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ABSTRACT

Waste rubber disposal is a critical environmental issue and calls for immediate attention. Partial replacement of fine and coarse aggregates in concrete by waste rubber can provide a sustainable solution for its disposal and reuse in civil engineering applications. This study experimentally investigated various mechanical properties of rubberized concrete having fine aggregates replaced by crumb rubber graded below 4.75 mm particle size. The concrete mechanical properties, i.e., 14-day and 28-day compressive strengths, elastic modulus, density, etc., were examined for varying crumb-rubber percentages of 10%, 20% and 30% by volume. A detailed microstructural investigation was performed using concrete micrographs through Scanning Electron Microscopy (SEM). A total of 12 standard cubes and cylinders were cast and tested. The test results showed a reduction of 14-37% in compressive strength, 4-21% for elastic modulus and 1- 4% for density of rubberized concrete compared to control specimens. SEM microstructure analysis revealed that the decrease in mechanical properties can be attributed to the lack of adhesion, generation of microcracks, and weak bonding of concrete matrix around rubber particles. Further, the potential use of rubberized concrete in double-skin tubular columns (DSTCs) is discussed to compensate for the negative effects of rubberized concrete through effective confinement.

KEYWORDS

Rubberized concrete, crumb rubber, compressive strength, micrograph, scanning-electron microscopy (SEM).

INTRODUCTION

For sustainable construction, research efforts are being made worldwide to transform environmental wastes, such as waste rubber, plastic, recycled gravel and other industrial wastes, into valuable construction materials for civil engineering applications (Aiello and Leuzzi 2010; Verian et al. 2018; Almohana et al. 2022). Waste rubber disposal is a complex environmental, health, and esthetic issue due to the intricate composition of rubber from different sources. From a sustainability point of view, a circular economy and green concrete production for civil engineering applications are essential for saving our depleting natural resources (Moustafa and ElGawady 2015). Incorporating waste products as a partial replacement for some concrete ingredients can conserve natural resources and safeguard the environment from waste accumulation. Waste rubber, especially from tyres, has seen applications in concrete in various forms, such as chipped rubber (> 4.75 mm;), crumb rubber (4.75-0.425 mm), rubber powder (< 0.425 mm)) and fiber rubber (Zrar and Younis 2022; Ganjian et al. 2009) as shown in Figure 1.

Chipped rubber (>4.75 mm) | *Crumb rubber (4.75-0.425 mm)* | *Rubber powder (<0.425 mm)* | *Fibre rubber*

Figure 1: Waste rubber forms used in concrete (Zrar and Younis 2022).

Past research studies reported that the concrete's fresh and hardened properties are significantly affected by the partial replacement of its ingredients with various forms of waste rubber (Li et al., 2019). The workability of concrete mix usually decreases with increased rubber particles/fibers percentages (Olivares and Barluenga 2004; Ozbay et al. 2011). In contrast, other researchers reported slightly improved workability by partially adding rubber to concrete (Aiello and Leuzzi 2010; Wang et al. 2013). Conclusively, the compressive strength, modulus of elasticity, flexural strength and splitting-tensile strength of rubberized concrete have been reported with a reduction with increased rubber content in most of the previous studies (Eldin and Senouci 1993; Khaloo et al. 2008; Taha et al. 2008; Ganjian et al. 2009; Yilmaz and Degirmenci 2009; Ozbay et al. 2011; Naito et al. 2013; Gupta et al. 2014; Moustafa and ElGawady 2015). This reduction in important mechanical properties of rubberized concrete can be attributed to (1) excessive deformation of rubber particles under load leading to early concrete microcracks (Alsaif et al. 2018), including rapid microcrack development at the interfacial transition zone (ITZ) between rubber and cement particles (Gonen 2018). (2) The poor adhesion at ITZ due to weak chemical interaction between rubber and cement particles, contrary to thorough spread and chemical bonding in a traditional concrete mix (Thomas et al. 2016). Gupta et al. (2019) attributed numerous air voids in rubberized concrete to reducing its mechanical properties. The density of rubberized concrete has been reported to decrease gradually, with an increased percentage of rubber replacing the natural aggregates due to the lower unit weight of rubber particles than natural aggregates (Batayneh et al. 2008; Yilmaz and Degirmenci 2009; Nayef et al. 2010; Aiello and Leuzzi 2010; Wang et al. 2013; Gupta et al. 2014). The abrasion resistance of concrete greatly influences the deterioration and durability of concrete to different exposures. Rubberized concrete has lesser abrasion resistance than the control mix (Sukontasukkul and Chaikaew 2006). Ozbay et al. (2011) reported a higher wear depth and mass loss of concrete due to the increased content of rubber particles in the mix.

In contrast, concrete properties that are reported to enhance with the addition of rubber content in the mix include toughness, energy absorption capability, fracture and impact behavior, and reduced brittleness. Turatsinze et al. (2005) and Taha et al. (2008) reported better fracture resistance of rubberized concrete compared to control specimens. Other studies (Zheng et al. 2008; Wong and Ting 2009) reported significant improvement by having a lower brittleness index and high energy absorption capability of rubberized concrete compared to regular mix. Khaloo et al. (2008) partially replaced coarse and fine aggregates with chip rubber and crumb rubber, respectively. About 25% replacement percentage was reported as the optimum volume percentage for maximum concrete toughness. Al-Tayeb et al. (2013) reported a noticeable enhancement in impact behavior for 25% optimum replacement of fine aggregates by crumb rubber.

Recent efforts to study the microstructure of rubberized concrete through scanning electron microscopy (SEM) have explained comparative behavior leading to change in its mechanical properties compared to traditional concrete mix (e.g., Gupta et al. 2014, 2017; Mohammed and Adamu 2018; Angelin et al. 2019; Sidhu and Siddique 2022). SEM analysis helped to visualize the distribution and orientation of rubber particles at the microscale level within the concrete matrix, the morphology of rubber particles including shape, size, and surface characteristics, details of ITZ layer, and identification of different phases including hydration products of cement, aggregate, and rubber.

The literature suggests that studies on using crumb rubber in the concrete and its experimental evaluation and results are limited. The present study experimentally investigated the mechanical properties of crumb rubberized concrete, including workability, compressive strength, modulus of elasticity, density, etc., when traditional fine aggregates were replaced partially by crumb rubber (< 4.75 mm particle size) in the volumetric percentage of 10, 20 and 30%. Then, a microstructure analysis was performed using SEM micrographs. The tested rubberized concrete is intended to be used for examining the confined stress-strain behavior of sandwiched concrete in double-skin tubular columns (DSTCs) under axial compression loading in an extensive further study. The results show that using crumb rubber as a partial replacement of fine aggregates in concrete can be a promising sustainable solution for waste rubber disposal by using it in such civil engineering applications where the confined concrete conditions can mitigate significant loss of its mechanical properties.

EXPERIMENTAL METHODOLOGY

In this study, a total of 12 standard cubes and cylinders were cast for a target characteristic 28-day compressive cube strength of 25 N/mm^2 (M25 grade) using Ordinary Portland Cement (OPC), locally available well-graded fine aggregates (< 4.75 mm), coarse aggregates (< 20 mm), and crumb rubber (< 4.75 mm). The crumb rubber particles were used in the concrete mix to partially replace fine aggregates in the volumetric percentages of 0%, 10%, 20% and 30%. Accordingly, the concrete mix is given a nomenclature as "M25Rx", where M25 represents the base concrete mix having crumb rubber (letter 'R) of 'x%' as a replacement by volume for fine aggregates. Mixing constituents is critical for rubberized concrete to obtain a homogeneous mix without segregation on account of the different sizes and densities of matrix constituents (Elchalakani et al. 2018). Too much mixing can lead to concrete segregation, whereas too little mixing causes inadequate hydration and homogenous matrix mixing. Traditional mixing of rubber particles can easily intensify the segregation of concrete matrix. Therefore, a timed mixing procedure was followed for rubberized concrete similar to Elchalakani et al. (2018). Concrete constituents (except cement) and rubber particles were mixed first in dry form, and then 10% of the total water quantity was added as per the trial water-cement ratio of 0.43 (by weight) before adding cement and mixing the constituents for 2 minutes. Then half of the remaining water quantity (45% of the total) was gradually added and the mixing operation was performed for another 2 minutes to prevent rubber-particle flotation and avoid the formation of air voids. The remaining 45% of the water quantity was gradually added to the mix to obtain uniform and consistent rubberized concrete without particle flotation or segregation.

Table 1 lists the standard material property test results for rubberized concrete constituents, i.e., cement, fine aggregates, crumb rubber and coarse aggregates, evaluated as per relevant codes of practice from the Bureau of Indian Standards. The concrete mix constituents' particle size distribution (PSD) was performed following procedures outlined in relevant Indian codes of practice. Figure 2 shows the results of the PSD for fine aggregates, coarse aggregates, and rubber particles, clearly, well-graded particle distribution can be observed. Table 2 summarizes the exact weight proportions of the constituent materials mixed per m^3 of rubberized concrete for different concrete mixes.

Table 1: Constituent material properties for rubberized concrete.

Properties	Cement	Fine aggregates	Coarse aggregates	Crumb rubber
Standard consistency	31%	-	-	-
Initial setting time	30-45 minutes	-	-	-
Final setting time	580-600 minutes	-	-	-
Fineness modulus	5.3%	2.53	-	3.73
Specific gravity	3.15	2.693	2.641	1.019
Water absorption	-	1.42%	4.10%	0.48%
Sand zone	-	Zone-II	-	-

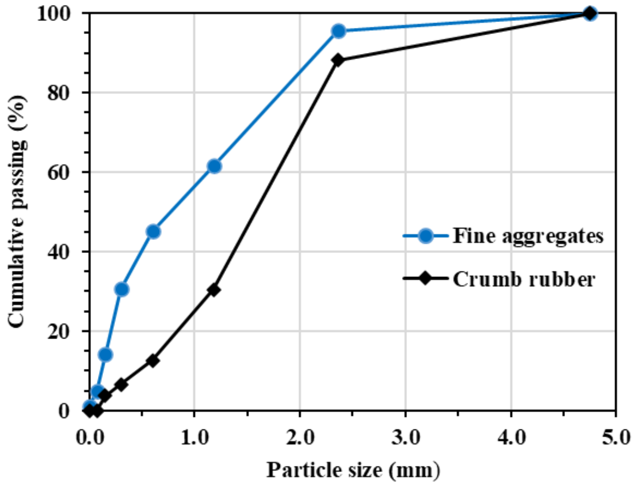


Figure 2: Particle size distribution (PSD) of fine aggregates and crumb rubber.

Table 2. Constituent proportions in the concrete mix.

Concrete mix	Crumb rubber %	Cement (kg/m^3)	Fine aggregates (kg/m^3)	Crumb rubber (kg/m^3)	Coarse aggregates (kg/m^3)	Water (kg/m^3)
M25R0	0	432.6	657	0	1116.35	186
M25R10	10	432.6	591.4	24.9	1116.35	186
M25R20	20	432.6	525.7	49.8	1116.35	186
M25R30	30	432.6	459.9	74.6	1116.35	186

Figure 3 shows the standard testing of concrete cubes and cylinders of rubberized concrete mixes in the SANS Universal Testing Machine (UTM) following BIS 516 (2006) and ASTM C39/C39M-20 (2020). The casting and testing of concrete cubes ($150\ mm \times 150\ mm\ \times 150\ mm$) followed procedures outlined in BIS 10262 (2019) and BIS 516 (2006). Standard concrete cylinders ($150\ mm \times 300\ mm$) were casted and tested in accordance with ASTM C39/C39M-20 (2020) standards. The slump cone method was employed to determine the workability of concrete. The curing was done for 14 days and 28 days for 14 days of testing and 28 days of testing, respectively. The modulus of elasticity of concrete was evaluated based on recommendations from BIS IS 456 standard for concrete specimens and ACI 318 standard for cylinder specimens.

Cube

Cylinder

Figure 3: Compression testing of standard cubes and cylinders of rubberized concrete.

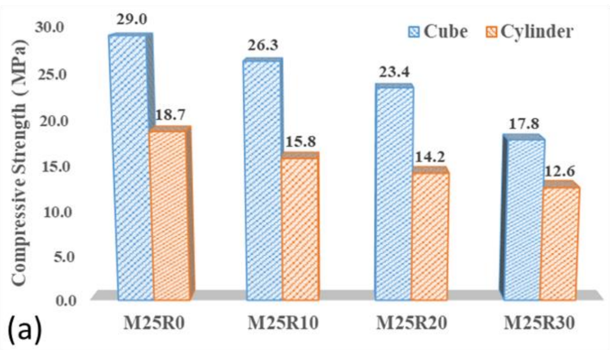
RESULTS AND DISCUSSIONS

Workability

Slump test results show that crumb rubber positively impacts the workability of concrete. The baseline specimen (M25R0) has a slump value of 49 mm and it increases to 52 mm, 56 mm, and 62 mm on substitution of 10%, 20%, and 30% of fine aggregate with crumb rubber. The workability is observed to improve by around 26.5% for 30% crumb rubber, which may indicate its potential use to reduce the consumption of palsticizers under certain circumstances.

Compressive Strength

Figure 4 presents the results of 14 days and 28 days compressive strength for different specimens (cubes as well as cylinders) with varying crumb rubber proportions under consideration in this study. A steady loss in the 14 days and 28 days compressive strength is noticed for concrete specimens with increasing rubber content. The incorporation of 10%, 20%, and 30% rubber in the concrete as an alternative to fine aggregates results in decrease of cube 14-days compressive strength from 29.0 Mpa to 26.3 MPa, 2304 MPa, and 17.8 MPa and 28-days strength from 33.3 MPa to 28.8 MPa, 25.9 MPa, and 20.8 MPa, respectively. The 14-day compressive strength of corresponding cylinder specimens reduces from 18.7 MPa to 15.8 MPa, 14.2 MPa, and 12.6 MPa and 28-days strength lowers from 25.9 MPa to 22.2 MPa, 18.3 MPa, and 16.5 MPa, respectively. The average (from cube and cylinder specimens) decrease observed in 14-days compressive strength of the concrete is 12.5%, 21.6%, and 35.6%, and for 28-days strength as 14.0%, 25.8%, and 36.8% for replacement levels of 10%, 20%, and 30%, respectively. The reduction in compressive strength also leads to a corresponding decrease in the modulus of elasticity of concrete as shown in Figure 5. The modulus of elasticity reduces by 4.2%, 13.9%, and 20.5% on the replacement of 10%, 20%, and 30% of fine aggregate with crumb rubber concrete. The corresponding strength and modulus reduction should be considered during design calculations.



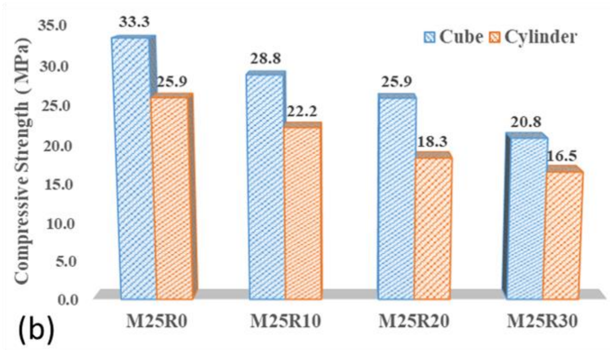


Figure 4: Compressive strength of crumb rubber concrete at (a) 14 days and (b) 28 days.

The decreasing trend in strength can be generally attributed to a lack of adhesion between cement paste and smooth rubber particles. Rubber is a soft particle and has lower stiffness compared to fine aggregates and, therefore has less load-carrying capacity. Rubber particles are elastically deformable which results in rapid formation of cracks areound rubber particles during loading as the cement paste is harder which can lead to quick rupture of concrete and consequent failure. The decrease in compressive strength can also result from an insubstantial bond between rubber particles and cement paste, leading to cracks. Reduction in compressive strength might also be contributed by the generation of voids which might have developed due to the fine nature of crumb rubber, and the size of voids increases with an increase in rubber content.

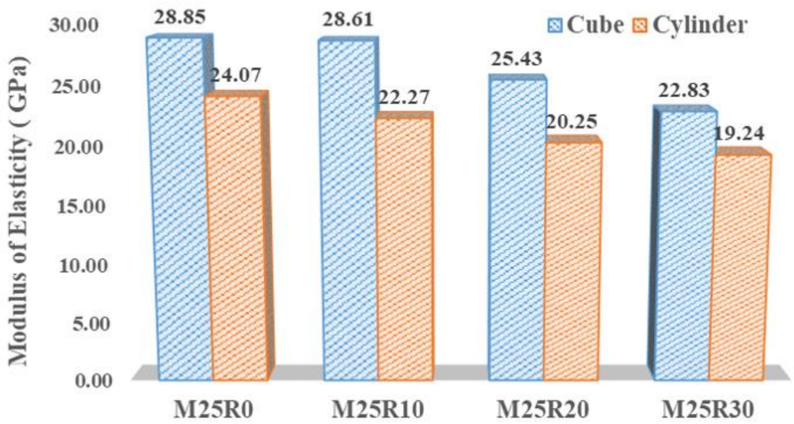


Figure 5: Modulus of Elasticity of crumb rubber concrete

Density

The addition of crumb rubber in concrete slightly influences its density, as shown in Figure 6. Compared to the baseline control mix, the average decrease in density for cubical and cylindrical specimens is 1.19%, 3.28%, and 3.63% on respective replacement of 10%, 20%, and 30% fine aggregates by rubber. This reduction is owed to low specific gravity of rubber (1.02) as compared to specific gravity of fine aggregates (2.69) as reported in Table 1. Other studies have also reported a steady reduction in density with the addition of rubber to concrete.

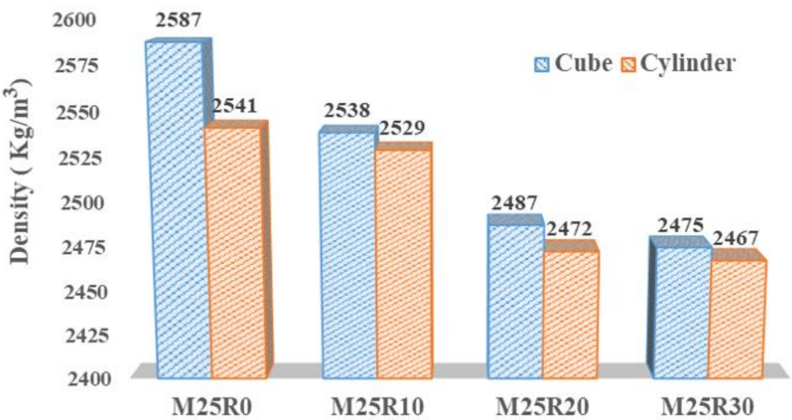


Figure 6: Density of crumb rubber concrete

Microstructural Analysis

SEM analysis technique is used to study the surface morphology and composition of a material and is a powerful tool for analysing the microstructure of materials. The SEM analysis was performed to study the microstructure of conventional and rubberized concrete. The images obtained from SEM analysis can reveal the size, shape, and orientation of the rubber particles, as well as their distribution throughout the concrete matrix. The homogeneity of the matrix of the baseline concrete mix is evident in Figure 7 which is indicative of good bonding between the aggregate and the cement paste. On the other hand, Figure 8 shows the existence of microcracks at the interface rubber particles and the cement paste. The observed cracks are probably due to higher elasticity, deformability, and softness of crumb rubber with respect to binding matrix, which consequently leads to strength loss. Further, the irregular shape of rubber particles 9 and the presence of pores and microcracks in the matrix is also observed in Figure 7 which reflects the weak bonding between the cement paste and rubber particles. This soft interfacial zone, acting as a microcrack, may result in the initiation of cracks and, therefore, accelerate the breakdown of the concrete matrix. The observed structure through SEM analysis explains the trend in loss in compressive strength and modulus of elasticity and possibly other properties such as tensile and flexural strengths.

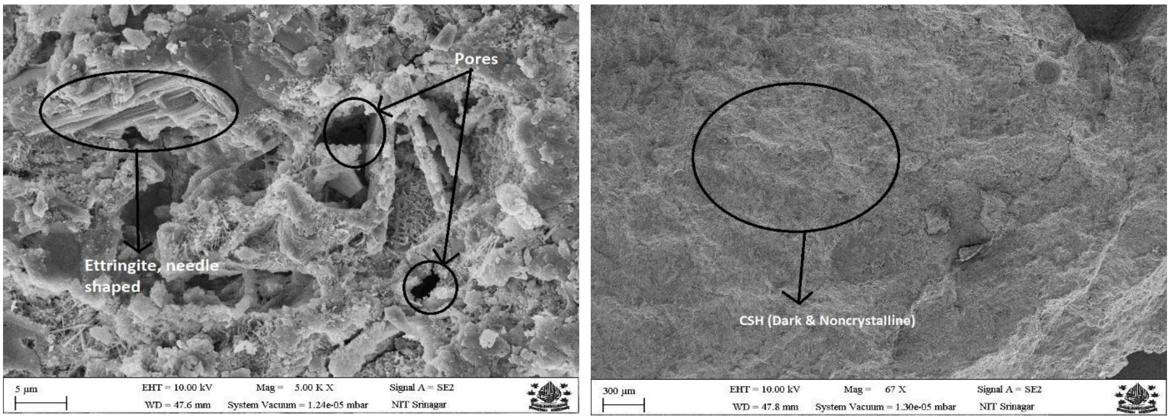


Figure 7: SEM images of baseline concrete (M25R0)

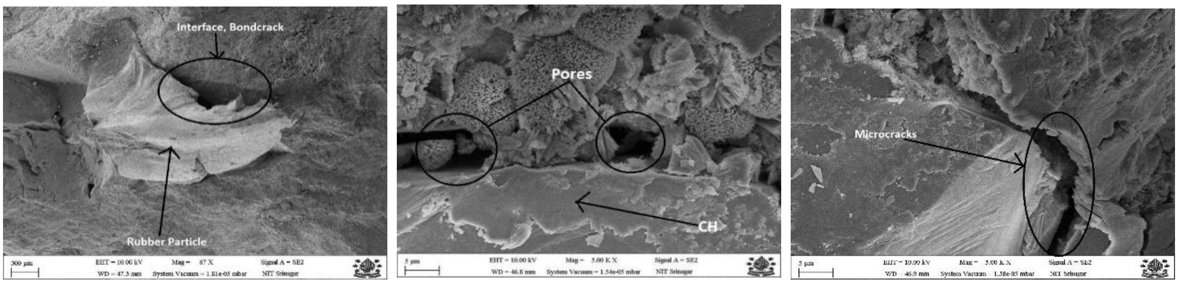


Figure 8: SEM images of rubberized concrete.

CONCLUSIONS

This paper presents the results of an experimental investigation on concrete where different proportions of fine aggregates are replaced with crumb rubber concrete. Based on the experiments performed and SEM analysis carried out, the following main conclusions are drawn:

- The crumb rubber replacement of upto 30% increased the slump value from 49 m to 62 mm which indicates the improved workability of rubberized concrete.
- The compressive strength of concrete reduces noticeably with an increase in rubber crumb content. It was observed to reduce by 14.0, 25.8 and 36.8%, and modulus of elasticity by 4.2, 13.9, and 20.5% by replacement of 10, 20, and 30% of fine aggregates with rubber, respectively.
- The density of concrete decreases with an increase in the proportion of replacement by rubber. It was reduced by 1.19, 3.28 and 3.63% for 10, 20 and 30% replacement by crumb rubber, respectively.
- The microstructural analysis using SEM shows the presence of pores and cracks and depicts the weak bonding between cement matrix and rubber particles which can lead to crack initiation and accelerated failure of concrete specimens.

FUTURE SCOPE

The steady loss in the compressive strength, density, and modulus of elasticity of concrete was observed with increasing substitution levels of rubber content. Future studies may also consider the evaluation of other mechanical and durability properties such as absorption capacity, shrinkage, etc. The negative effects, such as reduction in compressive strength and its elastic modulus, can be effectively compensated if the rubberized concrete is properly confined, such as if used in concrete-filled single and double-skin steel and fiber-reinforced columns (Sofi et al. 2022, Joo & Sofi 2023, Zakir & Sofi 2022). Future studies shall focus on the development of stress-strain models of rubberized concrete under unconfined and confined conditions similar to studies (Zakir et al. 2021a,b).

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