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Research Paper

Sustainable Concrete Innovation: Crumb Rubber as a Partial Fine Aggregate Replacement

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ABSTRACT

The exponential growth of the automobile industry contributes a significant accumulation of waste tires, presenting a substantial environmental challenge due to their non-biodegradable nature. This study investigates the potential of using crumb rubber produced from waste tires as a partial replacement for natural fine aggregates of concrete, aiming to enhance the material's properties while mitigating environmental impact. The mechanical and durability characteristics of concrete introducing 5%, 10%, and 15% crumb rubber were determined through various tests, including compressive strength, stress-strain behavior, and impact resistance. Results indicate that while there is a slight decrease in compressive strength with increased rubber content, the post-cracking behavior and impact resistance improve significantly, with energy absorption capacities increasing by 75%, 125%, and 158.4% for 5%, 10%, and 15% replacements, respectively. Additionally, durability tests reveal that rubberized concrete shows reduced chloride ion penetration and improved resistance to acid attack, with 30% reduction in chloride penetration at 15% rubber content. The findings suggest that incorporating crumb rubber can enhance the ductility and durability of concrete, making it a viable and sustainable alternative in construction, particularly in applications such as road pavements where impact resistance is crucial. This study contributes to the ongoing research on sustainable construction materials and emphasizes the importance of recycling waste materials to reduce environmental impact.

1 Introduction

Concrete is the most extensively used construction material globally, primarily because of its structural strength and durability [1]. Nevertheless, it has several limitations, including brittleness, low tensile strength, and poor impact resistance.

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Furthermore, the extensive use of conventional concrete in the construction sector contributes to a significant carbon footprint, driven by the over-exploitation of natural resources such as aggregates [2]. For the last few decades, the researchers have sought various alternatives to overcome the shortcomings of traditional concrete and promote sustainability within the construction industry. Among these alternatives, rubberized concrete has emerged as an innovative material that incorporates recycled rubber as a partial substitute for conventional aggregates, demonstrating promising enhancements in mechanical properties and environmental benefits [3].

It is assessed that around 1 billion rubber tires are discarded every year [4]. The discarding of rubber tires causes a pressing environmental issue due to their non-biodegradable nature, which poses detrimental effects on human health, the environment, and aesthetics. In this context, rubberized concrete represents a sustainable solution that can mitigate landfill waste, conserve natural resources, and improve the performance of concrete structures [5].

Previous study has focused on the effects of introducing waste rubber tires into concrete. Studies have shown that growing the percentage of crumb rubber results to a decline in workability [6-8]. However, this issue can be addressed by using superplasticizers [9]. Additionally, the density of rubberized concrete tends to decrease with higher rubber content [10, 11]. Moreover, research indicates that compressive strength decreases as the rubber content increases [12-15]. Yasser et al. [15] suggested that this reduction may be attributed to inadequate bonding with the smooth surface of rubber aggregates and cement paste. Enhancing the adhesion of rubber aggregates through pretreatment methods has shown promise in mitigating this issue [16]. Additionally, incorporating pozzolanic materials such as silica fume and metakaolin into rubberized concrete may improve compressive strength [17-19]. The splitting tensile strength of rubberized concrete is also affected by the incorporation of rubber aggregates. Previous studies have revealed that as the amount of crumb rubber increases, the splitting tensile strength tends to decline [13, 19]. Ahmad et al. [20] found that the incorporation of glass powder to rubberized concrete resulted in a 30% increase in tensile strength, while incorporating steel fibers led to a slight improvement in tensile strength [6, 13, 18, 21].

Numerous experimental investigations have been conducted to assess the durability properties of rubberized concrete [6, 12, 22-32]. The size of the rubber aggregate can significantly affect water absorption. Rubberized concrete containing coarser crumb rubber generally exhibits higher absorption compared to those with finer rubber [33]. Conversely, Yasser et al. [15] found no significant impact of rubber aggregate inclusion on water absorption. In their study, Li et al. [30] concluded that when the quantity of rubber is below 10%, the rise of water absorption is minimal or may even decrease. Furthermore, higher permeability was noted when coarse aggregates were substituted with rubber aggregates [25]. However, enhanced compaction levels can lead to better performance compared to the control sample.

Despite the existing body of literature, several gaps remain regarding the comprehensive understanding of the durability properties of the rubberized concrete, especially concerning absorption of water and resistance to penetration of chloride ion and acid attacks. Additionally, the impact of varying rubber aggregate sizes on concrete performance has not been sufficiently explored.

Present study aims to fill these research gaps by investigating the mechanical strength and durability properties of concrete with varying percentages (5%, 10%, and 15%) of crumb rubber chips derived from waste tires. The novelty of the present work focuses on the interaction between rubber content and the physical properties of concrete, particularly under various environmental stresses. Through a series of experimental tests, this research seeks to provide insights into how rubberized concrete can serve as a sustainable construction material while enhancing concrete's performance. The findings will contribute to the ongoing efforts in the construction industry to adopt environmentally friendly practices and materials, ultimately reducing the ecological impact of concrete production and use.

2 Materials Used for Experimental study

Materials used for the experimental study are collected and the mix proportion of the concrete sample has been made as per relevant IS code. The details of the different material used for the experiment are given below.

Cement: Fly Ash based Portland Pozzolana Cement affirming IS:1489-2015 (Part 1) is used for the present study.

Fine Aggregate (FA): Locally available river sand is utilized having fineness modulus of 2.32 and belongs to zone III sand as per IS 383: 2016. Particle size distribution curve for Fine aggregate is given in Fig. 1.

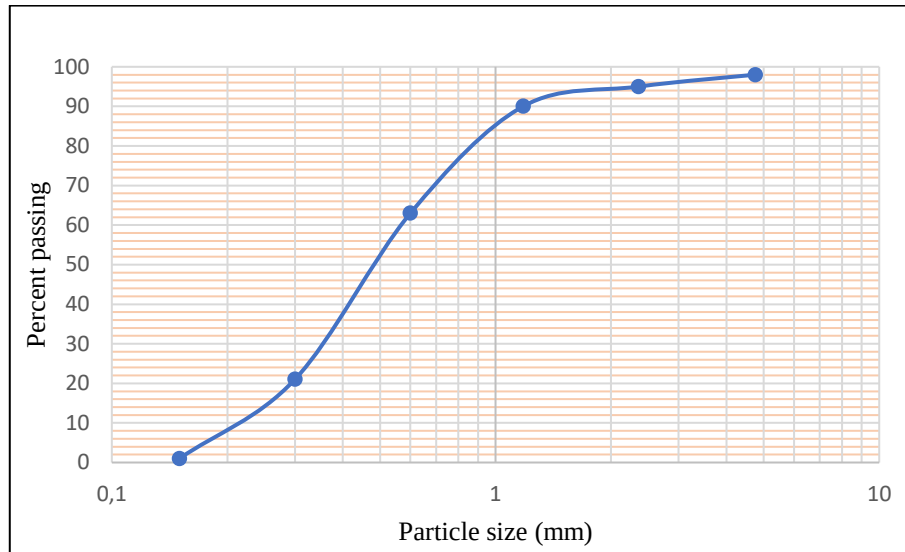


Fig. 1 – Distribution of particle size curve of used fine aggregate (FA)

Coarse Aggregate (CA): Coarse aggregates of maximum nominal size 20 mm as per IS 383:2016 and specific gravity of 2.87 has been used. Particle size distribution of coarse aggregate is shown in Table 1.

Table 1 – Particle size distribution of coarse aggregate

Sieve (mm)	Weight retained (gm)	Cumulative weight retained (gm)	Cumulative percentage weight retained	Percentage weight passing
40	0	0	0	100
20	185	185	9.25	90.75
10	1120	1305	65.25	34.75
4.75	580	1885	94.25	5.75
2.36	100	1985	99.25	0.75
1.18	10	1995	99.75	0.25
Pan	5	2000	100	0

Crumbed Rubber chips: Crumbed particles are collected by threading of waste rubber tyres. Waste crumbed rubber particles (Fig. 2) of average particle size below 4.75 mm having specific gravity of 1.25 have been used. Fig. 3 shows the particle size distribution curve of crumb rubber aggregate.



Fig. 2 – Waste crumb rubber particles

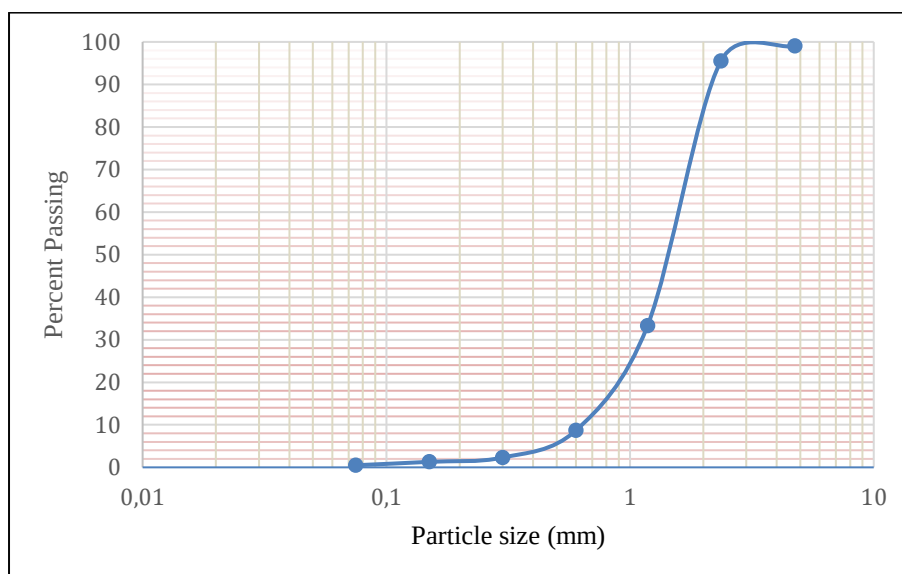


Fig. 3 – Distribution of particle size curve of used crumb rubber aggregate

Chemical admixture: Superplasticizer complying with IS 9103 - 1999 have been used. Appearance of the chemical is Light yellow coloured liquid and having pH: 6.0 to 6.5. Dosage of the chemical is 0.8% by weight of cement. Dosage has been adjusted by trial and error to maintain the slump value as 75 mm.

3 Mix proportion

Mix proportion for the concrete samples have been finalized based on several trials as per IS 10262:2019. One control mix (M1) for M25 grade of concrete have been used. The other mixes are made by partial replacement of fine aggregate having crumbed rubber by 5%, 10% and 15% respectively and named as mix M2, M3 and M4. The details of all mixes for one cubic meter of concrete are given in Table 2.

Table 2 - Concrete mix proportions

Mixture name	Cement (kg)	Water (kg)	FA (kg)	CA (kg)	Rubber Chip (kg)
M1 (Control Mix)	368	173	681.48	1184	0
M2 (5% RUBBER)	368	173	647.41	1184	34.074
M3 (10% RUBBER)	368	173	613.33	1184	68.148
M4 (15% RUBBER)	368	173	579.26	1184	102.22

4 Mix proportion Experimental program

In the present study, four different concrete mixes (M1, M2, M3 and M3) are prepared following the IS 10262:2019, where conventional fine aggregates were partially substituted by waste tire rubber aggregates as 0%, 5%, 10%, and 15% respectively. Tests for harden strength and durability has been conducted for every mix proportion after 30 days and 90 days to check the performance of the material. The details of the tests have been given below.

4.1 Compressive strength test

As per IS 516-1959, compressive strength test has been performed. The size of the sample is taken as 100 mm × 100 mm × 100 mm cube. Three no. of samples for each mix proportions have been tested after 28 days and 90 days. Fig. 4 shows the test setup for compressive strength test.



Fig. 4 – Compressive strength test

4.2 Impact test

Impact test has been performed as per the reference of ACI Committee 544. Test setup is shown in fig. 5. The drop-weight test has been conducted to determine the potential energy absorption for the concrete cylindrical samples. The sample size is 152 mm diameter with 65 mm depth. Three no. of samples are test for each mix proportions and the average value is taken for initial crack and final failure of the sample.



Fig. 5 – Impact test by drop hammer

4.3 Determination of Stress strain behaviour

Stress strain behaviour study has been done as per ASTM C469. The samples are tested in the standard compression testing machine and the size of sample is taken as 200 mm length and 100 mm diameter.

4.4 Sulphate attack test

Sulphate attack test has been performed as per ASTM C1898. This test has been performed with specimen size of 100 mm × 100 mm × 100 mm cube to evaluate the chemical resistance of the concrete samples. Fig. 6 shows that the test

specimens immersed in sulphuric acid. Three no. of samples of each proportion have been immersed into a solution of a sulfuric acid concentration resulting in a pH of 0.50 pH of the test Media prepared to 0.03(N). The compressive strength of the above-mentioned specimens tested after 28 days and 90 days of immersion to determine the residual strength of the concrete sample effected by the sulphate ion.



Fig. 6 – Sulphate resistance test

4.5 Rapid chloride penetration test

Following the guidelines set by ASTM C1202, the rapid chloride penetration test was performed. This test evaluates the electrical conductance of the concrete specimens, offering a quick assessment of their resistance to penetration of chloride ion. For the test, cylindrical samples measuring thickness of 50 mm and diameter of 100 mm were monitored over a 6-hour duration to measure the amount of electrical current passing through. A steady voltage of 60 V DC was applied across the ends of the specimen. One end of the specimen was submerged in a sodium chloride solution, while the opposite end was placed in a sodium hydroxide solution. The total electric charge, measured in coulombs, that passed through the specimen was recorded. This charge provides an indication of the material's resistance to the penetration of chloride ions (Fig.7).



Fig. 7 – Rapid chloride penetration sulphate resistance test

4.6 Sorptivity test

The sorptivity test was performed by following ASTM C1585:200. This procedure evaluates the rate at which water is absorbed by cement concrete by evaluating the increase in mass of a sample due to water absorption over time. In this experiment, only one surface of the specimen is open to water, whether the other surfaces are closed with a coating to prevent water penetration. The standard test samples are disc having a diameter of 100 mm with length 50 mm. Testing was performed on specimens aged 28 days and 90 days shown in fig. 8. The absorption, denoted as III, is calculated by dividing the mass change by the product of the test cross sectional area of specimen and the density of water. For this test, the variation in water

density with temperature is not considered, and a constant value having 0.001 g/mm^3 is used. The formula for absorption is expressed as:

$$I = m_t / (a * d) \quad (1)$$

where:

I = the absorption,

m_t = the change in specimen mass (gm), at the time t ,

a = specimen exposed area to water (mm^2), and

d = water density (g/mm^3)

Additionally, the initial water absorption rate ($\text{mm/s}^{1/2}$) is defined as the slope of the best-fit line for the plot of I alongside the square root of time ($\text{s}^{1/2}$).



Fig. 8 –Sorptivity test

5 Results and discussion

First of all, a control mix (M1) has been prepared with desired workability (75 mm slump). Then the other three mixes (M2, M3 and M4) are made by replacing the natural aggregate with crumbed rubber aggregate by 5%, 10% and 15% respectively. All the samples are kept in water for 28 days for curing purpose. After 28 days the samples are taken out of the water and the tests are performed accordingly. Available density of the concrete sample of all mixes is shown in fig. 9. Increasing the rubber content into the mix resulted reduction in density of concrete mix. Results are consistent with previous studies [3, 7, 10, 15].

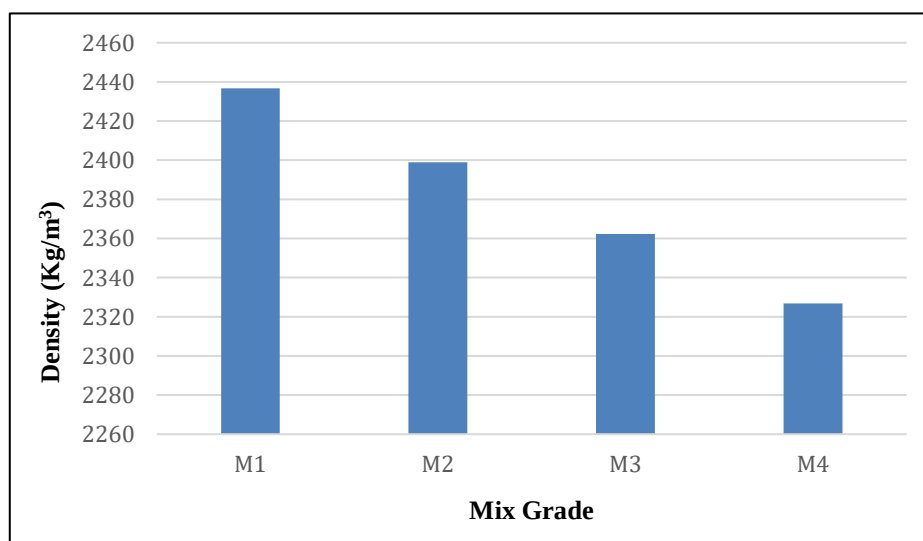


Fig. 9 –Density of different concrete mixes

5.1 Compressive strength test

The results of compressive strength of the concrete samples at 28 days and 90 days post-casting for various mix designs are presented in Fig. 10 and Fig 11 shows the microscopic view of rubberized concrete. The rubberized concrete specimens exhibit a gradual decline in compressive strength as the quantity of rubber increases. For the control mix (M1), the compressive strength at 28 days is measured at 31.1 MPa. The introduction of rubber at 5%, 10%, and 15% leads to reductions in compressive strength of 0.32%, 26%, and 37.62%, respectively. At 90 days, the control mix achieves a compressive strength of 35.4 MPa, with corresponding reductions of 0.57%, 12.43%, and 32.97% for rubber replacement ratios of 5%, 10%, and 15%. Notably, the 5% rubber replacement shows almost negligible loss in compressive strength. Findings of most of the previous studies are in accordance with the result obtained in this study [3, 5, 9, 11, 12]. However, the more significant reductions observed in higher proportions may be attributed to several factors. Initial cracking may occur around the rubber particles when subjected to load, likely due to the elastically deformable characteristics of the rubber. Since the crumbed rubber particles are smoother, softer, and more elastic compared to the hydrated cement paste, there may be a weak bond between the paste and the particles of rubber, resulting in decreased strength when rubber content exceeds 5%.

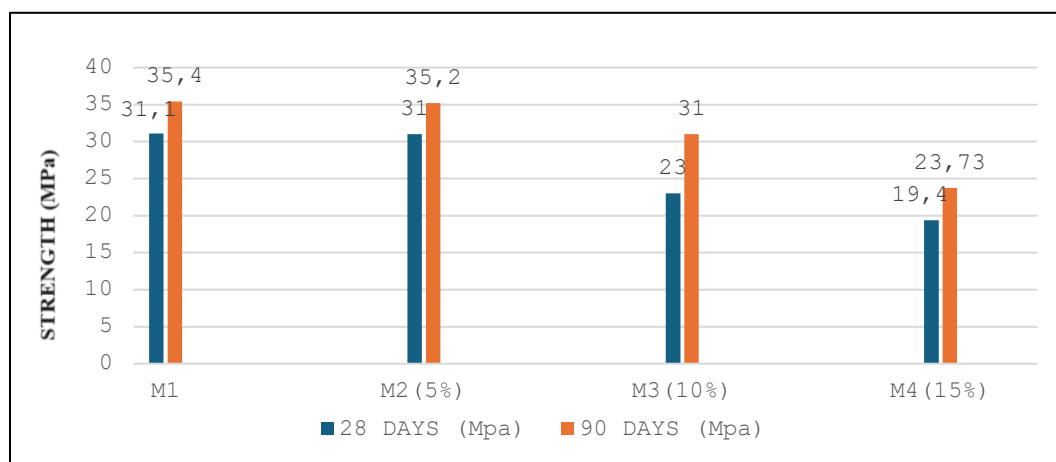


Fig. 10 –compressive strength of different concrete mixes

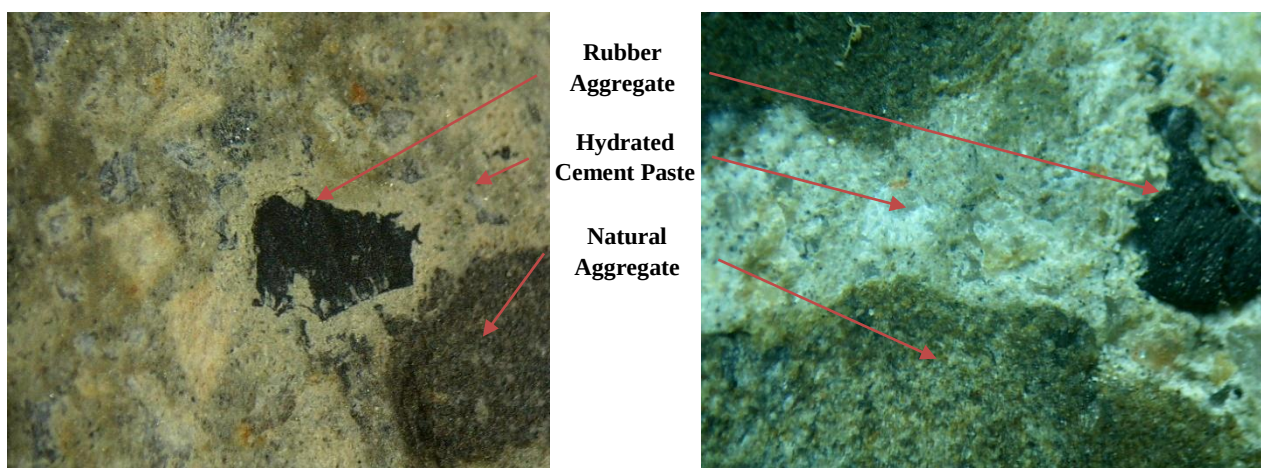


Fig. 11 – Microscopic view of rubberized concrete

5.2 Impact Resistance

The impact resistance of concrete specimen shows the absorption of energy due to the sudden applied load by drop hammer test. It has been observed that increasing the crumb rubber content the concrete impact resistance increases as compare to normal concrete. Fig. 12 shows the energy absorption values in terms of initial and final crack. For normal concrete the initial absorption of energy is 125.33 N-m, this value increased by 20%, 40% and 120% with increase in rubber

content of 5%, 10% and 15% respectively. Similarly, up to final failure the energy absorption of normal specimen is 300.77 N-m, which is increased by 75%, 125% and 158.4% with increase in rubber content of 5%, 10%, and 15% respectively. Reda et al. [34] also observed similar results in their study. This upsurge in energy absorption is due to the softer behaviour of rubber particles than surrounding hydrated cement paste. First loading cracks are originated around the particles of rubber. The rubber particles act as crack arrester which delaying the propagation of cracks and thus preventing the damages of concrete.

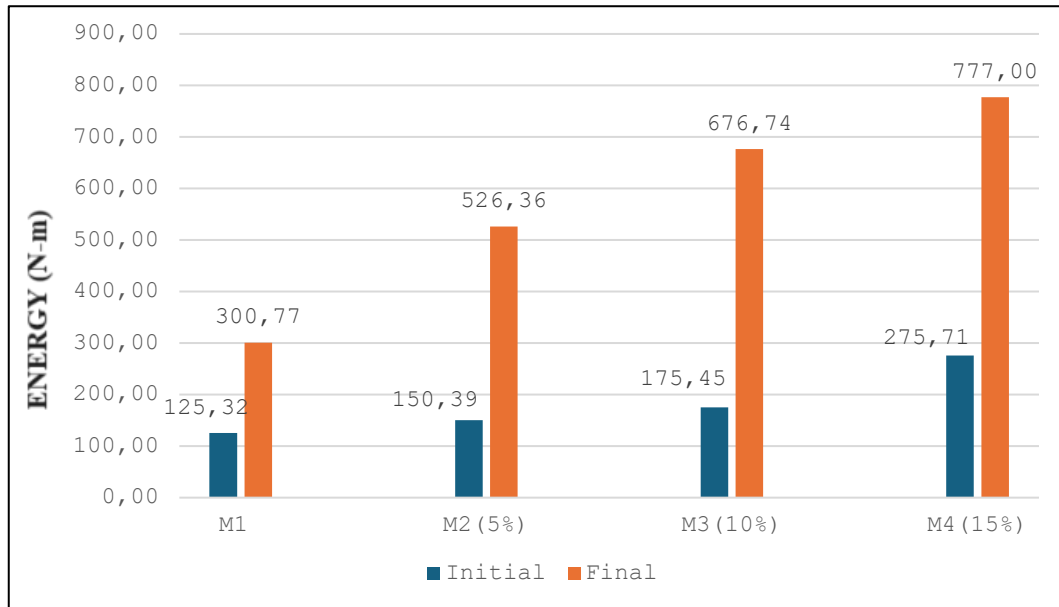


Fig. 12 –Impact strength values of different concrete mixes

5.3 Determination of Stress-Strain Behaviour

The stress-strain behaviour has been studied to measure the toughness of the material. Toughness indicates energy absorption capacity of the material before failure. Lateral elongation of concrete cylinder is measured along with the uniaxial compressive stress to calculate the stress-strain behaviour of the sample. Fig. 13 shows the stress-strain curve of the normal and rubberized concrete.

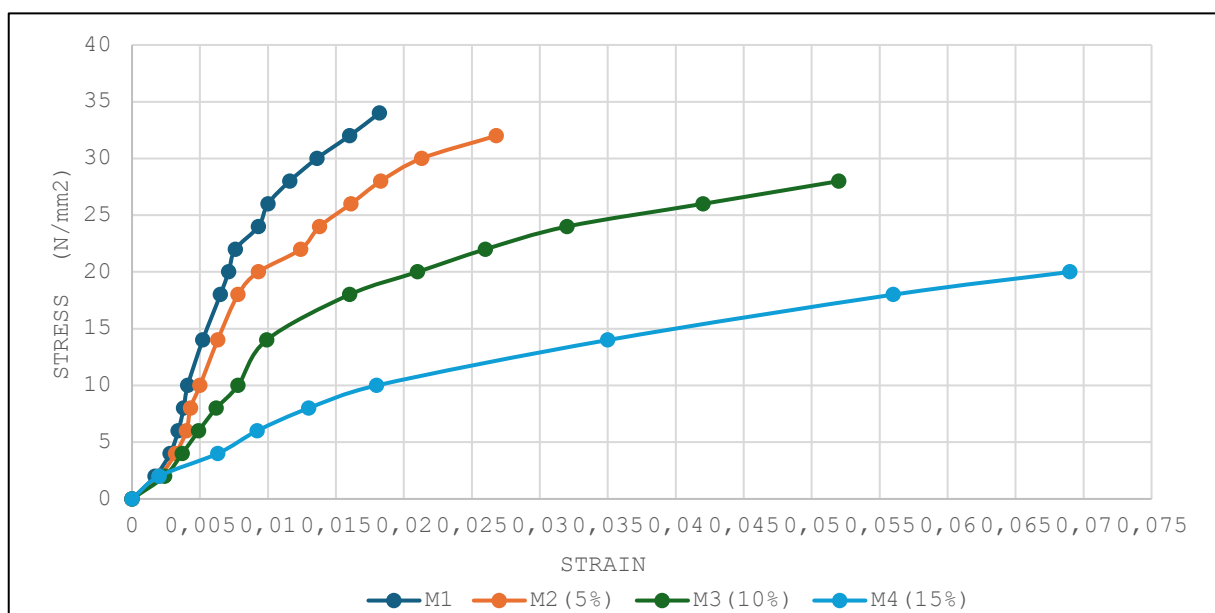


Fig. 13 –Stress vs strain curve of different concrete mixes

It has been noticed that increasing the rubber content results a rise in the strain capacity of the concrete. Furthermore, a higher rubber content enhances the toughness of the material prior to failure, indicating an improved capacity for shock absorption. Consequently, rubberized concrete with elevated rubber percentages can withstand greater levels of strain before failing, resulting in increased ductility of the material and this finding is strongly supported by the study done by Guo et al. [9], and Ataria and Wang [12] on rubberized concrete.

5.4 Sulphate attack test

The compressive strength of specimens exposed to sulfuric acid decreases as the rubber content increases, as presented in Fig. 14. For the control samples, the compressive strength after 28 days drops from 19.70 MPa to 19.50 MPa, 15.4 MPa, and 13.26 MPa with 5%, 10%, and 15% rubber replacement, respectively.

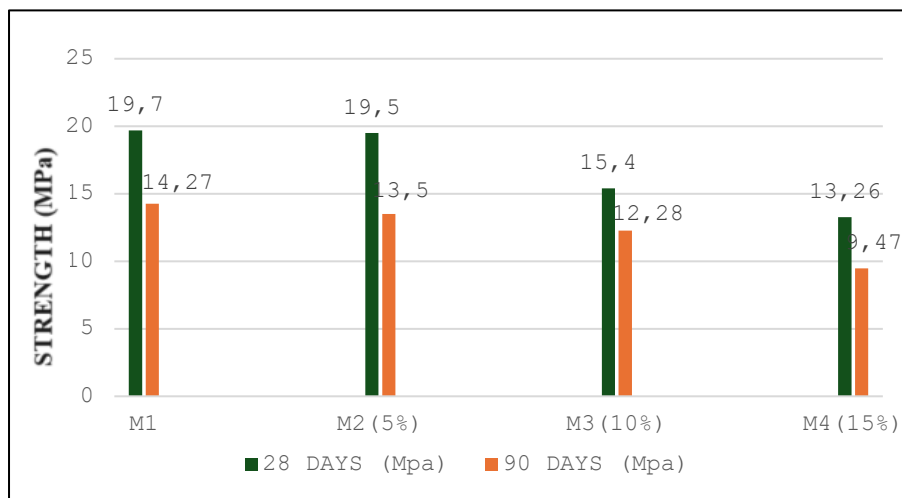


Fig. 14 – Compressive strength after acid exposure of different concrete mixes

Fig. 15 shows the tested samples immersed in sulphuric acid for 28 days after compressive strength test. Similarly, for the 90-day specimens, the strength decreases from 14.27 MPa to 13.5 MPa, 12.28 MPa, and 9.47 MPa at the same rubber replacement levels. However, an increase in rubber aggregate percentages shows a noticeable improvement in the residual compressive strength when comparing acid-exposed specimens to those unexposed to acid. The control samples exhibit a residual strength of 63.02%, which is the lowest, while this figure increases to 64.15%, 66.95%, and 68.35% for 5%, 10%, and 15% rubber replacements, respectively. A similar trend is observed in the 90-day specimens. Similar findings were noted by Ahmad et al. [20], Assagaf et al. [22], and Islam et al. [25] while studying the durability property of rubberized concrete.



Fig. 15 – Compressive strength test on acid exposed specimen

The reaction between sulfuric acid and cement concrete results in the formation of calcium sulphoaluminate, similar to ettringite, which increases the volume of the concrete and creates significant internal pressure. This pressure can cause cracks and loss of material from the upper layers of the concrete, thereby reducing its strength. In contrast, rubber aggregates have voids within their microstructure, providing more space for the byproducts to expand without generating internal pressure. Additionally, the soft and elastic nature of the rubber particles enables them to absorb the energy associated with the expansion caused by the sulphoaluminate, thereby mitigating the failure of the concrete samples.

5.5 Rapid chloride penetration test (RCPT)

In order to assess the conductivity of concrete, RCPT was conducted, which reflects its resistance to rapid chloride ion penetration. Fig. 16 presents the RCPT results for concrete samples at both 28 days and 90 days. The findings show that chloride ion penetration decreases as the rubber content increases. For the 28-day samples, the control mix (M1) exhibited the highest charge of 2186 C. In contrast, when rubber aggregates were replaced at levels of 5%, 10%, and 15%, there were corresponding reductions in coulomb charges of 6.86%, 23.6%, and 30.46%, respectively, compared to the control mix. Assagaf et al. [25] also observed reduced chloride ion penetration when percentage of rubber content increased.

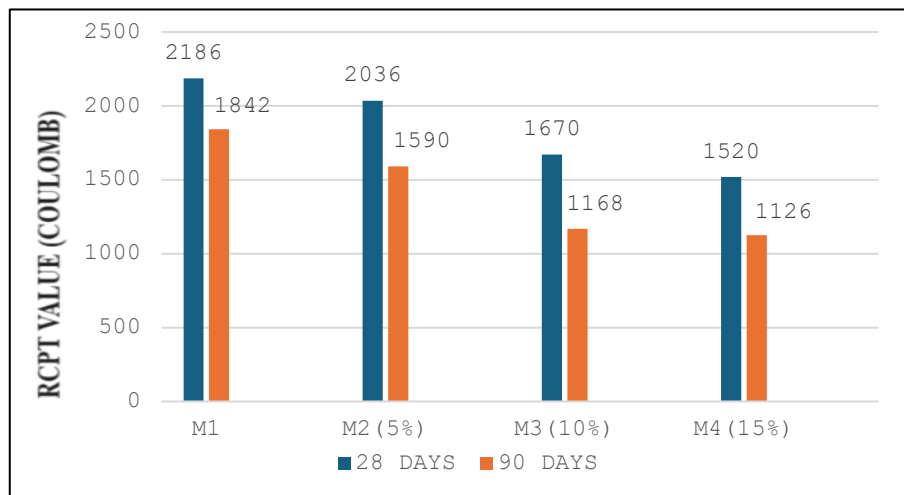


Fig. 16 – RCPT values of different concrete mixes



Fig. 17 – RCPT test on cylindrical specimen

A similar trend is observed in the 90-day samples, where the control mix again recorded the highest charge at 1842 C. The replacement of rubber aggregates at 5%, 10%, and 15% led to reductions in coulomb charges of 13.7%, 36.6%, and 38.9%, respectively, relative to the control mix. This decrease in chloride ion penetration can be linked to the characteristics of rubber particles, which absorb less water and have impermeable properties, thus obstructing the movement of chloride ions. Fig. 17 shows the RCPT test on cylindrical specimen.

5.6 Sorptivity test

The sorptivity index, which measures capillary water absorption, is determined in relation to the square root of time and penetration depth. The sorptivity of concrete is heavily influenced by the physical characteristics of the aggregates utilized. Factors such as curing duration, the presence of voids, and moisture conditions also play crucial roles. Figures 18 and 19 illustrate how water absorption changes according to the square root of time.

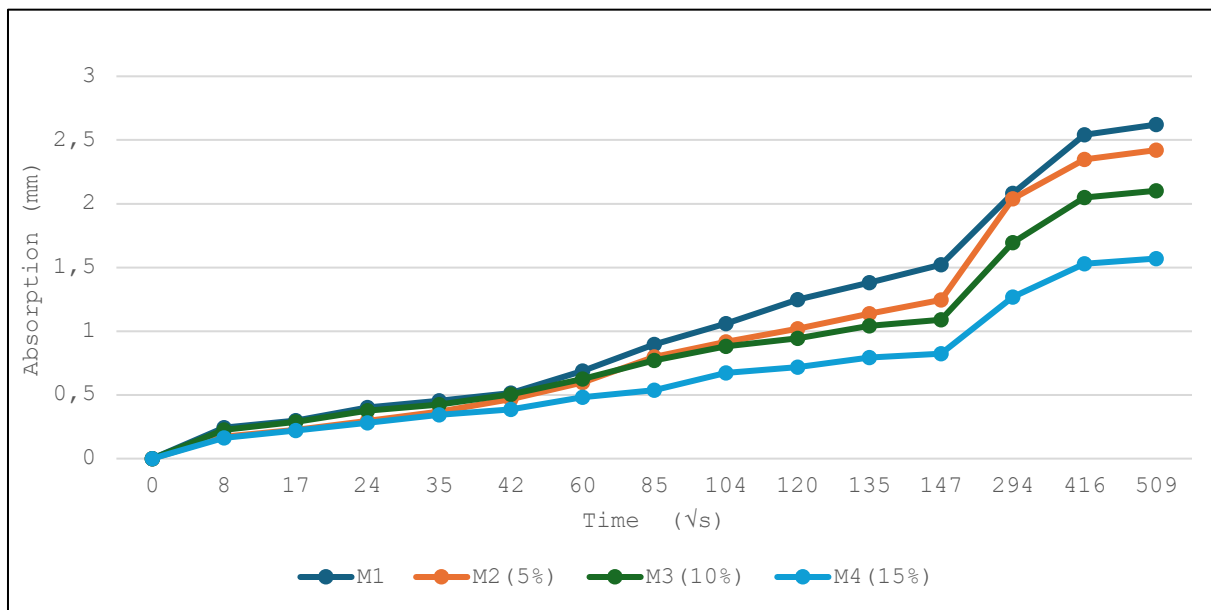


Fig. 18 – Sorptivity test values of different concrete mixes for 28 days sample

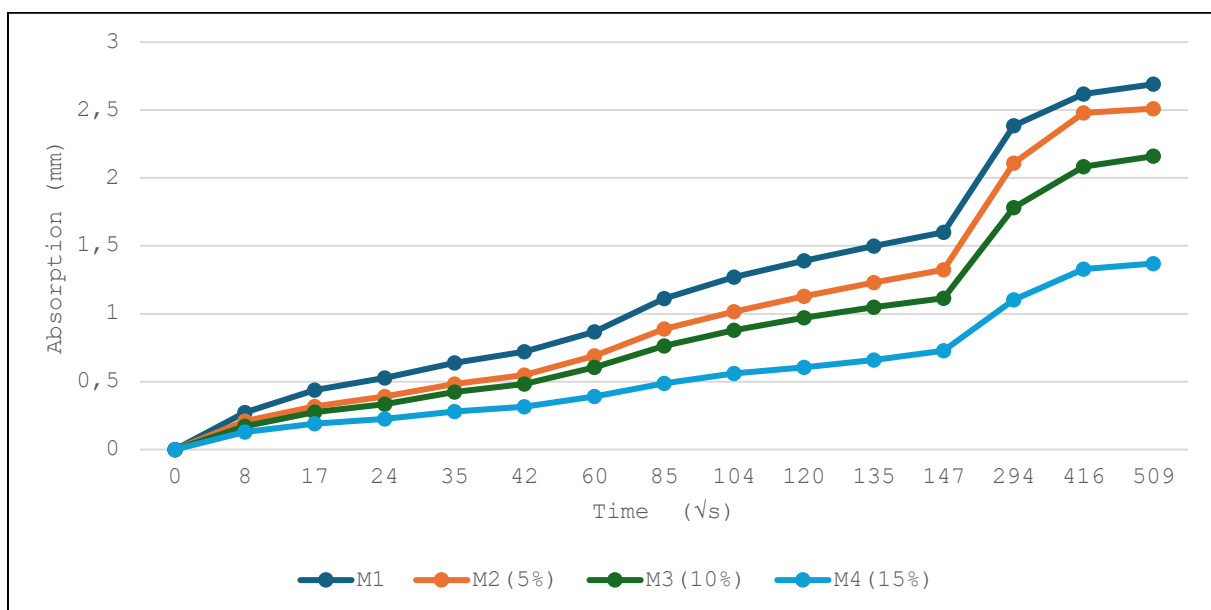


Fig. 19 – Sorptivity test values of different concrete mixes for 90 days sample

It is to be noted that sorptivity increases with a higher rubber content. At 28 days, the control specimen (M1) displays a relatively poor initial absorption rate of 2.621 mm. In contrast, as the rubber content rises, a decrease in sorptivity is noted. The measurements for specimens containing 5%, 10%, and 15% rubber aggregates are 2.421 mm, 2.102 mm, and 1.57 mm, reflecting reductions of 7.63%, 19.8%, and 40.1%, respectively. The mix with 15% rubber aggregates demonstrates the most favourable results. A similar trend is observed at 90 days, where the control specimen (M1) exhibits an absorption rate of 2.69 mm. The results for 5%, 10%, and 15% rubber aggregate content are 2.51 mm, 2.16 mm, and 1.37 mm, corresponding to reductions of 6.7%, 17.9%, and 49%, respectively. The presence of discontinuous air-entraining voids in the specimens helps to obstruct water transmission. Moreover, the non-absorbent nature of rubber aggregates reduces the amount of available water, leading to a decrease in capillary porosity.

6 Conclusion

This research investigates the viability of using crumb rubber obtained from waste tires as a partial replacement for natural fine aggregates in concrete, addressing the environmental challenges posed by the increasing accumulation of waste tires. A series of mechanical and durability tests were performed to evaluate the impact of incorporating 5%, 10%, and 15% crumb rubber on concrete performance. The key findings from this research are summarized as follows:

- The addition of crumb rubber results in a slight reduction in compressive strength; however, it remains within acceptable limits up to a 10% replacement, suggesting potential applications in construction where high strength is not the primary concern.
- Rubberized concrete exhibits significant improvements in impact resistance, with energy absorption capacities increasing by 75%, 125%, and 158.4% for 5%, 10%, and 15% rubber replacements, respectively, indicating its suitability for high-impact applications like road pavements.
- The stress-strain analysis shows that increasing rubber content enhances the ductility of concrete, allowing for greater deformation before failure, which can contribute to structural resilience.
- Rubberized concrete demonstrates lower water absorption and sorptivity values, indicating a reduction in voids and improved durability against moisture ingress.
- The study reveals a 30% reduction in chloride ion penetration at 15% rubber content, enhancing the material's resistance to corrosion and prolonging its lifespan.
- Residual compressive strength increases with higher rubber aggregate percentages post-acid attack, with values improving from 63.02% (control) to 68.35% (15% rubber), suggesting better durability in aggressive environments.

Despite these findings, the study acknowledges limitations, particularly the reduction in compressive strength with increased rubber content, which poses a challenge for applications demanding high structural integrity. While the decrease in compressive strength may limit some applications, the advantages—such as enhanced ductility, improved impact resistance, and increased durability—underscore the potential of rubberized concrete as a viable construction material.

In conclusion, this research highlights the importance of utilizing crumb rubber in concrete, contributing to sustainable environmental practices through the reuse of the waste materials. By promoting recycling, this method not only reduces landfill waste but also offers societal benefits, including the potential for safer and more resilient infrastructure. Emphasizing the need for innovative construction materials, this study advocates for a shift toward sustainable practices that align with environmental goals and support community well-being.

Declaration

Conflict of interest: The authors declare no conflict of interest.

REFERENCES

- [1]- C.R. Gagg, Cement and concrete as an engineering material: An historic appraisal and case study analysis. *Eng. Fail. Anal.*, 40 (2014) 114-140. <https://doi.org/10.1016/j.engfailanal.2014.02.004>
- [2]- W.H. Yung, L.C. Yung, L.H. Hua, A study of the durability properties of waste tire rubber applied to self-

- compacting concrete. *Constr. Build. Mater.*, 41 (2013) 665-672. <https://doi.org/10.1016/j.conbuildmat.2012.11.019>
- [3]- M.A. Aiello, F. Leuzzi, Waste tyre rubberized concrete: Properties at fresh and hardened state. *Waste Manage.*, 30 (2010) 1696-1704. <https://doi.org/10.1016/j.wasman.2010.02.005>
- [4]- D. Rigotti, A. Dorigato, Novel uses of recycled rubber in civil applications. *Adv. Ind. Eng. Polym. Res.*, 5 (2022) 214-233. <https://doi.org/10.1016/j.aiepr.2022.08.005>
- [5]- A. Sofi, Effect of waste tyre rubber on mechanical and durability properties of concrete – A review. *Ain Shams Eng. J.*, 9 (2018) 2691-2700. <https://doi.org/10.1016/j.asej.2017.08.007>
- [6]- A. Alsaif, Y.R. Alharbi, Strength, durability and shrinkage behaviours of steel fiber reinforced rubberized concrete. *Constr. Build. Mater.*, 345 (2022) 128295. <https://doi.org/10.1016/j.conbuildmat.2022.128295>
- [7]- A.H. Beiram, H.M.K. Al-Mutairee, The effect of chip rubber on the properties of concrete. *Mater. Today: Proc.*, 60(3) (2022) 1981-1988. <https://doi.org/10.1016/j.matpr.2022.01.209>
- [8]- G.P. Singh, A. Tiwary, S. Singh, R.S. Kumar, J.S. Chohan, S. Sharma, C.H. Li, P. Sharma, A.F. Deifalla, Incorporation of Silica Fumes and Waste Glass Powder on Concrete Properties Containing Crumb Rubber as a Partial Replacement of Fine Aggregates. *Sustainability*, 14(21) (2022) 14453. <https://doi.org/10.3390/su142114453>
- [9]- J. Guo, M. Huang, S. Huang, S. Wang, An Experimental Study on Mechanical and Thermal Insulation Properties of Rubberized Concrete Including Its Microstructure. *Appl. Sci.*, 9(14) (2019) 2943. <https://doi.org/10.3390/app9142943>
- [10]- N.N. Gerges, C.A. Issa, S.A. Fawaz, Rubber concrete: Mechanical and dynamical properties. *Case Stud. Constr. Mater.*, 9 (2018) e00184. <https://doi.org/10.1016/j.cscm.2018.e00184>
- [11]- A. Grinys, M. Balamurugan, A. Augonis, E. Ivanauskas, Mechanical Properties and Durability of Rubberized and Glass Powder Modified Rubberized Concrete for Whitetopping Structures. *Materials*, 14(9) (2021) 2321. <https://doi.org/10.3390/ma14092321>
- [12]- R. Ataria, Y.C. Wang, Mechanical Properties and Durability Performance of Recycled Aggregate Concrete Containing Crumb Rubber. *Materials*, 15(5) (2022) 1776. <https://doi.org/10.3390/ma15051776>
- [13]- A. Khaled, A. Al-Sodani, Mix design, mechanical properties and durability of the rubberized geopolymer concrete: A review. *Case Stud. Constr. Mater.*, 17 (2022) e01480. <https://doi.org/10.1016/j.cscm.2022.e01480>
- [14]- R. Kumar, N. Dev, Effect of acids and freeze–thaw on the durability of modified rubberized concrete with optimum rubber crumb content. *J. Appl. Polym. Sci.*, 139(21) (2022) 52191. <https://doi.org/10.1002/app.52191>
- [15]- N. Yasser, A. Abdelrahman, M. Kohail, A. Moustafa, Experimental investigation of durability properties of rubberized Concrete. *Ain Shams Eng. J.*, 14(6) (2023) 102111. <https://doi.org/10.1016/j.asej.2022.102111>
- [16]- M. Dong, M. Elchalakani, A. Karrech, B. Yang, Strength and durability of geopolymer concrete with high volume rubber replacement. *Constr. Build. Mater.*, 274 (2021) 121783. <https://doi.org/10.1016/j.conbuildmat.2020.121783>
- [17]- T. Gupta, S. Chaudhary, R.K. Sharma, Mechanical and durability properties of waste rubber fiber concrete with and without silica fume. *J. Clean. Prod.*, 112 (2016) 702-711. <https://doi.org/10.1016/j.jclepro.2015.07.081>
- [18]- S. Mehdipour, I.M. Nikbin, S. Dezhmpanah, R.H. Moghadam, S. Charkhtab, A. Moradi, Mechanical properties, durability and environmental evaluation of rubberized concrete incorporating steel fibre and metakaolin at elevated temperatures. *J. Clean. Prod.*, 254 (2020) 120126. <https://doi.org/10.1016/j.jclepro.2020.120126>
- [19]- I.O. Toma, S.S. Alexa, P. Mihai, A. Toma, G. Taranu, Experimental Investigations on the Long-Term Material Properties of Rubberized Portland Cement Concrete. *Appl. Sci.*, 11(22) (2021) 10868. <https://doi.org/10.3390/app112210868>
- [20]- J. Ahmad, Z. Zhou, R.M. García, A study on the microstructure and durability performance of rubberized concrete with waste glass as binding material. *J. Build. Eng.*, 49 (2022) 104054. <https://doi.org/10.1016/j.job.2022.104054>
- [21]- H. Ahmed, M. Tiznobaik, M.S. Alam, Mechanical and Durability Properties of Rubberized Recycled Aggregate Concrete. *CSCE Annu. Conf.*, (2019) 12-15.
- [22]- R.A. Assaggaf, S.A. Al-Dulaijan, M. Maslehuddin, O.S.B. Al-Amoudi, S. Ahmad, M. Ibrahim, Effect of different treatments of crumb rubber on the durability characteristics of rubberized concrete. *Constr. Build. Mater.*, 318 (2022) 126030. <https://doi.org/10.1016/j.conbuildmat.2021.126030>
- [23]- M. Amiri, F. Hatami, E.M. Golafshani, Evaluating the synergic effect of waste rubber powder and recycled concrete aggregate on mechanical properties and durability of concrete. *Case Stud. Constr. Mater.*, 15 (2021) e00639. <https://doi.org/10.1016/j.cscm.2021.e00639>
- [24]- E. Güneş, M. Gesoğlu, K. Mermerdas, S. İpek, Experimental investigation on durability performance of rubberized concrete. *Adv. Concr. Constr.*, 2(3) (2014) 187-201. <https://doi.org/10.12989/acc.2014.2.3.187>

-
- [25]- M.M.U. Islam, J. Li, R. Roychand, M. Saberian, Investigation of durability properties for structural lightweight concrete with discarded vehicle tire rubbers: A study for the complete replacement of conventional coarse aggregates. *Constr. Build. Mater.*, 369 (2023) 130634. <https://doi.org/10.1016/j.conbuildmat.2023.130634>
- [26]- T. Gupta, S. Siddique, R. Sharma, S. Chaudhary, Effect of aggressive environment on durability of concrete containing fibrous rubber shreds and silica fume. *Struct. Concr.*, 22(5) (2021) 2611-2623. <https://doi.org/10.1002/suco.202000043>
- [27]- K. Kamaruddin, D.S.Q.A. Adenan, Durability Performance of Polymeric Waste Crumb Rubber as Fine Aggregates Replacement in Concrete. *Adv. Mater. Res.*, 1129 (2015) 508-515. <https://doi.org/10.4028/www.scientific.net/AMR.1129.508>
- [28]- C. Kechkar, M. Belachia, Y. Cherait, Contribution to the study of the durability of rubberized concrete in aggressive environments. *Civ. Environ. Eng. Rep.*, 30(1) (2020) 111-129. <https://doi.org/10.2478/ceer-2020-0009>
- [29]- S.E. Kelechi, M. Adamu, A. Mohammed, Y.E. Ibrahim, I. Obianyo, Durability Performance of Self-Compacting Concrete Containing Crumb Rubber, Fly Ash and Calcium Carbide Waste. *Materials*, 15(2) (2022) 488. <https://doi.org/10.3390/ma15020488>
- [30]- Y.J. Li, R. Wang, Y. Zhou, X. Tong, A Review of the Durability-Related Features of Waste Tyre Rubber as a Partial Substitute for Natural Aggregate in Concrete. *Buildings*, 12(11) (2022) 1975. <https://doi.org/10.3390/buildings12111975>
- [31]- S. Luhar, I. Luhar, D. Nicolaides, R. Gupta, Durability Performance Evaluation of Rubberized Geopolymer Concrete. *Sustainability*, 13(11) (2021) 5969. <https://doi.org/10.3390/su13115969>
- [32]- S. Luhar, S. Chaudhary, I. Luhar, Development of rubberized geopolymer concrete: Strength and durability studies. *Constr. Build. Mater.*, 204 (2019) 740-753. <https://doi.org/10.1016/j.conbuildmat.2019.01.185>
- [33]- P. Sukontasukkul, K. Tiamlom, Expansion under water and drying shrinkage of rubberized concrete mixed with crumb rubber with different size. *Constr. Build. Mater.*, 29 (2012) 520-526. <https://doi.org/10.1016/j.conbuildmat.2011.07.032>
- [34]- M.M.R. Taha, A.S. El-Dieb, M.A. Abd El-Wahab, M.E. Abdel-Hameed, Mechanical, fracture, and microstructural investigations of rubber concrete. *J. Mater. Civ. Eng.*, 20(10) (2008) 640-649. [https://doi.org/10.1061/\(ASCE\)0899-1561\(2008\)20:10\(640\)](https://doi.org/10.1061/(ASCE)0899-1561(2008)20:10(640))