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A Review on Effects of Waste Tire Rubber Polymer on Fresh, Mechanical, and Impact Resistance Properties of Rubberized Concrete

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Abstract

According to the collective findings of numerous researchers, waste tire rubber has proven to be a valuable addition to concrete, contributing to advancements in construction. Rubber crumb is artificial rubber polymers, such as butadiene rubber (BR). The chemical composition of tire rubber crumb that is discarded can be represented by the combination of $(C_5H_8)n$, $(C_8H_8)x$-$(C_4H_6)y$, $(C_4H_6)n$, *C,* S_8, *ZnO, and complicated hydrocarbons. Various studies have explored the mechanical and impact resistance characteristics of rubberized concrete when rubber crumbs partially replace traditional aggregates. The utility of rubber crumbs in construction is attributed to their favourable attributes, including excellent flexibility and a lower unit weight compared to natural rock aggregates. Consequently, rubberized concrete becomes particularly advantageous in scenarios requiring increased flexibility. The inherent ability of rubber tires to absorb impact energy and exhibit good ductility properties also positions it as a beneficial component, mitigating the structural damage caused by earthquakes. However, it is crucial to note that an excessive increase in the quantity of rubber can have detrimental effects on the mechanical properties of rubberized concrete. Notably, there is a gap in research focusing on the cement rubber matrix to enhance the mechanical properties of rubberized concrete, indicating the need for further studies in this area.*

Keywords: Rubber crumbs, rubberized concrete, composite material, mechanical properties, plasticizers, resistance to impact

INTRODUCTION

The global expansion of the automotive industry has led to substantial environmental concerns regarding the disposal of waste tires. Tires have become a problematic waste source due to two main factors: high production volume and material durability. A tire can stay in a landfill for up to 100 years because it doesn't break down. The correct disposal of used tires has become an increasingly important environmental concern over time. The main components of waste tire rubber crumb are cross-linked polymer chains, specifically styrene-butadiene rubber (SBR) and polyisoprene (natural rubber). Additionally, it comprises a variety of chemicals utilized in the vulcanization process, including sulfur, carbon black, zinc oxide, and processing oils. Furthermore, there could be trace amounts of artificial rubber polymers, such as butadiene rubber (BR). The combination of $(C_5H_8)n$, $(C_8H_8)x$-$(C_4H_6)y$, $(C_4H_6)n$, C, S_8, ZnO, and complex hydrocarbons can be used to represent the chemical composition of discarded tire rubber crumb.

Over time, the proper disposal of used tires has grown to be a serious environmental problem.

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After being retired from service, rubber tires have little possibility of being recycled and wind up in landfills, degrading the environment. Utilizing rubber in concrete holds significant potential, offering a solution to prevent the area from turning into a landfill and promoting environmental benefits. To increase the impact resistance of Rubberized concrete (RuC), a specific amount of aggregates added to the concrete are replaced with rubber particles. RuC effectively reduces the black pollution caused by waste rubber. Earthquakes and explosions lead to concrete structures collapsing suddenly, causing significant damage to property and human life. Consequently, a new concrete material with strong toughness, blast resistance, and impact resistance is required. Because rubber is both elastic and durable, it can improve RuC's impact resistance [1]. Derived easily from used tires, rubber proves to be a cost-effective alternative to other concrete ingredients. Its incorporation leads to more economical concrete, given its superior flexibility and lower unit weight compared to traditional natural rock aggregates. Consequently, RuC becomes predominantly advantageous in regions demanding greater flexibility. In RuC, the key issue is that it loses mechanical characteristics when rubber crumbs (RC) are added to concrete. It also decreases both static and dynamic MOE, density, and slight workability(Figure.1) The hardness characteristic of the composite was enhanced by the addition of fiber to the rubber matrix [2–6].

Gaining rubber from old used tires is a cost-effective substitute related to other constituents usually used in concrete. Using RC in concrete can lead to a further cost-effective construction material. RC shows greater flexibility and a lower unit weight in comparison to the natural rock aggregates typically employed in traditional concrete. Consequently, the use of RuC becomes advantageous in situations demanding increased flexibility. In RuC, the main problem is that it loses mechanical properties. It also reduced the static and dynamic MOE, density, and slightly workability.

In conclusion, the intersection of waste tire disposal and construction materials, particularly the innovative use of rubberized concrete, represents a crucial step towards addressing environmental challenges associated with tire waste. This sustainable approach not only diverts rubber from landfills but also contributes to the development of more resilient and eco-friendly construction practices. Further research and widespread adoption of such practices hold the potential to usher in a new era of environmentally conscious construction methodologies.

WASTE RUBBER

Synthetic rubber, natural rubber, or a mix of synthetic and natural rubber are used to make vehicle tires. The tire compound was chosen based on its appropriateness for usage. Tire compositions vary according to vehicle type. Previous investigations have indicated that rubber has the largest proportion of ingredients, and carbon black is an important substance other than rubber [8]. Tire waste rubber is often shredded into various pieces by machines and reused in construction for various uses in order to limit trash generation in landfills and dumping operations, hence preventing harm to people and nature. Chipped rubber (CR), RC, and powder rubber (PR) are the three types of waste rubber that are being used in different studies [9]. The manufacturing process of rubber particles from rubber tyres is shown in Figure 2.

Figure 1. Waste tire rubber (7).

Figure 2. (a) Process of making fine and coarse rubber aggregate (10) (b) End product of tire rubber (11).

PROPERTIES OF RUC

Workability

Any waste material that is considered for use in concrete must be considered in terms of workability. Lack of concrete compaction may result in air voids, which will compromise the concrete's strength and lifespan. A proper w/c ratio should be adopted to reduce the influence of air voids and provide efficient concrete compaction [12,13]. As the rubber content increases, the workability of RuC tends to decline [8,14–17](Figure.3) The variance in the results was responsible for the differences in particle size. The workability of concrete is influenced significantly by both the size and quantity of rubber [18]. Additionally, when powdered rubber is combined with RC along with an appropriate admixture, favourable results are achieved, especially when compared to using chipped rubber. Due to RC's increased particle size, the overall result revealed a decline in workability, with the slump test showing a 50% drop in RuC compared to control concrete [15]. Treating rubber with a 10% NaOH solution for 120 minutes, followed by a water wash and drying, led to a decline in workability [19].

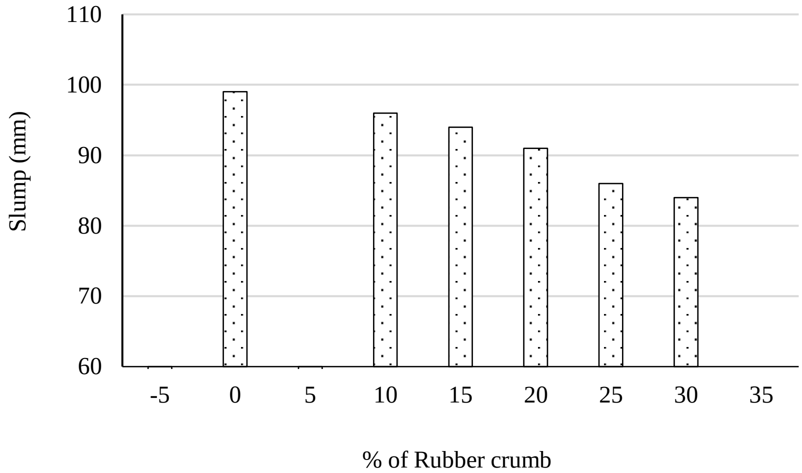


Figure 3. Workability of RuC (20).

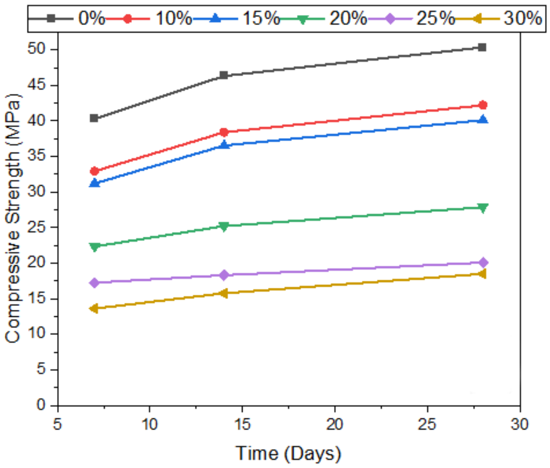
Mechanical Characteristics

The mechanical characteristics are an essential parameter of the concrete, indicating whether it meets the minimum structural requirements or not. RC has been observed to contribute to the decrease in compressive strength of concrete in several previous studies. Reduction in mechanical properties of RuC depends upon the size and quantity of RC [21,22]. Many reviewers also concluded that replacing coarse aggregate (CA) with rubber chipped exhibits more loss in compressive strength values of RuC than fine aggregate (FA) replacement with RC. When comparing RC to chipped rubber, chipped rubber concrete loses more strength than crumb rubber concrete. The poor bond between the rubber and the other elements in the concrete is the cause of this loss in mechanical characteristics. This inadequate bonding results in a space and trapped air between the RC and the cement paste.

Increasing the rubber percentage by replacing CA or FA, both replacing methods may decrease the concrete strength. Rubber's capacity to serve as a partial substitute for FA is prompted by some research [22,23]. Researchers also discovered that compressive strength decreases when the amount of RC in concrete increases [21,24–26]. The quantity of RC which replaces FA should be restricted to 20%-30%, and the RC should also be surface treated. For RuC to be made, pozzolanic material is necessary since it improves both the mechanical properties of RuC and the bond between rubber and cement paste [25]. According to some studies, a 10% replacement of FA by RC provides the best mechanical characteristics [18]. However, other researchers claim that replacing FA with RC with less than 25% shows greater compressive strength]27]. “The low RC stiffness, uneven distribution of the rubber aggregate in the concrete mix, lightweight, and weak bonding between the rubber aggregate and the cement paste all contributed to the mechanical characteristics decreasing trend” [18,28].

Pre-treating the surface of reinforced carbon (RC) enhances the compressive strength of RuC when incorporated into concrete (19). The mechanical properties of RuC can be improved by treating the RC surface with a solution of NaOH [19,29,30]. It was discovered that soaking RC in water for 24 hours improved the mechanical characteristics significantly [31]. Researchers concluded that soaking rubber particles improves the bonding properties of rubber with cement by removing air trapped in the particles. The influence of pre-treatment of RC by NaOH, H_2SO_4, $Ca(OH)_2$, and CH_3COOH solutions on the mechanical characteristics of RuC was investigated in previous research [32]. When compared to untreated rubber concrete, researchers discovered that all treatment methods increased compressive strength after 28 days (32). It happens because of the increasing RC's surface roughness. The compressive strength of RuC was found to be the best after all of the pre-treatment processes. Moreover, pozzolana which contains silica fume, fly ash, or rice husk ash can strengthen RuC [32–34]. Most investigations discovered that tensile strength outcomes followed compressive strength results pattern [34,35].

According to the previous study, the modulus of elasticity (MOE) tends to rise as particle size increases [36]. Some researchers agreed that when the rubber content increased, the MOE decreased [30,37]. When compared to natural aggregates for both treated and untreated rubber samples, the rubber aggregate had a low elastic modulus, according to Gupta et al. (38). The partial substitution of stiff FA with rubber crumbs with low elastic modulus decreases the MOE of RuC(Figure.4) The MOE of concrete is shown to be dependent on the elastic modulus of the aggregate [39]. RuC's MOE was enhanced by 24.4 % with the addition of silica fume. As per the author's findings, the inclusion of silica facilitated the filling of gaps between the aggregate and cement paste, thereby augmenting bonding [40].



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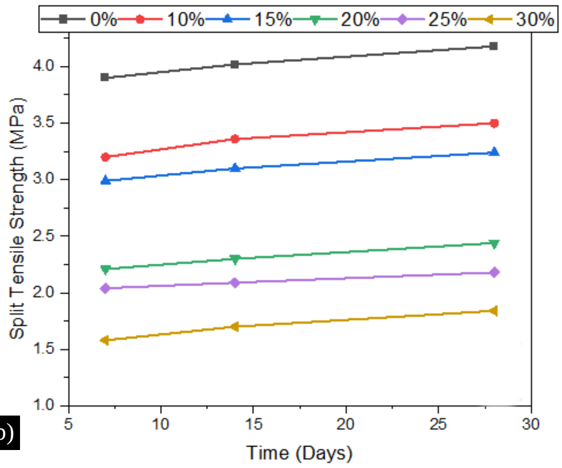

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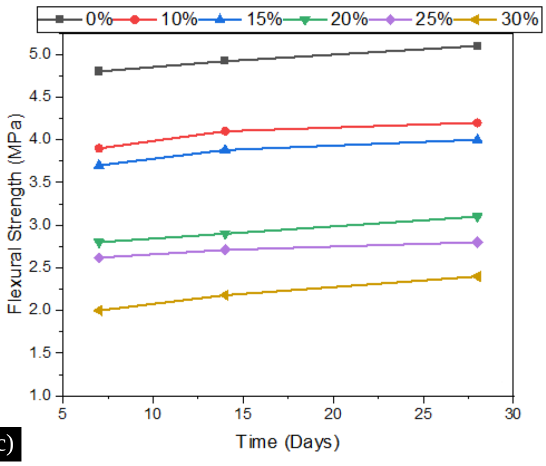

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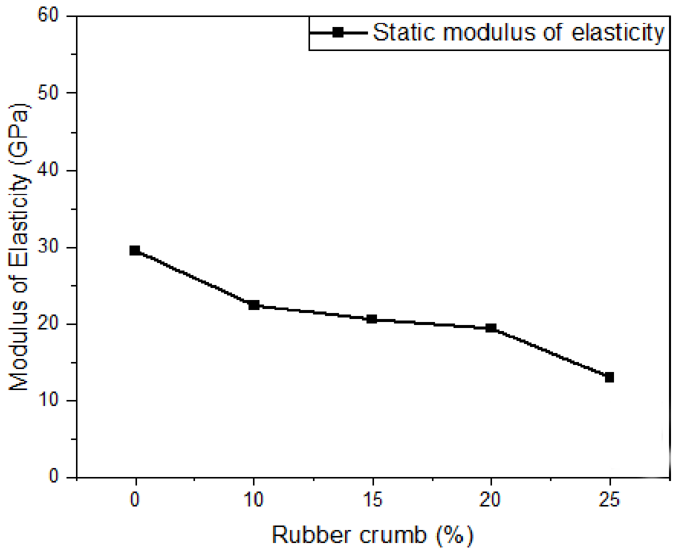

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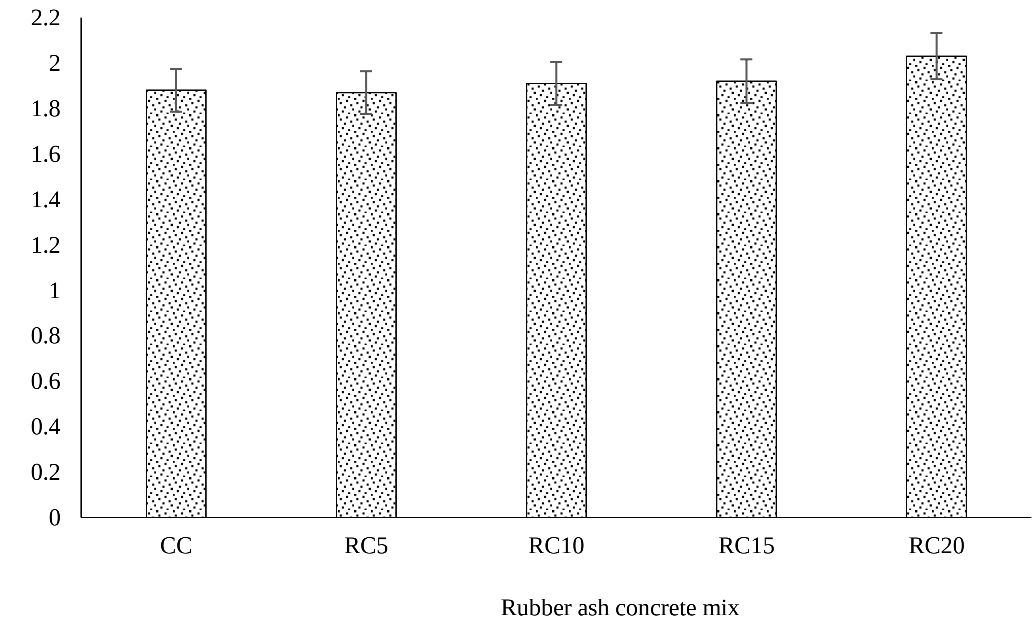
Figure 4. Mechanical properties of RuC (41).

Energy Absorption

RuC's ability to absorb energy is associated with its concrete stiffness [42]. Many researchers have suggested that using rubber as a component in concrete to replace partial aggregate can help RuC absorb more impact energy compared to conventional concrete [30,38,43,44]. RuC fracture energy rises to a 20 percent replacement level of RC, according to the study [43]. Furthermore, according to these researchers [37,45,46], the substitution of RC in FA had good results in terms of energy absorption as the proportion of RC increased. Waste rubber RC may also be utilized as a sustainable resource for improving the impact resistance and flexibility of concrete, according to studies [38,47]. Furthermore, research [48,49] revealed that the energy absorption capacity of RC concrete is superior to that of conventional concrete and that the rubber content is more important than the rubber size in improving energy absorption(Figure.5)



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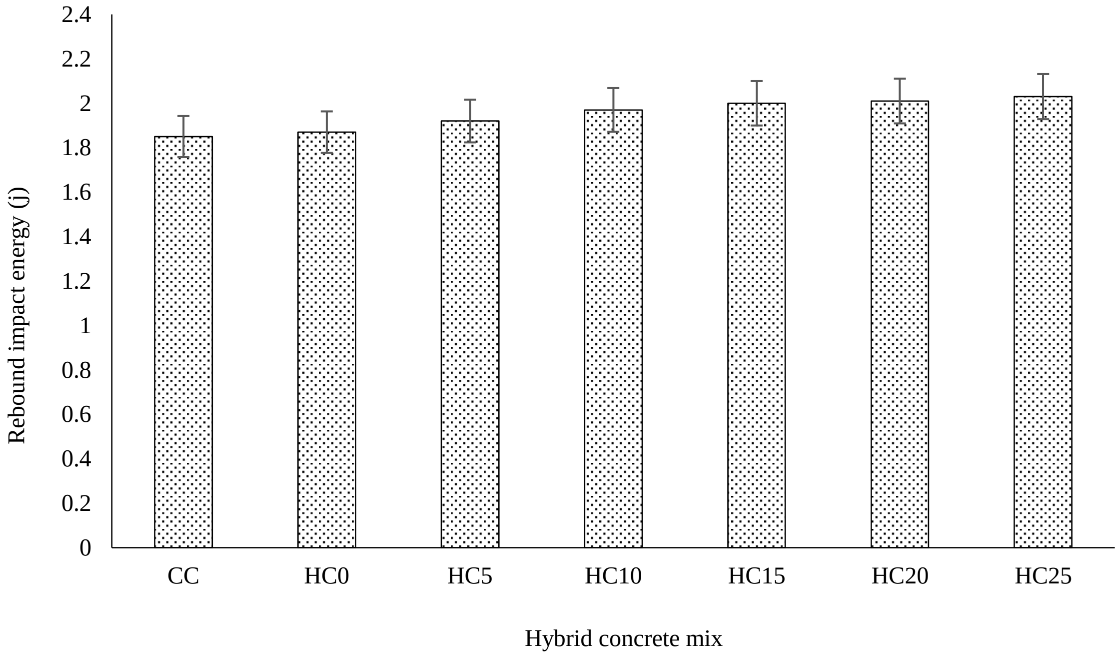

(b)

Figure 5. (a) Impact energy under rebound of rubber ash concrete mixes (b) Impact energy under rebound of hybrid concrete mixes (50).

CONCLUSION

After a review of many articles, some conclusions have been introduced. RuC workability is reduced when rubber content is increased. The size of the rubber aggregate also impacts the workability of RuC. The workability of RuC decreases as the size of the rubber increases, while rubber pre-treatment does not affect concrete workability. Mechanical characteristics such as compressive strength, tensile strength, and MOE are reduced due to increased rubber replacement and size. Still, adding pozzolanic material in RuC and the surface treatment of RC helps in increasing the mechanical properties of RuC. Many studies have proposed that NaOH solution be used to treat the surface of rubber aggregate. When compared to chipped rubber for partially replacing CA, RC is a perfect size to replace FA partially. With a rise in rubber content, the outcomes of MOE similarly reduce. Finally, when the proportion of rubber increases, energy absorption capacity increases, indicating that RC is excellent for producing a good energy absorption capacity of RuC. As a result of the studies, it appears that replacing FA with RC in concrete is suitable for use as an energy absorber.

REFERENCES

1. Xiong Z, Fang Z, Feng W, Liu F, Yang F, Li L. Review of dynamic behaviour of rubberised concrete at material and member levels [Internet]. Vol. 38, Journal of Building Engineering. Elsevier Ltd; 2021. p. 102237. Available from: https://doi.org/10.1016/j.jobe.2021.102237
2. Palanisamy S, Kalimuthu M, Dharmalingam S, Alavudeen A, Nagarajan R, Ismail SO, et al. Effects of fiber loadings and lengths on mechanical properties of Sansevieria Cylindrica fiber reinforced natural rubber biocomposites. Mater Res Express [Internet]. 2023 Aug 1;10(8):085503. Available from: https://iopscience.iop.org/article/10.1088/2053-1591/acefb0
3. Sivasubramanian P, Mayandi K, Santulli C, Alavudeen A, Rajini N. Effect of Fiber Length on Curing and Mechanical Behavior of Pineapple Leaf Fiber (PALF) Reinforced Natural Rubber Composites. J Nat Fibers [Internet]. 2022 Nov 2;19(11):4326–37. Available from: https://doi.org/10.1080/15440478.2020.1856281
4. Murugesan TM, Palanisamy S, Santulli C, Palaniappan M. Mechanical characterization of alkali treated Sansevieria cylindrica fibers–Natural rubber composites. Mater Today Proc [Internet]. 2022;62:5402–6. Available from: https://doi.org/10.1016/j.matpr.2022.03.609

5. Palanisamy S, Mani Murugesan T, Palaniappan M, Santulli C. Characterization of an eco-friendly rubber composite material based on Sansevieria cylindrica fibers. Mater Today Proc [Internet]. 2023 Aug;(June):4–8. Available from: https://doi.org/10.1016/j.matpr.2023.08.202
6. Palanisamy S, Mayandi K, Palaniappan M, Alavudeen A, Rajini N, Vannucchi de Camargo F, et al. Mechanical Properties of Phormium Tenax Reinforced Natural Rubber Composites. Fibers [Internet]. 2021 Feb 1;9(2):11. Available from: https://www.mdpi.com/2079-6439/9/2/11
7. Alfayez SA, Suleiman AR, Nehdi ML. Recycling tire rubber in asphalt pavements: State of the art. Sustain. 2020;12(21):1–15.
8. Su H, Yang J, Ling TC, Ghataora GS, Dirar S. Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes. J Clean Prod [Internet]. 2015;91:288–96. Available from: http://dx.doi.org/10.1016/j.jclepro.2014.12.022
9. Ganjian E, Khorami M, Maghsoudi AA. Scrap-tyre-rubber replacement for aggregate and filler in concrete. Constr Build Mater [Internet]. 2009;23(5):1828–36. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2008.09.020
10. Mhaya AM, Fahim Huseien G, Faridmehr I, Razin Zainal Abidin A, Alyousef R, Ismail M. Evaluating mechanical properties and impact resistance of modified concrete containing ground Blast Furnace slag and discarded rubber tire crumbs. Constr Build Mater [Internet]. 2021;295. Available from: https://doi.org/10.1016/j.conbuildmat.2021.123603
11. Mutalib NANA, Mokhatar SN, Budiea AMA, Jaini ZM, Kamarudin AF, Noh MSM. A review: Study on waste rubber as construction material. IOP Conf Ser Mater Sci Eng. 2021;1144(1):012003.
12. Kumar R, Verma M, Dev N. Investigation on the Effect of Seawater Condition, Sulphate Attack, Acid Attack, Freeze–Thaw Condition, and Wetting–Drying on the Geopolymer Concrete. Iran J Sci Technol Trans Civ Eng [Internet]. 2021 Nov 23; Available from: https://doi.org/10.1007/s40996-021-00767-9
13. Kumar R, Dev N. Effect of acids and freeze–thaw on the durability of modified rubberized concrete with optimum rubber crumb content. J Appl Polym Sci [Internet]. 2022 Jun 5;139(21):52191. Available from: https://onlinelibrary.wiley.com/doi/10.1002/app.52191
14. Rashid K, Yazdanbakhsh A, Rehman MU. Sustainable selection of the concrete incorporating recycled tire aggregate to be used as medium to low strength material. J Clean Prod [Internet]. 2019;224:396–410. Available from: https://doi.org/10.1016/j.jclepro.2019.03.197
15. Holmes N, Browne A, Montague C. Acoustic properties of concrete panels with crumb rubber as a fine aggregate replacement. Constr Build Mater [Internet]. 2014;73:195–204. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2014.09.107
16. Kumar R, Dev N, Ram S, Verma M. Investigation of dry-wet cycles effect on the durability of modified rubberised concrete. Forces Mech [Internet]. 2023 Feb;10(December 2022):100168. Available from: https://doi.org/10.1016/j.finmec.2023.100168
17. Kumar R, Verma M, Dev N. Investigation of fresh, mechanical, and impact resistance properties of rubberized concrete. In: International e-Conference on Sustainable Development & Recent Trends in Civil Engineering [Internet]. 2022. p. 88–94. Available from: https://doi.org/10.1016/j.finmec.2023.100168
18. Elchalakani M. High strength rubberized concrete containing silica fume for the construction of sustainable road side barriers. Structures [Internet]. 2015;1:20–38. Available from: http://dx.doi.org/10.1016/j.istruc.2014.06.001
19. Youssf O, Hassanli R, Mills JE, Skinner W, Ma X, Zhuge Y, et al. Influence of mixing procedures, rubber treatment, and fibre additives on rubcrete performance. J Compos Sci. 2019;3(2).
20. Kumar R, Dev N. Mechanical and Microstructural Properties of Rubberized Concrete After Surface Modification of Waste Tire Rubber Crumb. Arab J Sci Eng [Internet]. 2022 Apr 27;47(4):4571–87. Available from: https://doi.org/10.1007/s13369-021-06154-w
21. Raffoul S, Garcia R, Pilakoutas K, Guadagnini M, Medina NF. Optimisation of rubberised concrete with high rubber content: An experimental investigation. Constr Build Mater [Internet]. 2016;124:391–404. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2016.07.054
22. Si R, Guo S, Dai Q. Durability performance of rubberized mortar and concrete with NaOH-Solution treated rubber particles. Constr Build Mater [Internet]. 2017;153:496–505. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2017.07.085

23. He L, Ma Y, Liu Q, Mu Y. Surface modification of crumb rubber and its influence on the mechanical properties of rubber-cement concrete. Constr Build Mater [Internet]. 2016 Sep;120:403–7. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061816307462
24. Abdelmonem A, El-Feky MS, Nasr ESAR, Kohail M. Performance of high strength concrete containing recycled rubber. Constr Build Mater [Internet]. 2019;227:116660. Available from: https://doi.org/10.1016/j.conbuildmat.2019.08.041
25. Strukar K, Kalman T, Miličević I, Bušić R. Potential use of rubber as aggregate in structural reinforced concrete element – A review. Eng Struct [Internet]. 2019;188(August 2018):452–68. Available from: https://doi.org/10.1016/j.engstruct.2019.03.031
26. Kumar R, Verma M, Dev N, Lamba N. Influence of chloride and sulfate solution on the long-term durability of modified rubberized concrete. J Appl Polym Sci [Internet]. 2022 Oct 5;139(37):1–15. Available from: https://onlinelibrary.wiley.com/doi/10.1002/app.52880
27. Liu H, Wang X, Jiao Y, Sha T. Experimental investigation of the mechanical and durability properties of crumb rubber concrete. Materials (Basel). 2016;9(3).
28. Thomas BS, Kumar S, Mehra P, Gupta RC, Joseph M, Csetenyi LJ. Abrasion resistance of sustainable green concrete containing waste tire rubber particles. Constr Build Mater [Internet]. 2016;124:906–9. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2016.07.110
29. Najim KB, Hall MR. Crumb rubber aggregate coatings/pre-treatments and their effects on interfacial bonding, air entrapment and fracture toughness in self-compacting rubberised concrete (SCRC). Mater Struct Constr. 2013;46(12):2029–43.
30. Li D, Zhuge Y, Gravina R, Mills JE. Compressive stress strain behavior of crumb rubber concrete (CRC) and application in reinforced CRC slab. Constr Build Mater [Internet]. 2018;166:745–59. Available from: https://doi.org/10.1016/j.conbuildmat.2018.01.142
31. Mohammadi I, Khabbaz H. Shrinkage performance of Crumb Rubber Concrete (CRC) prepared by water-soaking treatment method for rigid pavements. Cem Concr Compos [Internet]. 2015;62:106–16. Available from: http://dx.doi.org/10.1016/j.cemconcomp.2015.02.010
32. Muñoz-Sánchez B, Arévalo-Caballero MJ, Pacheco-Menor MC. Influence of acetic acid and calcium hydroxide treatments of rubber waste on the properties of rubberized mortars. Mater Struct Constr. 2017;50(1).
33. Hadipramana J, Samad AAA, Ibrahim R, Mohamad N, Riza FV. The energy absorption of modified foamed concrete with rice husk ash subjected to impact loading. ARPN J Eng Appl Sci. 2016;11(12):7437–42.
34. Copetti CM, Borges PM, Squiavon JZ, da Silva SR, de Oliveira Andrade JJ. Evaluation of tire rubber surface pre-treatment and silica fume on physical-mechanical behavior and microstructural properties of concrete. J Clean Prod. 2020;256.
35. Jokar F, Khorram M, Karimi G, Hataf N. Experimental investigation of mechanical properties of crumbed rubber concrete containing natural zeolite. Constr Build Mater [Internet]. 2019;208:651–8. Available from: https://doi.org/10.1016/j.conbuildmat.2019.03.063
36. Li L, Ruan S, Zeng L. Mechanical properties and constitutive equations of concrete containing a low volume of tire rubber particles. Constr Build Mater [Internet]. 2014;70:291–308. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2014.07.105
37. Atahan AO, Yücel AÖ. Crumb rubber in concrete: Static and dynamic evaluation. Constr Build Mater [Internet]. 2012;36:617–22. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2012.04.068
38. Gupta T, Chaudhary S, Sharma RK. Assessment of mechanical and durability properties of concrete containing waste rubber tire as fine aggregate. Constr Build Mater [Internet]. 2014 Dec;73:562–74. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2014.09.102
39. Onuaguluchi O, Panesar DK. Hardened properties of concrete mixtures containing pre-coated crumb rubber and silica fume. J Clean Prod [Internet]. 2014;82:125–31. Available from: http://dx.doi.org/10.1016/j.jclepro.2014.06.068
40. Gupta T, Chaudhary S, Sharma RK. Mechanical and durability properties of waste rubber fiber concrete with and without silica fume. J Clean Prod [Internet]. 2016;112:702–11. Available from: http://dx.doi.org/10.1016/j.jclepro.2015.07.081

41. Kumar R, Dev N. Assessment of Mechanical and Impact Resistance Properties of Rubberized Concrete After Surface Modification of Rubber Crumb. Iran J Sci Technol Trans Civ Eng [Internet]. 2022 Aug 23;46(4):2855–71. Available from: https://doi.org/10.1007/s13369-021-06154-w
42. Topçu IB. The properties of rubberized concretes. Cem Concr Res. 1995;25(2):304–10.
43. Roychand R, Gravina RJ, Zhuge Y, Ma X, Youssf O, Mills JE. A comprehensive review on the mechanical properties of waste tire rubber concrete. Constr Build Mater [Internet]. 2020;237:117651. Available from: https://doi.org/10.1016/j.conbuildmat.2019.117651
44. Gerges NN, Issa CA, Fawaz SA. Rubber concrete: Mechanical and dynamical properties. Case Stud Constr Mater [Internet]. 2018;9. Available from: https://doi.org/10.1016/j.cscm.2018.e00184
45. Ozbay E, Lachemi M. Compressive strength, abrasion resistance and energy absorption capacity of rubberized concretes with and without slag. Mater Struct. 2011;1297–307.
46. Ganesan N, Raj B, Shashikala AP. Behavior of self-consolidating rubberized concrete beam-column joints. ACI Mater J. 2013;110(6):697–704.
47. Najim KB, Hall MR. Mechanical and dynamic properties of self-compacting crumb rubber modified concrete. Constr Build Mater [Internet]. 2012;27(1):521–30. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2011.07.013
48. XU J, Yao Z, Yang G, Han Q. Research on crumb rubber concrete: From a multi-scale review. Constr Build Mater [Internet]. 2020;232:117282. Available from: https://doi.org/10.1016/j.conbuildmat.2019.117282
49. Issa CA, Salem G. Utilization of recycled crumb rubber as fine aggregates in concrete mix design. Constr Build Mater [Internet]. 2013;42:48–52. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2012.12.054
50. Gupta T, Tiwari A, Siddique S, Sharma RK, Chaudhary S. Response assessment under dynamic loading and microstructural investigations of rubberized concrete. J Mater Civ Eng. 2017;29(8):1–15.

