on the properties of raw materials used in the relevant concrete mix and some environmental facts as well. Crumbed rubber is a porous material and requires more water to overcome friction, recycled concrete aggregate has a higher water absorption and higher surface roughness. Because of those reasons, workability was reduced. Another reason behind this dramatic workability reduction is that adhered mortar with crumbed rubber and recycled concrete aggregate entraps air in the mixture and creates air bubbles. Decrement of particle size of rubber reduces workability of concrete because it increases surface area of angular shape particles.

B. Compressive strength

A summary of hardened concrete Compressive strength test results of cube and cylindrical specimens at 7day and 28day are presented in Table 2. It was observed that in the 7-day compressive strength test for cube and cylinder, a higher strength was achieved than control concrete for all mixes except for rubber-only mix ($C_{15}R_0A_0$) and 10% recycled concrete aggregate mix ($C_{15}R_{10}A_0$). Approximately 59% of design characteristic strength was achieved in the 7-day test for control concrete. The lowest compressive strength resulted in a 15% replacement of crumbed rubber over natural fine aggregate.

Introducing recycled concrete aggregate resulted in an increment in compressive strength. Further to that, from 15% recycled concrete aggregate mix onwards, it showed higher compressive strength than control concrete. But the optimum compressive strength is received in 20% recycled concrete aggregate mix and a little lower value is received in 30% recycled concrete aggregate mix. Replacement of 15% rubber resulted in 57% and 54% compressive strength decrements in cubical and cylindrical specimens, respectively, at the 7-day test. When it comes to the 28-day test, replacement of 15% rubber resulted in a 59% and 61% compressive strength decrement in cubical and cylindrical specimens, respectively. Compared to control concrete, the addition of 10% recycled concrete aggregate resulted in a 27%, 34%, 38%, and 49% strength decrement in the 7-day cube and cylinder and 28-day cube and cylinder, respectively. When it comes to the cylinder at 28 days, only 20% recycled concrete aggregate mix achieved a 3.8% increment in compressive strength compared to control concrete. But all recycled concrete aggregate mixes showed higher compressive strength values compared to crumbed rubber only concrete mixes.

The cement used in this study was PLC, since it is a slow strength gain cement. The results showed a slow strength gain over 7 days. The addition and increase of recycled concrete aggregate increased strength gain, but was not continuous till 28 days. The decrease in compressive strength in crumbed rubber only mix happens due to the weaker bond created by crumbed rubber with aggregate and cement paste. The transition zone gets weaker due to the higher amount of free water in the concrete mix because of the crumbed rubber. Crumbed rubber has very low strength compared to natural fine aggregate. Therefore, crumbed rubber is unable to achieve some strength results with natural fine aggregate itself. This crumbed rubber contains a lot of impurities like sulfur and zinc, and they result in low bonding capacity with the cement matrix. The crumbed rubber has a very low elastic modulus and hydrophobic properties that increase the porosity, which results in a lower compressive strength. Another reason behind this strength decrement is deformability. Crumbed rubber particles relative to the cement matrix developed crack pattens similar to the air void created by crumbed rubber. In this study, a huge amount of crumbed rubber was used, which clearly means that the concrete contains a huge number of air voids as well. Due to these voids, we can see sudden failures in loading time. Figure 2 & 3 Present failure patterns and (a) $C_0R_0A_0$ (b) $C_{15}R_0A_0$ (c) $C_{15}R_{10}A_0$ (d) $C_{15}R_{15}A_1$ (e) $C_{15}R_{20}A_1$ (f) $C_{15}R_{30}A_1$ represent respectively.

. The increment of compressive strength with the increase of recycled concrete aggregate may occur by better/optimal internal curing provided by a higher amount of water that is absorbed by the recycled concrete aggregate and thus the w/c ratio gets a lower value at the interfacial zone. Thus, the bond between the attached old mortar in the recycled concrete aggregate surface and the new cement paste will improve. But strength increases by up to 20% with recycled concrete aggregate and decreases by 30%. This may happen due to the higher amount of porosity introduced by recycled concrete aggregate. The strength reduction may happen due to the multiple layers of interfacial transition zone (ITZ)

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Figure 2. Cubes after failure in 7 days

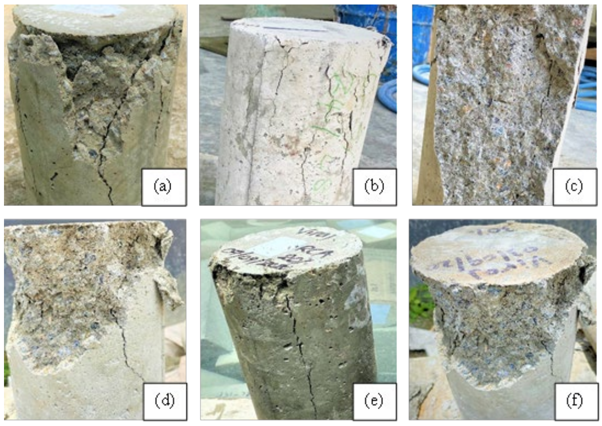

Figure 3. Cylinders after failure in 7 days

C. Splitting tensile strength

A summary of the hardened concrete splitting tensile strength test results is presented in Table 2. It can be seen that maximum splitting tensile occurred in control concrete at 28 days. 20% recycled concrete aggregate addition gets a splitting tensile strength value of 2.62 MPa, which is closer to the control concrete value of 2.77 MPa. But when it comes to the 7-day test, maximum splitting tensile strength was achieved in 20% recycled concrete aggregate mix and it was equal to 2.53 MPa while control concrete got 1.64 MPa. As mentioned in compressive strength, PLC cement shows low strength gain, but addition and increment of recycled concrete aggregate increase the strength gain in 7 days, but it is not continuous to 28 days. Compared to control concrete, crumbed rubber's only concrete splitting tensile strength was decreased by 37%. 10% Recycled concrete aggregate mix splitting tensile strength value was decreased by 16%, but in recycled concrete aggregate 15%, 20%, and 30% samples, splitting tensile strength was increased by 16%, 54%, and 8%, respectively in 7 days. But when it comes to the 28-day test, splitting tensile strength decreased compared to control concrete by 47%, 32%, 13%, 5%, and 17%, respectively, in 0%, 10%, 15%, 20%, and 30% recycled concrete aggregate mixes.

The control sample failed gradually. The rubber-only sample also failed gradually, but the increment of recycled concrete aggregate up to 20% gave more sudden failure with a slight increment of failure sound. Figure 4 presents failure specimens after a splitting tensile strength test. Crumbed rubber has low elastic modulus, and it is fragile in tension. The bond between crumpled rubber and cement paste was weak. Therefore, it broke suddenly more than control concrete. The reason behind this tensile strength reduction in the concrete containing crumb rubber is that small rubber particles isolate other solid constituents of the mix from each other and act as voids that induce stress concentration, leading to a quicker concrete failure in tension.

D. Modulus of rupture

After taking out the specimens from the curing tank and preparing them by removing surface water using a towel, measurements of prism height, width, and diameter were taken. Support points were marked 50mm apart from each end. Therefore, the clear distance between supports is equal to 400 mm, and it was divided into 3 equal sections, and symmetrical loading points were marked. BS EN 12390–5:2000 suggests a beam size of 100 mm × 100 mm × 500 mm for less than 25 mm of aggregate concrete. A summary of the hardened concrete flexural strength test results of prisms after 28 days is presented in Table 2. All failures occurred in the middle third of the distance (in between loading points as shown in Figure 5). All concrete mixes had higher flexural strength than control concrete, except rubber only concrete. Flexural strength was decreased by 36% in the rubber-only concrete mix.

The highest flexural strength resulted from a 20% recycled concrete aggregate mix, which was equal to 5.68 MPa, and flexural strength was increased by 20% compared to the control mix. The flexural strength of the recycled concrete aggregate 10% mix was equal to the control concrete mix. The flexural strength of 15% and 30% recycled concrete aggregate mixes increased by 3% and 4%, respectively. The 15% crumbed rubber replacement created a weaker ITZ and a weaker bond between the aggregate and the cement matrix. Due to its low density, it was not uniformly distributed within the cement matrix. As in the compressive strength and splitting tensile strength tests, strength increased to an optimum value in 20% recycled concrete aggregate and 30% recycled concrete aggregate concrete mix, but resulted in a lower strength.

Figure 4. Cylinders after failure at 7 days

Figure 5. (a) Failure point (b) dimension check

Table 2. Material properties of various mixes at 7 day and 28 da

Ref No	Compressive strength (MPa)				Splitting tensile strength (MPa)		Modulus of rupture (MPa)	Slump (mm)
	Cube		Cylinder					
	7 days	28 days	7 days	28 days	7 days	28 days	28 days	
$C_0R_0A_0$	17.65	27.62	14.28	23.13	1.64	2.77	4.75	200
$C_{15}R_0A_0$	7.53	11.12	6.55	9.00	1.04	1.46	3.04	175
$C_{15}R_{10}A_0$	12.8	17.12	9.42	11.70	1.38	1.89	4.75	110
$C_{15}R_{15}A_1$	24.47	32.71	18.22	22.65	1.91	2.48	4.88	90
$C_{15}R_{20}A_1$	28.22	36.50	20.5	24.02	2.53	2.62	5.68	80
$C_{15}R_{30}A_1$	20.67	28.09	14.79	20.14	1.77	2.29	4.93	115

E. Water absorption, Density, Volume of voids

Four different weights were selected as: dry weight, saturated weight, weight after boiling, and apparent mass in water collected. Water absorption capacity increased in rubber-only concrete compared to control concrete. With the addition of recycled concrete aggregate, water absorption decreased to 4%

in the 15% and 20% recycled concrete aggregate mixes but got a slightly higher value in the 20% recycled concrete aggregate mix.

Overall, all mixes in which recycled concrete aggregate was included gave a low water absorption rate compared to control concrete. In all mixes, density values had a similar variation as follows: Bulk density dry < Bulk density after immersion < Bulk density after immersion and boiling < Apparent density. In Crumbed rubber only concrete, dry density was decreased by 16% and with addition of Recycle concrete aggregate, the density was increased compared to Crumbed rubber only concrete. 15% from recycled concrete aggregate mix onwards, the density reached a similar value compared to control concrete. In the other 3 densities also, a similar variation to dry density was observed. Voids increased by up to 21% in rubber-only concrete compared to control concrete, but with the addition of recycled concrete aggregate, it decreased to 11% in the 15% recycled concrete aggregate mix. 20% Recycled Concrete Aggregate Mix got a slightly higher value than the 15% Recycled Concrete Aggregate Mix, but it was decreased again in the 30% Recycled Concrete Aggregate Mix. A summary of test results regarding water absorption, density, and volume of void is presented in Table 3.

Table 3 Variation in Water Absorption, Density, and Volume of Void in each mix

Ref No	Water absorption (%)		Bulk density (Mg/m3)			Apparent density (Mg/m3)	Volume of voids (%)
	After immersion	After immersion & boiling	Dry	After immersion	After immersion & boiling		
$C_0R_0A_0$	7.45	8.17	2.36	2.53	2.55	2.92	19.24
$C_{15}R_0A_0$	8.11	10.01	2.12	2.29	2.29	2.69	21.22
$C_{15}R_{10}A_0$	6.72	7.21	2.17	2.32	2.33	2.58	15.68
$C_{15}R_{15}A_1$	3.69	4.69	2.38	2.47	2.5	2.69	11.2
$C_{15}R_{20}A_1$	5.03	5.81	2.38	2.51	2.51	2.77	13.87
$C_{15}R_{30}A_1$	4	5.03	2.33	2.43	2.45	2.64	11.73

F. Comparison with standard code in practice

Standard available guidelines (EC2) were used to predict 28-day compressive strength values using 7-day values and to get the ratio between the experimental value and the calculated value. Using this method, compressive strength was calculated for both cylinder and cube specimens. Figure 6. Shows a summary of the ratio between the experimental and calculated values of compressive strength in cube & cylinder. Figure 7 presents the calculated tensile strength values. The ratio between experimental and calculated values of splitting tensile strength is presented in Figure 8. The ratio between experimental and calculated values of flexural strength is presented in Figure 09.

Figure 6 shows that the experimental value of the compressive strength of concrete gets a higher value than calculated values from EC2. When it comes to crumbed rubber and concrete, the difference in strength can be neglected. With the introduction of recycled concrete aggregate to concrete, the calculated value of strength gets a higher value than the experimental value. The variation between experimental and calculated values is greater in cylinder specimens up to a 20% addition of recycled concrete aggregate. The 30% recycled concrete aggregate mix variation was much closer. Due to addition of Recycle concrete aggregate, concrete strength gain increased. But all the variations were in the 15% range.

The tensile strength of concrete was calculated using AS3600, fib2010, and EC2. In all concrete mixes except crumbed rubber only mix, the highest tensile strength was shown for AS3600. EC2 showed the second highest strength, and fib2010 showed the lowest strength values. In the crumbed rubber only mix, the highest tensile was shown by fib2010 and the lowest tensile strength was shown by AS3600. EC2 showed an in between value (Figure 7). For normal concrete, strength values showed a small variation for all design codes, which was approximately equal to 2.6 MPa. Crumbed rubber only mixes got the lowest tensile strength and addition of 10% Recycle concrete aggregate increased the strength values, but it was still less than the control concrete. From the addition of 15% recycled concrete aggregate onwards, tensile strength increased compared to control concrete for AS3600 and fib2010 standards. But EC2 still shows less value compared to control concrete.

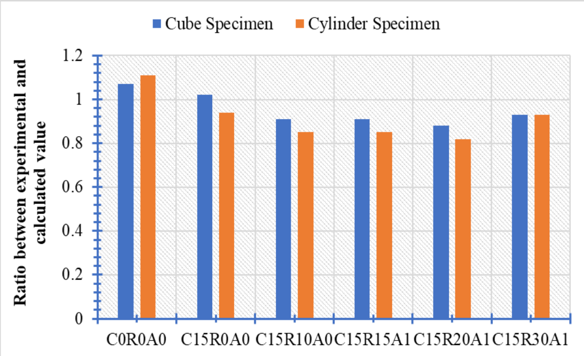

Figure 6. Ratio of experiment & calculate values using EC2

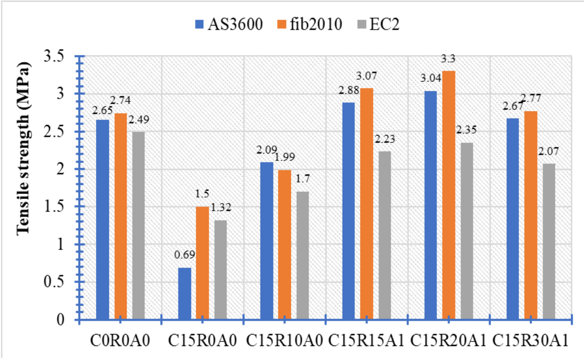

Figure 7. Calculated tensile strength for 28 days

Figure 8 shows the ratio between the experimental and calculated values of splitting tensile strength using available codes. The result shows that control concrete achieved all splitting tensile strength values within a 10% range. For all other mixes, AS3600 shows less than 23% variation. ACI codes shows less than 37% variation. fib2010 shows much closer value to experimental values in control mix, Crumbed rubber only mix and 10% Recycle concrete aggregate mix, but variation goes up to 21% in 15%, 20%, 30% Recycle concrete aggregate mixes. All calculated values show a higher splitting tensile strength value than the results achieved in the experiment. Due to this large variation in all mixes, further studies must be carried out to check the adequacy of crumbed rubber concrete with recycled concrete aggregate.

Figure 9 shows the ratio between the experimental and calculated values of flexural strength using available codes. The control concrete shows 1.51 and 1.46 variations in experimental and calculated values, as calculated by AS3600 and ACI 318-14 standards. ACI 363-92 and fib2010 show small variation ratios. Crumbed rubber only concrete mixes and 15%, 20%, and 30% recycled concrete aggregate concrete mixes show approximately similar ratios as control concrete. But in 10% recycled concrete aggregate, a higher variation in ratios can be seen.

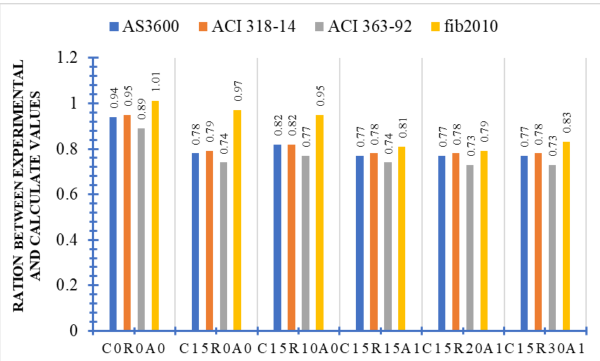

Figure 9. Ratios of splitting tensile strength

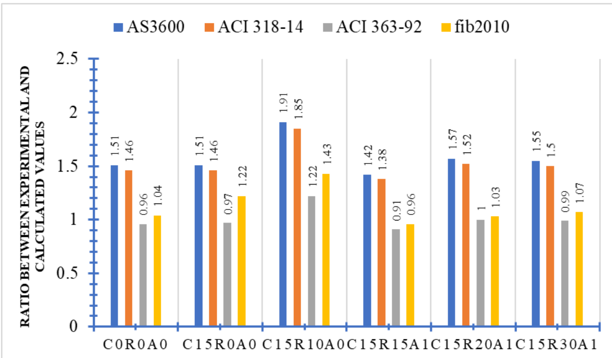

Figure 8. Ratios of flexural strength

2 CONCLUSION

This study was conducted to investigate the mechanical and durability properties of CR concrete, which contains RCA. 15% of CR was replaced by fine aggregate and different RCA was added to the developed concrete. The result of this study can be summarized as follows:

- Workability decreased with replacement of Crumbed rubber, and it further reduced with increase of level of Recycled concrete aggregate.
- Compressive strength decreased by 59% due to the replacement of 15% Crumbed rubber. Addition of Recycled concrete aggregate. in each level increased Compressive strength but the optimum value was received in 20% Recycled concrete aggregate.
- A maximum Compressive strength of 36.5 MPa was achieved in a 20% Recycled concrete aggregate. mix. Compared to Control, it is a 32% increment.
- Splitting tensile decreased by 47% with the replacement of 15% Crumbed rubber. and increased in each level of Recycled concrete aggregate. But reached an optimum value of 2.62 in 20% Recycled concrete aggregate. The reduction in splitting tensile strength compared to Control concrete was 5% in the 20% Recycled concrete aggregate. mix.
- Flexural strength of concrete decreased by 36% in 15% of Crumbed rubber replacement. It increased with the addition of Recycled concrete aggregate. at each level and got an optimum value at 20% Recycled concrete aggregate mix. The flexural strength increment in the 20% Recycled concrete aggregate. mix was 20%.
- Based on the mechanical behavior of concrete, a 20% Recycled concrete aggregate. Addition can successfully improve loosen strength due to a 15% Crumbed rubber replacement.
- But existing design guidelines cannot be directly used with these concrete mixes. There are rapid changes in strength values that were achieved using Recycled concrete aggregate.
- Existing guidelines cannot be directly used with these concrete mixes. There are rapid changes in strength values that were achieved using Recycled concrete aggregate.

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