ENGINEER - Vol. LIX, No. 01, pp. [35-46], 2026

DOI: https://doi.org/10.4038/engineer.v59i1.7731

Waste Rice Husk Ash and Waste Rubber Chips Added Light Weight Concrete Paving Blocks: Mechanical Behaviour and Forecasting Strength Properties

P.H.T. Maduranga and G.H.M.J. Subashi De Silva

Abstract: This paper investigates the potential application of waste Rice Husk Ash (RHA) and waste crumbed rubber (CR) as substitutes for cement and fine aggregates, respectively, and the potential of forecasting the mechanical properties of concrete paving blocks. Mechanical properties were experimentally investigated, and predictive formulas were derived, enabling forecasting of strength properties. Paving blocks of Grade 20 were cast by replacing fine aggregate with 5% CR (by weight) and replacing cement with waste RHA at four percentages: 0%, 5%, 10%, and 15% (by weight). Specific gravity, bulk density, compressive strength, flexural strength, and splitting tensile strength were experimentally tested. The bulk density of blocks decreases by 12% when the CR content increases from 0% to 5%, resulting in lightweight blocks. The 5%CR10%RHA paving blocks satisfied the minimum 28 day compressive strength requirement. Compared to the control block, 28 day compressive strength, flexural strength and splitting tensile strengths were decreased by 58%, 40% and 43%, respectively, with the addition of 5% CR. By replacing 10% of cement with RHA, the reductions were recovered by 32% in compressive strength and 40% in flexural strength. Flexural failure modes confirmed that adding CR contributed to overcoming the quasi-brittle behaviour of the blocks. It was found that the strength properties were proportionately varied with the density, leading to a potential for forecasting the mechanical properties of the blocks.

Keywords: Compressive Strength, Concrete Paving Blocks, Flexural Strength, Splitting Tensile Strength, Waste Rice Husk Ash, Waste Rubber Chips

1. Introduction

Paving blocks are potentially gaining attraction as economical pre-cast engineering construction units for the construction of walkways, pedestrian roads and gardens, owing to their speed of construction, easy maintenance, aesthetically pleasant, less labour work and low cost. However, the production of concrete paving blocks inherently requires cement and aggregates.

Cement production involves massive extraction of natural materials, vast consumption of global energy (5% of worldwide industry energy (Sousa et al. [1])) and significant amount of greenhouse gas emission into the environment (Kajaste and Hurme [2]). For example, 2.8 billion tons of cement were annually produced (Habert [3]), leading to extraction of around billion tons of natural materials (1.16 tons of limestone and 0.39 tons of shale for production of one ton of clinker (Manning et al. [4])), consumption of 4000 MJ (Sousa et al. [1]) x 2.8 billions of energy and releasing around 2.2 billion tons (800kg CO_2/t) (Sousa et al. [1]) of CO_2 (~5-8% of global carbon emissions) annually (Kajaste and Hurme [2]). Every ton of cement production emits 0.8 tons of CO_2 into the atmosphere, challenging the equilibrium of natural carbon cycle. Imbalanced natural carbon cycle will contribute to heat the globe, posing a threat to human and ecological systems (Sousa et al. [1]). On the other hand, the average annual extraction of sand in the world is around 230 million m^3/year (Koehnken et al. [5]), which is negatively impacting on the environment such as lowering water table, bank erosion, land degradation and salinity intrusion. Therefore, to decrease the environmental impact of using virgin materials and global CO_2 emission, there is an urgent need to use substitutes for cement and sand.

Eng. P.H.T. Maduranga, AMIE (Sri Lanka), B.Sc. Eng. (Hons) (Ruhuna), Research Student, Department of Civil and Environmental Engineering, Faculty of Engineering, University of Ruhuna, Sri Lanka
Email:phtmaduranga@gmail.com
ORCID ID: https://orcid.org/0009-0006-5954-5461
Eng. (Prof.) (Mrs.) G.H.M.J. Subashi De Silva, C.Eng. MIE (Sri Lanka), PhD (Saitama), PG Diploma (Struct), B.Sc.Eng. (Hons) (Moratuwa), Professor, Department of Civil and Environmental Engineering, Faculty of Engineering, University of Ruhuna, Sri Lanka.
Email:subashi@cee.ruh.ac.lk
ORCID ID: https://orcid.org/0000-0002-0350-7793

Among many, one of the low-cost cementitious materials is waste RHA. Rice husks are used as a fuel for boilers to produce steam in power plants (Prasara and Gheewala [6]) and as a fuel in brick manufacturing industry to fire clay bricks (Kazmi et al. [7]), which results in RHA as a byproduct. Waste RHA consists of high content (more than 85%) of reactive amorphous silica (Jaya et al. [8]). With the absence of unburnt carbon in burnt waste RHA, it is gaining attraction as a potential low-cost cement substitute (De Silva et al. [9]). Waste RHA has been identified as a potential cement substitute for various applications, including mortar (Srikanth et al. [10]; De Silva et al. [9]), cement blocks (Pushpakumara and De Silva [11]), paving blocks (De Silva and Priyamali [12]; Ranasinghe and De Silva [13]), high strength concrete (Hakeem et al. [14]) and self-compacting concrete (Le and Ludwig [15]; Safiuddin et al. [16]), owing to its contribution to enhanced mechanical strengths. Abundant quantities of waste RHA are available in most of agricultural countries that can be utilized as a cement substitute, as an emerging technology for managing the solid waste.

Waste CR, a by-product of the rubber products manufacturing industry, has elastic properties (Gerges et al. [17]). However, CR inevitably has lower strength, rigidity and adhesion compared to natural aggregates (Chen et al. [18]), consequently, have limitations in structural applications. Besides, the weak adhesion between rubber aggregates and cement paste negatively impacts structural properties (Chen et al. [18]). Due to their elastic nature, such aggregates can contribute to reducing matrix fracture toughness, promote multiple cracking behavior (Lijuan et al. [19]), and enhance tensile strain capacity and fracture energy (Wang and Pang [20]). Reduced mechanical properties caused by low strength and less rigid rubber aggregates (Lijuan et al. [19]) can be possibly enhanced by the addition of cementitious materials and improving the bond between cement paste and the rubber aggregates. However, the effect of crumped rubber aggregates on mechanical properties of waste RHA based concrete paving block is not yet understood.

Incorporation of several types of waste substitutes increases the number of variables and complication in the concrete mix design process, which is expensive and time consuming in the manual prediction and calculation (Thilakarathna et al. [21]; Alyami et al. [22]). Prediction of such properties is important, because the testing of each and all possible replacement levels are not economical. Prediction of properties of paving blocks will facilitate the industry to maximize sustainable and efficient production with optimum properties. With complication of this material property identification, production, cost and time, forecasting of mechanical properties is proposed.

Investigation on mechanical properties and derivation of formula to forecast the mechanical properties of CR-RHA incorporated paving blocks are desired in this study.

2. Methodology

The method used for the study is summarized in Figure 1. Raw materials were selected and tested for specific gravity and bulk density. Further, sieve analysis was conducted to observe particle size distribution of aggregates, which is essential in determination of material mix proportions. Grade 20 Paving Blocks having dimensions of 200 mm × 100 mm × 60 mm were cast, which satisfy to requirements of class 4 paving blocks specified in SLS 1425 (2011) [23]. Blocks were cast by replacing 5% (by weight) of fine aggregate with CR and cement with waste RHA at varying percentages: 0%, 5%, 10%, 15% (by weight). For this study, 5% CR was selected based on literature (Ranasinghe and De Silva [13]), in which the optimum compressive strength was

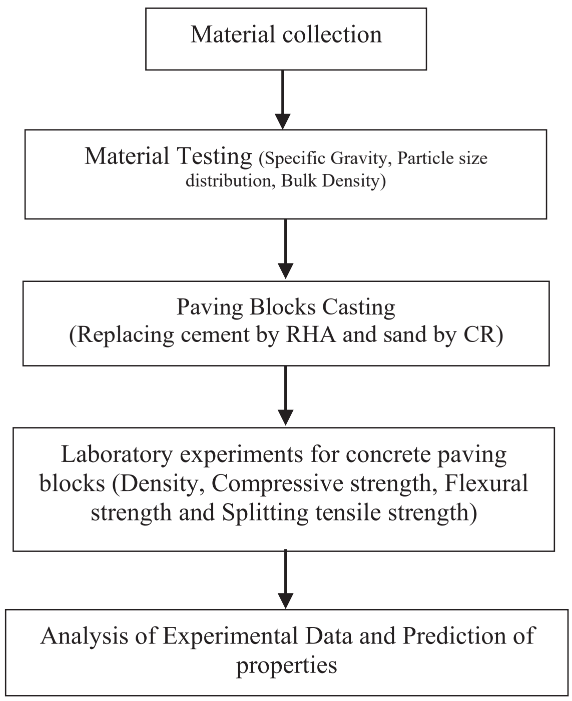

Figure 1 - Methodology used for the study

observed at 5% CR. Strength properties were tested at 28 and 56 days after curing in water.

2.1 Raw Materials Used

Waste RHA was collected from a rice husk fuelled brick kiln without applying any treatment. Waste crumbed rubber was collected from a rubber slipper producing company and were sieved to particle size in the range of 0 to 4.75 mm, to be compatible with fine aggregates. Portland cement of strength class 42.5 kN was used as a binding material. Natural river sand was used as fine aggregate passing through sieve size of 4.75 mm. Crushed aggregates, passing through 10 mm sieve, were used as coarse aggregates. The water supplied by the National Water Supply and Drainage Board (NWSDB) was used.

2.2 Paving Block Casting

Grade 20 (20 N/mm^2) paving blocks were cast. This strength grade was selected as applicable for building premises, footpaths, shopping malls, landscaping, pedestrian plazas and non-traffic strength roads under strength class 4 of SLS 1425 (2011) [23]. Coarse aggregate, fine aggregate (sand), cement, waste RHA and rubber were dry mixed in a pan-type concrete mixing machine for 3 minutes. Then, water was added and mixed well to get a homogeneous mixture. Mould oil was applied to paving block moulds, the mixture was poured into moulds, and machine vibration for 5 seconds was applied to moulds. Excess concrete was removed and moulds were placed on a flat surface. Blocks were applied a stress of 3kN/m^2 (for 4 hours) to improve the bonding strength of rubber and materials. A total of 90 blocks were cast, with three for each test of each mix proportion for averaging of the results. Blocks were de moulded after 24 hours and put into water for curing. Curing period was 28 days and 56 days depending on the testing period. Mix proportions are given in Table 1.

2.3 Raw Material Testing

2.3.1 Sieve analysis test

Sieve analysis test for RHA, cement, sand, rubber and coarse aggregate was performed according to ASTM C136 (2006) [24].

2.3.2 Specific gravity test

Specific gravity test was performed for all raw materials according to ASTM D 854-14 (2000) [25].

2.3.3 Bulk density test

Bulk density test was performed for all raw materials according to ASTM C-29 (2011) [26].

2.4 Paving Block Testing

2.4.1 Density

Density of paving blocks was tested according to ASTM C67-03 (2003) [27] using Equation (1).

$$Density = Mass\ of\ block/Volume\ of\ block \quad \ldots(1)$$

2.4.2 Compressive strength test

Compressive strength test of paving blocks was carried out using a compression testing machine following ASTM C140 (2008) [28] at 28 and 56 days. Compressive strength was determined by using Equation (2).

$$Compressive\ strength = Applied\ load/Area\ of\ top\ surface \quad \ldots(2)$$

2.4.3 Flexural strength test

Flexural strength test of paving blocks was conducted under three-point loading condition according to IS15658 (2006) [29] at 28 and 56 days. Flexural strength was determined by Equation (3).

$$F=1.5Fl/bd^2 \quad \ldots(3)$$

where, F– measured load at failure, l- spacing of support rollers, b– width and d– depth of the paving block.

2.4.4 Splitting tensile strength test

Splitting tensile strength test of paving blocks was performed along the longest splitting section of blocks according to IS15658 (2006)

Table 1 - Material proportions of paving blocks (kgm^{-3})

Mixture	Cement	Fine aggregate	Coarse aggregate	Waste RHA	Waste rubber chips	Water
0%CR0%WRHA	333.29	975.54	798.17	0.00	0.00	233
5%CR0%WRHA	333.29	926.76	798.17	0.00	48.78	233
5%CR5%WRHA	316.63	926.76	798.17	16.66	48.78	233
5%CR10%WRHA	299.96	926.76	798.17	33.33	48.78	233
5%CR15%WRHA	283.30	926.76	798.17	49.99	48.78	233

[29] at 28 and 56 days. Splitting tensile strength was determined by using Equation (4).

$$T = 0.637kp/s \qquad \dots(4)$$

where, p = measured load at failure (N), k = is correction factor (=0.87 for 60 mm thick blocks), s = area of the failure plane (mm²) (= $l \times t$), t = paving block thickness (mm), l = the mean of two measured failure lengths (mm).

3. Results and Discussion

3.1 Properties of Raw Materials

3.1.1 Particle size distribution

The particle size distribution of raw materials is shown in Figure 2. Particle size distribution depicts that waste RHA, cement, sand and rubber chips are well graded materials. Fineness (percentage passing sieve no. 200) of the materials was assessed based on the particle size distribution (De Silva and Priyamali [12]). The fineness of rubber and sand was 0% and 0.4%, respectively, indicating that waste RHA is coarser than cement and waste rubber chips are coarser than river sand.

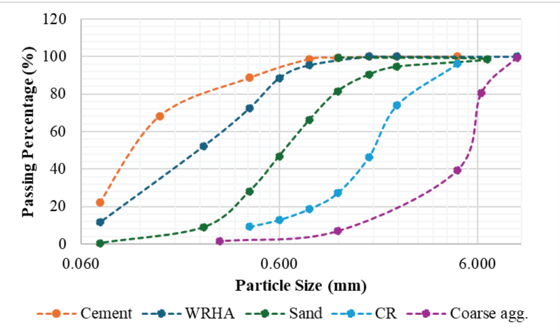

Figure 2 - Particle size distribution of materials

3.1.2 Specific gravity

Specific gravity of waste RHA and cement were 1.96 and 2.79, respectively, similar to values in previous studies for waste RHA (i.e., 2.02 [De Silva et al. [30]]) and for cement (i.e., 3.07 [De Silva and Priyamali [12]]). Specific gravity of sand, waste rubber chips and coarse aggregate were 2.58, 1.16 and 2.54, respectively, similar to previous studies for sand 2.6 (Mendis et al. [31]), for waste rubber 0.98 (Sukontasukkul and Chaikaew [32]) and for coarse aggregate 2.45 (Mendis et al. [31]).

Lesser specific gravity of rubber chips than that of sand, and lesser specific gravity of waste RHA than that of cement, contributed to achieve a light weight paving block.

3.1.3 Bulk density

Bulk density of cement, waste RHA, waste rubber chips, sand and coarse aggregate were 1252 kgm^{-3}, 357 kgm^{-3}, 457 kgm^{-3}, 1503 kgm^{-3} and 1450 kgm^{-3}, respectively, close to the values reported in prior studies for RHA (301 kgm^{-3}) and rubber (527 kgm^{-3}) (Wang and Pang [20]). Waste RHA is denser than RHA that has been used in previous studies. Rubber chips have a lower density than in previous studies.

3.2. Properties of Paving Blocks

3.2.1 Density

Figure 3 shows the variation of density with different CR and RHA replacement levels of the produced paving blocks. Replacement of fine aggregate with 5% CR shows a 12% and 12.6% reduction in the density of blocks at 28 and 56 days, respectively, than conventional paving blocks. Reduction of the density of paving blocks with sand replacement by waste CR has been reported previously in Ling et al. [33] and Murugan and Natarajan [34].

Reduction in the density of paving blocks is attributed to the lower specific gravity of CR compared to fine aggregates (Fadiel et al. [35]) and trapped air within surface of rubber particles (Sheraz et al. [36]). Incorporation of CR increases the occupied volume due to its low specific gravity and trapped air, which results in a reduction in density.

The cement replacement with waste RHA at 5% and 10% (when sand is replaced by 5% CR) shows the density improvement of 0.5% and 2.9%, respectively, at 28 days and also 0.1% and 0.7%, respectively, at 56 days, compared to 5%CR0%RHA blocks (Figure 3), probably due to the enhanced packing density. Intrusion of RHA reduces the porosity of concrete by increasing packing density (Amran et al. [37]). However, the 10% RHA added blocks demonstrated 9.4% and 12% of density reductions compared to control sample (0%CR0%RHA), yet maintaining reduced density.

The observed reduction in paving block density

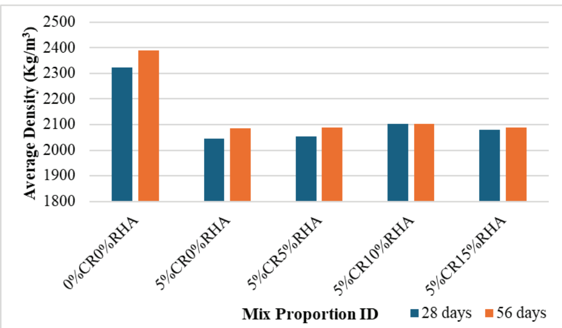

Figure 3 - Variation of density with different CR and RHA replacement levels

confirms that the incorporation of waste CR and RHA leads to the production of lightweight blocks.

3.2.2 Compressive strength

Figure 4 shows the compressive strength of paving blocks at 28 and 56 days. By adding 5% CR, compressive strength of paving blocks decreased from 32 N/mm² to 13 N/mm² at 28 days and from 37 N/mm² to 16 N/mm² at 56 days. With 5% CR content, 28 day compressive strength was reduced by 59%, compared to that of the control block (i.e., 0%CR 0% RHA).

The strength reduction can be attributed to lower stiffness of waste CR (Sofi et al. [38]; Gerges et al. [17]) and fragile bond between waste CR and cement paste (Lotfollahi et al. [39]). Lower stiffness of CR particles makes them deform under loads and form cracks resulting lower compressive strength. Fragile bonds result in non uniform distribution of stress, which causes particle failure under lower compressive loads.

By addition of waste RHA as 5% and 10%, compressive strength of paving blocks gradually increased and when the percentage exceeds 10%, the strength decreased as observed in De Silva and Priyamali [12]. The cement replacement with waste RHA at 0%, 5%, 10% and 15% shows compressive strength of 13.4 MPa, 15.6 MPa, 19.3 MPa and 17.52 MPa at 28 days and 15.6 MPa, 16 MPa, 20.2 MPa, and 18.1 MPa at 56 days (Figure 4).

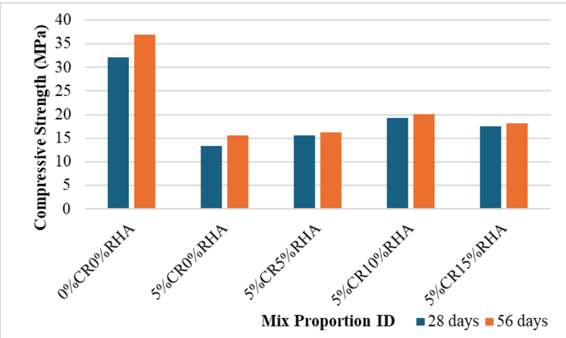

Figure 4 - Compressive strength of paving blocks

The incorporation of 10% RHA increased the compressive strength by 44% compared to paving blocks containing 5% CR without RHA (5%CR0%RHA) at 28 days, indicating RHA has the potential to improve the compressive strength (Figure 4). Addition of 10%RHA records a 32% recovery of lost strength observed with incorporation of 5%CR (5%CR0%RHA). However, the incorporation of 15% of RHA increased the compressive strength by only 30.7%.

In this study, blocks were subjected to a stress of 3 kN/m² (for 4 hours) to improve the bonding between CR and cement paste. Static pressure applied on the blocks during casting might have affected improvements in compressive strength (Figure 4). When pressure has not been applied to the blocks in the casting process, such an improvement in compressive strength has not been noticed (Wang and Pang [20]).

The compressive strength improvement of paving blocks at 5%CR10%RHA may be correlated due to highly reactive amorphous silica in RHA, which reacted with calcium hydrate and formed calcium silicate hydrate gel (CSH). By further increment of RHA, ettringite morphology and lump particles are formed, which are randomly connected in the mixture (De Silva and Priyamali [12]). However, by 5%CR10%RHA (Figure 4), the minimum average crushing strength of 15 MPa of class 4 paving blocks was achieved, satisfying the requirement specified in SLS 1425 (2011) [23].

Figure 5 shows the failure modes of paving blocks observed under compressive strength test. Rubber added blocks showed a ductile behavior due to energy-absorbing and deformable nature of CR (He et al. [40]; Du et al. [41]). Cracked particles of blocks were retained due to the effect of rubber.

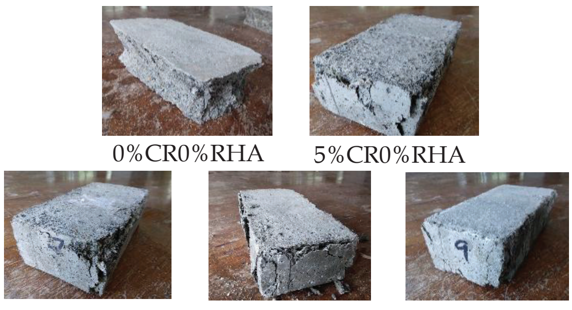

Figure 5 - Modes of failure of paving blocks under compressive strength test

Figure 6 shows variation of compressive strength with density of the blocks at 28 and 56 days. Compressive strength increased when density of blocks increased, indicating a correlation. This linear variation can be expressed by $y = 0.096x - 183.2$ at 28 day age and $y = 0.21x - 417.3$ at 56 day age. The derived linear variation demonstrated an excellent fit to the experimental data, with coefficient of determination (R^2) of 0.97 and 0.96 at 28 and 56 days, respectively. With time, gradient increases from 0.096 to 0.2 indicating that, strength increases rapidly with density for 56 day aged blocks.

The derived formula enables prediction of compressive strength at a specified density and, conversely, estimation of density corresponding to a target compressive strength. Further, selection of a balanced material proportion, in both density and compressive strength, enables identifying the corresponding material proportions (i.e., RHA, CR) for casting of paving blocks.

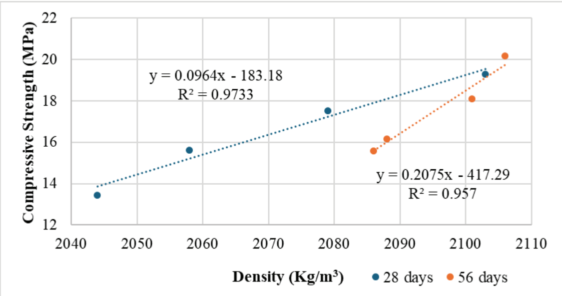

Figure 6 - Density vs compressive strength of paving blocks

Figure 7 compares the variation of compressive strength ratio with density ratio found in the current study with previous studies (Babar et al. [42]; Bheel et al. [43,44]; Anwar et al. [45]; Zareei et al. [46]). In these previous studies, the blocks were developed with different waste materials. For comparison of all studies, the compressive strength ratio and density ratio were considered (Figure 7). Density ratio was determined by dividing densities by the lowest density. Strength ratio was determined by dividing the strength by the strength corresponding to the lowest density. Compared to previous studies, the current study exhibits a higher rate of increase in compressive strength (indicated by a higher gradient) with density, reflecting a stronger correlation between these two parameters. A reduced rate of strength achievements was observed with Zareei et al. [46], who used RHA up to 25% and maintained Microsilica as 10%, possibly due to inappropriate particle size distribution. A trend similar to the current study was noticed with Anwar et al. [45], (Figure 7). Anwar et al. [45] used ground RHA as a substitute for cement. Strength achievement was increased in Bheel et al. [43], who replaced cement with both RHA and Wheat Straw Ash (WSA) in similar quantities for cement, and Babar et al. [42], who replaced cement with WSA, possibly due to fine particles of RHA and the reaction of RHA and WSA with a higher content of SiO_2 (Figure 7). However, strength achievement was reduced with Wheat Straw Ash (WSA) (Bheel et al. [44]).

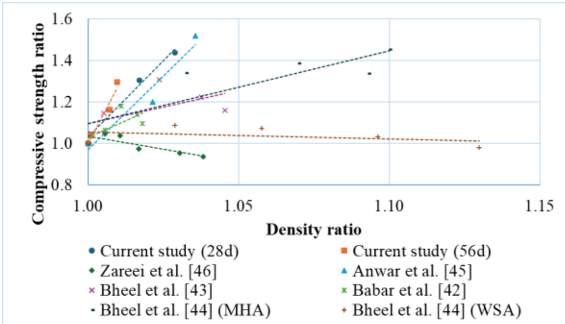

Figure 7 - Density ratio vs compressive strength ratio observed in current study & previous studies

Table 2 shows the details of the fitting lines of the similar studies. It is apparent that, gradient of Anwar et al. [45] is almost similar to that of the current study with a higher R^2 (Table 2), indicating that the waste RHA, instead of ground RHA, can be used effectively to achieve greater strength with lighter blocks. Comparing to ground RHA, utilization of waste RHA is

Table 2 - Coefficient of determination of density and compressive strength of concrete with different waste materials

Reference	Substituent	Replaced material	Gradient of line (m)	R^2
Current study	Waste RHA	Cement	0.0964 (28d)	0.973
			0.2075 (56d)	0.957
Zareei et al. [46]	RHA Micro silica	Cement	-0.0922	0.686
Anwar et al. [45]	Grinded RHA	Cement	0.1288	0.942
Bheel et al. [43]	RHA/WSA	Cement	0.0322	0.307
Babar et al. [42]	WSA	Cement	0.0846	0.485
Bheel et al. [44]	MHA	Cement	0.0364	0.711
	WSA		-0.0048	0.139

sustainable, as no CO_2 emission and energy consumptions for ash production (De Silva and Naveen [9]).

3.2.3 Flexural strength

The flexural strength reduced from 6.7 MPa to 4.0 MPa by 5% CR incorporation at 28 days (Figure 8), indicating a 40% strength reduction compared to the control blocks (0%CR0%RHA). The flexural strength of 5%CR0%RHA blocks was increased with increment of waste RHA. With the addition of RHA from 0% to 10% by weight into the CR incorporated blocks (i.e., 5%CR0%RHA and 5%CR10%RHA), the 28 day flexural strength was increased from 4.0 MPa to 5.1 MPa (Figure 8), indicating 28% flexural strength improvement compared to the 5%CR0%RHA paving block. This further confirms that the RHA has a potential to gain the reduced strength of the blocks caused by CR addition.

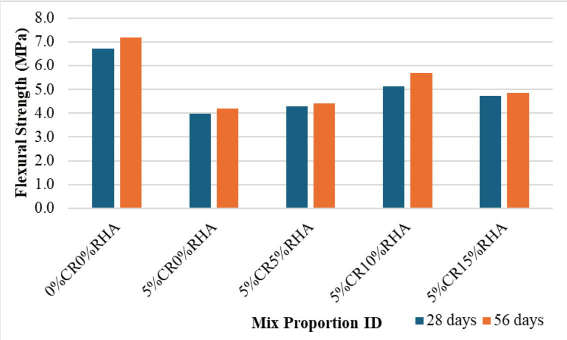

Figure 8 - Flexural strength of paving blocks

The reduction of flexural strength with incorporation of CR can be attributed to lower stiffness of rubber (Sofi et al. [38]) and weaker bond between rubber and cement paste (Lotfollahi et al. [39]), compared to the conventional blocks. Top of blocks is subjected to compression, which tends to fail due to lower stiffness of rubber than mineral aggregates, while bottom of blocks is subjected to tension, which fails due to weaker bond between CR and cement paste. However, formation of calcium silicate hydrate gel (CSH) may have resulted in flexural strength increment when waste RHA is added as observed in (De Silva and Priyamali [12]). When waste RHA is increased from 10% to 15%, the flexural strength of paving blocks has been reduced from 5.1MPa to 4.7MPa (Figure 8).

A ductile behaviour was observed during the flexural strength test of CR incorporated blocks which agrees with the observations of Strukar et al. [47]). Unlike control block (0%CR0%RHA), which failed in a brittle manner with sudden separation of specimen to two sections, CR incorporated blocks showed a ductile behaviour in which blocks failed but did not completely separated into two parts (Figure 9) showing a recovery by reducing deflection due to deformable and elastic nature of rubber (Zheng et al. [49]).

0%CR0%RHA 5%CR0%RHA

Figure 9 - Failure modes of flexural strength test

Figure 10 shows the variation of flexural strength with the density of blocks at 28 and 56 days. Flexural strength increased when the density of blocks increased, indicating a correlation. This linear variation can be expressed by $y = 0.019x - 34$ at 28 days age and $y = 0.063x - 128$ at 56 days age. The R^2 was observed as 1.00 and 0.86 at 28 and 56 days respectively, which is important for an accurate forecasting the density and flexural strength properties. With the age of the blocks, gradient increases from 0.019 to 0.06.

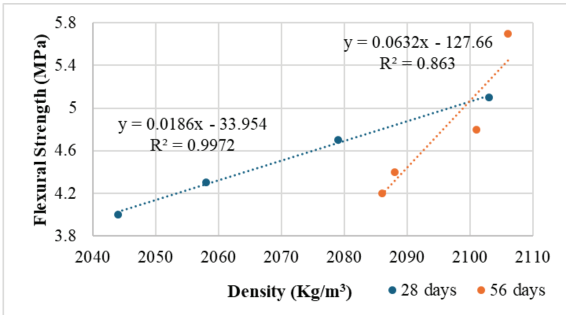

Figure 10 - Density vs flexural strength of paving blocks

Figure 11 compares the variation of flexural strength ratio with density ratio found in current study with previous studies (Bheel et al. [43,44]; Anwar et al. [45]). Some of the previous studies show that strength ratio increases with density ratio (Figure 11). However, compared to the current study, the rate of increase in the flexural strength is found to be less in (Bheel et al. [44]), in which WSA was used (Figure 11). Lesser SiO_2 content (i.e. 67%) in WSA (Bheel et al. [43]) than in RHA (i.e. 87% (Srikanth et al. [10])) may lead to reduced rates of strength increment. However, the formula, proposed in the current study, demonstrated highest gradient, reflecting a significant correlation between the density and flexural strength (Table 3).

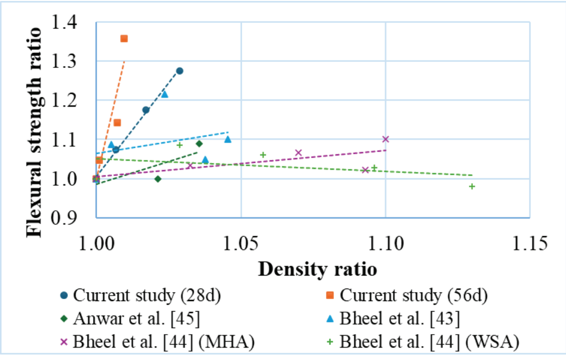

Figure 11 - Density ratio vs flexural strength ratio observed in current study & previous studies

3.2.4 Splitting tensile strength

Results of the splitting tensile strength test obtained for Grade 20 blocks at 28 and 56 days are shown in Figure 12. The 28 day splitting tensile strength decreased from 1.73MPa to 0.98MPa (43% strength reduction) in 5% CR incorporated blocks, compared to the control blocks. When the waste RHA is added as 5%, 10% and 15%, the 28 day splitting tensile strength of paving blocks varied as 1.26 MPa, 0.95 MPa and 1.21 MPa, respectively (Figure 12). The 5% RHA addition contributed to increasing the tensile strength than that for the 5%CR0%RHA paving blocks (Figure 12). However, the splitting tensile strength variation did not demonstrate a continuous increment or decrement as observed in compressive and flexural strength test results, demonstrating an increased strength variation up to 10% RHA added (5%CR10%RHA) blocks.

The reduction of splitting tensile strength, with incorporation of CR, can be attributed to weaker bonding between CR and cement paste (Lotfollahi et al. [39]) similar to the observations of Singaravel et al. [49]. Despite the cementitious properties of the added RHA, the blocks exhibited a lower splitting tensile strength, possibly due to inconsistent stress transfer of RHA particle (Amran et al. [37]).

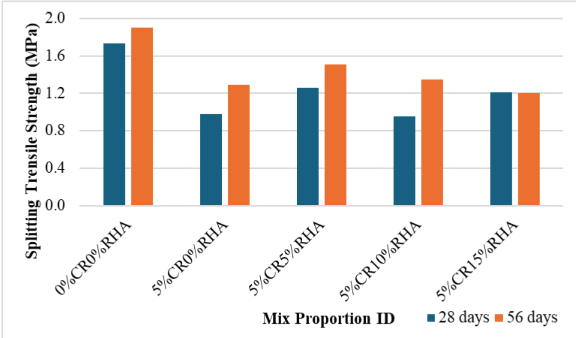

Figure 12 - Splitting tensile strength of paving blocks

Figure 13 shows the variation of splitting tensile strength of paving blocks at 28 and 56 days. Similar to the compressive strength and flexural strength trend, splitting tensile strength increases with increasing density. This linear variation can be expressed by $y = 0.0005x + 0.0038$ at 28 day age and $y = 0.0007x - 0.1952$ at 56 days of age as shown in Figure 13. However, weak correlations were observed for the fitting lines with R^2 values less than 0.3 at 28 and 56 days (Figure 13).

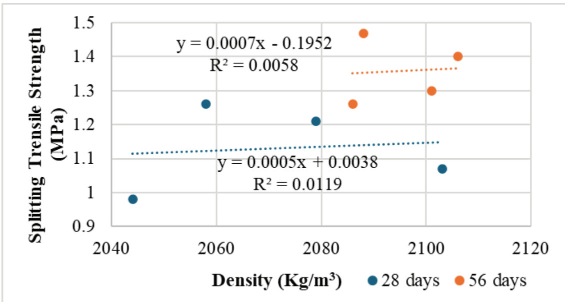

Figure 13 - Density vs splitting tensile strength of paving blocks

Table 3 - Coefficient of determination of density and flexural strength of concrete with different waste materials

Reference	Substituent	Replaced material	Gradient of line (m)	R^2
Current study	RHA	Cement	0.0186	0.997
			0.0632	0.863
Anwar et al. [45]	Grinded RHA	Cement	0.0045	0.645
Bheel et al. [43]	RHA/WSA	Cement	0.0021	0.085
Bheel et al. [44]	MHA	Cement	0.0014	0.497
	WSA		-0.0007	0.159

Figure 14 compares the variation of the splitting tensile strength ratio with the density ratio observed in the current study and previous studies (Bheel et al. [43,44]; Anwar et al. [45]; Zareei et al. [46]). The current study shows a slightly positive gradient of strength than other studies (Table 4).

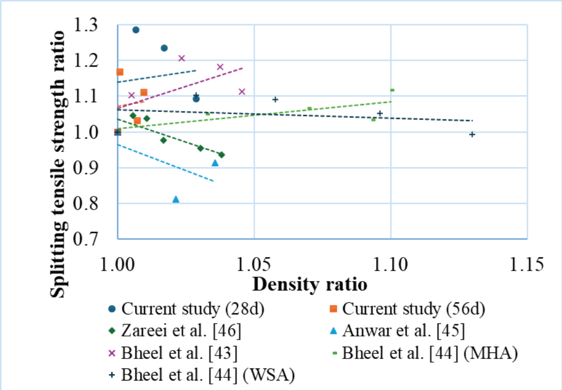

Figure 14 - Density ratio vs splitting tensile strength ratio observed in current study & previous studies

4. Conclusion

Structural properties of waste rice husk ash (RHA) and waste Crumbed Rubber (CR) added paving blocks were experimentally investigated and numerically forecasted in this study. Compared to the conventional paving blocks, with the incorporation of crumbed rubber, the density of paving blocks significantly decreased, providing an advantage in easy handling, low self-weight on subgrade of roads and low cost of production. At 5% waste rubber level, Grade 20 paving blocks showed a 12% density reduction compared to the conventional block.

Optimum mechanical properties were found with 5%CR10%RHA, satisfying the minimum compressive strength requirement of Grade20 paving blocks strength class 4. Although compressive strength and flexural strength of blocks are reduced with the addition of rubber, 10% waste RHA has the potential to gain reduced strength.

Compressive strength and flexural strength of the paving blocks are improved by 44% and 28% with 10% waste RHA at 28 days compared to 5%CR incorporated blocks (i.e., 5%CR0%RHA blocks).

Formulas were derived for predicting 28 day compressive, flexural and splitting tensile strengths with density. The formulas may help material scientists and designers to select the best density and strength parameters to utilize in manufacturing paving blocks with the desired properties, while utilizing waste RHA and crumped rubber as a solution for resource scarcity, environmental pollution, heavy construction materials and high cost of production.

References

1. Sousa, V., Bogas, J.A., Real, S., Meireles, I., 2023. Industrial Production of Recycled Cement: Energy Consumption and Carbon Dioxide Emission Estimation. *Environ. Sci. Pollut. Res.* 30, 8778–8789. https://doi.org/10.1007/s11356-022-20887-7

2. Kajaste, R., Hurme, M., 2016. Cement Industry Greenhouse Gas Emissions - Management Options and Abatement Cost. *J. Clean. Prod.* 112, 4041–4052.

3. Habert, G., 2013. Assessing the Environmental Impact of Conventional and "Green" Cement Production, *Eco-Efficient Construction and Building Materials*. https://doi.org/10.1533/9780857097729.2.199

4. Manning, D.A.C., Tangtinthai, N., Heidrich, O.,

Table 4 - Coefficient of determination of density and splitting tensile strength of concrete with different waste materials

Reference	Substituent	Replaced material	Gradient of line (m)	R^2
Current study	RHA	Cement	0.0005	-
			0.0007	-
Zareei et al. [46]	RHA Micro silica	Cement	-0.0064	0.687
Anwar et al. [45]	Grinded RHA	Cement	-0.0045	0.306
Bheel et al. [43]	RHA/WSA	Cement	0.0032	0.37
Bheel et al. [44]	MHA	Cement	0.001	0.528
	WSA		-0.0004	0.063

2019. Evaluation of Raw Material Extraction, Processing, Construction and Disposal of Cement and Concrete Products: Datasets and Calculations. *Data Br. 24*, 103929. https://doi.org/10.1016/j.dib.2019.103929

5. Koehnken, L., Rintoul, M.S., Goichot, M., Tickner, D., Loftus, A.C., Acreman, M.C., 2020. Impacts of Riverine Sand Mining on Freshwater Ecosystems: A Review of the Scientific Evidence and Guidance for Future Research. *River Res. Appl.* 36, 362–370. https://doi.org/10.1002/rra.3586

6. Prasara-A, J. and Gheewala, S.H., 2017. Sustainable Utilization of Rice Husk Ash from Power Plants: A Review. *Journal of cleaner production*, *167*, pp.1020-1028.

7. Kazmi, S.M.S., Abbas, S., Munir, M.J. and Khitab, A., 2016. Exploratory Study on the Effect of Waste Rice Husk and Sugarcane Bagasse Ashes in Burnt Clay Bricks. *Journal of Building Engineering*, *7*, pp.372-378.

8. Jaya, R.P., Muhamad Nor, M.A.A., Ahmad, Z.A., Mohd Amin, Z., 2013. Properties of Mortar Containing Rice Husk Ash at Different Temperature and Exposed to Aggressive Environment. *Adv. Mater. Res.* 620, 87–93. https://doi.org/10.4028/www.scientific.net/AMR.620.87

9. De Silva, G.S. and Naveen, P., 2024. Effect of Rice Husk Ash and Coconut Coir Fiber on Cement Mortar: Enhancing Sustainability and Efficiency in Buildings. *Construction and Building Materials*, *440*, p.137326.

10. Srikanth, G., Fernando, A., Selvaranjan, K., Gamage, J.C.P.H., Ekanayake, L., 2022. Development of a Plastering Mortar Using Waste Bagasse and Rice Husk Ashes with Sound Mechanical and Thermal Properties. *Case Stud. Constr. Mater. 16*, e00956. https://doi.org/10.1016/j.cscm.2022.e00956

11. Pushpakumara, B.H.J., De Silva, G.H.M.J.S., 2012. Characteristics of Masonry Blocks Manufactured with Rice Husk Ash (RHA) and Lime. *Eng. J. Inst. Eng. Sri Lanka* 45, 1. https://doi.org/10.4038/engineer.v45i3.6928

12. De Silva, G.H.M.J.S., Priyamali, M.W.S., 2020. Potential use of Waste Rice Husk Ash for Concrete Paving Blocks: Strength, Durability, and Run-Off Properties. *Int. J. Pavement Eng.* https://doi.org/10.1080/10298436.2020.1851029

13. Ranasinghe, Y.K.K.N., De Silva, G.H.M.J.S., 2021. Mechanical Properties and Failure Modes of Paving Blocks Made by Adding Waste Rubber and Waste Rice Husk Ash. *Proceedings of the 8th Int. Symp. on Advances in Civil and Env. Eng. Practices for Sustainable Dev*. 211-219.

14. Hakeem, I.Y., Agwa, I.S., Tayeh, B.A., Abd-Elrahman, M.H., 2022. Effect of using a Combination of Rice Husk and Olive Waste Ashes on High-Strength Concrete Properties. Case Stud. *Constr. Mater. 17*, e01486. https://doi.org/10.1016/j.cscm.2022.e01486

15. Le, H.T., Ludwig, H.M., 2016. Effect of Rice Husk Ash and Other Mineral Admixtures on Properties of Self-Compacting High Performance Concrete. *Mater. Des. 89,* 156–166. https://doi.org/10.1016/j.matdes.2015.09.120

16. Safiuddin, M., West, J.S., Soudki, K.A., 2010. Hardened Properties of Self-Consolidating High Performance Concrete Including Rice Husk Ash. *Cem. Concr. Compos*. 32, 708–717. https://doi.org/10.1016/j.cemconcomp.2010.07.006

17. Gerges, N.N., Issa, C.A., Fawaz, S.A., 2018. Rubber Concrete: Mechanical and Dynamical Properties. Case Stud. *Constr. Mater. 9*, e00184.

18. Chen, H., Li, D., Ma, X., Zhong, Z., Abd-Elaal, E.-S., 2023. Compressive Strength Prediction of Crumb Rubber Mortar Based on Mesoscale Model. *Eng. Fail. Anal.* 45, 104–108. https://doi.org/10.1016/j.prostr.2023.05.020

19. Lijuan Li, Fang Xing, Zhijun Xu, Wang Chen, Wuxin Chen, Y.L., 2023. Numerical Analysis of Modified PVA Fiber Rubber Concrete in Frame Beams. *Buildings*. https://doi.org/https://doi.org/10.3390/buildings13030791

20. Wang, H., Pang, J., 2023. Mechanical Properties and Microstructure of Rubber Concrete under Coupling Action of Sulfate Attack and Dry – Wet Cycle. *Sustainability*.

21. Thilakarathna, P.S.M., Seo, S., Baduge, K.K., Lee, H., Mendis, P. and Foliente, G., 2020. Embodied Carbon Analysis and Benchmarking Emissions of High and Ultra-High Strength Concrete Using Machine Learning Algorithms. *Journal of Cleaner Production*, *262*, p.121281.

22. Alyami, M., Khan, M., Hammad, A.W., Alabduljabbar, H., Nawaz, R., Fawad, M. and Gamil, Y., 2024. Estimating Compressive Strength of Concrete Containing Rice Husk Ash Using Interpretable Machine Learning-Based Models. *Case Studies in Construction Materials*, *20*, p.e02901.

23. SLS 1425 Specifications for concrete paving blocks – Part 1: Requirements. Colombo, Sri Lanka: Sri Lankan Standards., 2011.

24. ASTM, 2006. ASTM C 136-06: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates 1–5. https://doi.org/10.1520/C0136

25. ASTM, 2000. D854 - Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. *Astm D854* 2458000, 1–7. https://doi.org/10.1520/D0854-14.

26. ASTM, 2011. ASTM C29: Standard Test Method for Bulk Density ("unit weight") and Voids in Aggregate. *Historia Santiago*. 97.

27. ASTM 2003.67-03, 2003. ASTM C 67: Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile. *American Society for Testing and Materials,* Philadelphia, PA. i, 67–03.

28. American Society for Testing & Mater, 2008. ASTM C140: Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units 1–18.

29. IS:15658-2006, 2006. IS15658: Indian Standard Precast Concrete Block for Paving-Specification. Bur. *Indian Stand*. 1–27.

30. De Silva, G.H.M.J.S., Vishvalingam, S., Etampawala, T., 2021. Effect of Waste Rice Husk Ash from Rice Husk Fuelled Brick Kilns on Strength, Durability and Thermal Performances of Mortar. *Constr. Build. Mater*. 268, 121794. https://doi.org/10.1016/j.conbuildmat.2020.121794

31. Mendis, A.S.M., Al-Deen, S., Ashraf, M., 2017. Behaviour of Similar Strength Crumbed Rubber Concrete (CRC) Mixes with Different Mix Proportions. *Constr. Build. Mater*. 137, 354–366.

32. Sukontasukkul, P., Chaikaew, C., 2006. Properties of Concrete Pedestrian Block Mixed with Crumb Rubber. *Constr. Build. Mater*. 20, 450–457.

33. Ling, T.C., Nor, H.M., Lim, S.K., 2010. Using Recycled Waste Tyre in Concrete Paving Blocks. *Proc. Inst. Civ. Eng. Waste Resour. Manag*. 163, 37–45. https://doi.org/10.1680/warm.2010.163.1.37

34. Murugan, R.B., Natarajan, C., 2017. Investigation on the Use of Waste Tyre Crumb Rubber in Concrete Paving Blocks. *Comput. Concr*. 20, 311–318. https://doi.org/10.12989/cac.2017.20.3.311

35. Fadiel, A.A., Mohammed, N.S., Abu-Lebdeh, T., Munteanu, I.S., Niculae, E. and Petrescu, F.I.T., 2023. A Comprehensive Evaluation of the Mechanical Properties of Rubberized Concrete. *Journal of Composites Science*, *7*(3), p.129.

36. Sheraz, M., Yuan, Q., Alam, M., Javed, M.F., Rehman, M.F. and Mohamed, A., 2023. Fresh and Hardened Properties of Waste Rubber Tires Based Concrete: A State Art of Review. *SN Applied Sciences*, *5*(4), p.119.

37. Amran, M., Fediuk, R., Murali, G., Vatin, N., Karelina, M., Ozbakkaloglu, T., Krishna, R.S., Sahoo, A.K., Das, S.K. and Mishra, J., 2021. Rice Husk Ash-Based Concrete Composites: A Critical Review of Their Properties and Applications. *Crystals*, *11*(2), p.168.

38. Sofi, A., 2018. Effect of Waste Tyre Rubber on Mechanical and Durability Properties of Concrete–A Review. *Ain Shams Engineering Journal*, *9*(4), pp.2691-2700.

39. Lotfollahi, S., Jaidari, A., Bakhtiari, P., Hosseini, M. and Ghorbani, M., 2023. Effect of Wollastonite Microfibers and Waste Tire Rubber on Mechanical Properties of Concrete. *International Journal of Concrete Structures and Materials*, *17*(1), p.33.

40. He, S., Jiang, Z., Chen, H., Chen, Z., Ding, J., Deng, H. and Mosallam, A.S., 2023. Mechanical Properties, Durability, and Structural Applications of Rubber Concrete: A State-of-the-Art-Review. *Sustainability*, *15*(11), p.8541.

41. Du, T., Yang, Y., Cao, H., Si, N., Kordestani, H., Sktani, Z.D.I., Arab, A. and Zhang, C., 2024. Rubberized Concrete: Effect of the Rubber Size and Content on Static and Dynamic Behavior. *Buildings*, *14*(6), p.1541.

42. Babar, A.A., Memon, H.L.M.A., Hasnain Gul, F.A. and Memon, F.H.S., 2022. The Impact of Wheat Straw Ash as a Partial Cement Replacement Material on Concrete Properties. *Resour. Conserv. Recycl*. 3, 2616–4396.

43. Bheel, N., Awoyera, P., Shar, I.A., Sohu, S., Abbasi, S.A., Krishna Prakash, A., 2021b. Mechanical Properties of Concrete Incorporating Rice Husk Ash and Wheat Straw Ash as Ternary Cementitious Material. *Adv. Civ. Eng*. 2021. https://doi.org/10.1155/2021/2977428

44. Bheel, N., Ali, M.O.A., Kirgiz, M.S., de Sousa Galdino, A.G., Kumar, A., 2021a. Fresh and Mechanical Properties of Concrete Made of Binary Substitution of Millet Husk Ash and Wheat Straw Ash for Cement and Fine Aggregate. *J. Mater. Res. Technol*. 13, 872–893. https://doi.org/10.1016/j.jmrt.2021.04.095

45. Anwar, M., Miyagawa, T. and Gaweesh, M., 2000. Using Rice Husk Ash as a Cement Replacement Material in Concrete. *Waste Materials Constr*. 1–23.

46. Zareei, S.A., Ameri, F., Dorostkar, F., Ahmadi, M., 2017. Rice Husk Ash as a Partial Replacement of Cement in High Strength

Concrete Containing Micro Silica: Evaluating Durability and Mechanical Properties. Case Stud. *Constr. Mater. 7,* 73–81. https://doi.org/10.1016/j.cscm.2017.05.001

47. Strukar, K., Kalman Šipoš, T., Dokšanović, T. and Rodrigues, H., 2018. Experimental Study of Rubberized Concrete Stress-Strain Behavior for Improving Constitutive Models. *Materials,* 11(11), p.2245.

48. Zheng, L., Huo, X.S. and Yuan, Y., 2008. Strength, Modulus of Elasticity, and Brittleness Index of Rubberized Concrete. *Journal of Materials in Civil Engineering*, 20(11), pp.692-699.

49. Singaravel, D.A., Veerapandian, P., Rajendran, S. and Dhairiyasamy, R., 2024. Enhancing High-Performance Concrete Sustainability: Integration of Waste Tire Rubber for Innovation. *Scientific Reports*, *14*(1), p.4635.