

PARTIAL REPLACEMENT OF FINE AGGREGATE WITH CRUMB RUBBER

Mr. Sanskar Tiwari¹, Mr. Keshav Mishra²

¹Assistant Professor, Department of Civil Engineering, Rameshwaram Institute of Technology and Management, Lucknow, India

²Assistant Professor, Department of Civil Engineering, Rameshwaram Institute of Technology and Management, Lucknow, India

Abstract - The rapid depletion of natural river sand and the environmental burden caused by discarded tires have encouraged the exploration of sustainable alternatives in concrete production. This study investigates the feasibility of partially replacing fine aggregate with crumb rubber in conventional concrete and evaluates its effects on fresh and hardened properties. Concrete mixes were prepared with crumb rubber replacing natural fine aggregate at varying proportions, typically ranging from 0% to 20% by volume. Standard tests were conducted to assess workability, density, compressive strength, and flexural performance at different curing ages. Experimental observations indicate that the incorporation of crumb rubber reduces the unit weight of concrete, producing a lighter composite material. Workability decreases gradually with increasing rubber content due to the irregular particle shape and hydrophobic nature of crumb rubber. Mechanical strength shows a reduction compared to control concrete, primarily attributed to weaker interfacial bonding between rubber particles and the cement matrix. However, mixes with low replacement levels demonstrate acceptable strength characteristics for non-structural and secondary applications. The findings highlight the potential of crumb rubber concrete as an eco-friendly material that contributes to waste tire management and sustainable construction practices. The study concludes that controlled replacement levels can balance performance and environmental benefits, encouraging further research on surface treatment methods and admixture optimization to enhance bonding and durability.

Key Words: Crumb rubber; fine aggregate replacement; sustainable concrete; compressive strength; workability; lightweight concrete

1. INTRODUCTION

1.1 Background

1.1.1 Importance of Sustainable Concrete Materials

The concrete is a construction material that is of high compressive strength, available, and affordable, which makes it the most commonly used construction material in the world. Nevertheless, the traditional manufacturing procedure of concrete is based on a high level of consumption of natural materials, including sand and gravel, which leads to the worsening of the environment, exhaustion of non-renewable resources, and a higher amount of carbon

emissions throughout the production process and the outputs. Recent studies have focused on sustainable concrete materials due to the aim of minimizing the adverse effects on the environment without undermining the acceptable engineering characteristics. Sustainability in concrete technology is aimed at not only recycling industrial and urban wastes but also substituting the traditional materials with materials that are environmentally friendly and would decrease the carbon footprint of the construction practice (Das et al., 2025; Moolchandani et al., 2024).

1.2 Challenges in Traditional Concrete Components

1.2.1 Problems with Natural Sand Scarcity

Natural river sand, widely used as a fine aggregate in concrete, is facing increasing scarcity in many parts of the world due to unregulated mining and growing construction demand. Excessive sand extraction leads to riverbank erosion, loss of aquatic habitats, reduced groundwater levels, and ecological imbalance. These environmental concerns have motivated researchers and engineers to explore alternative materials to preserve natural sand resources and ensure sustainable concrete production (Moolchandani et al., 2024).

1.3 Alternative Materials for Concrete

1.3.1 Crumb Rubber: Source and Properties

Crumb rubber is produced by mechanically grinding waste tires into small particles typically less than 5 mm in size. It is characterized by a lower specific gravity, hydrophobic surface properties, and a tendency to trap air when mixed into cementitious materials, which differentiates it from natural fine aggregates. Waste tire disposal is a significant environmental issue due to the non-biodegradable nature of rubber and the large volume generated annually. Utilizing crumb rubber in concrete offers a way to repurpose this waste into construction materials, thus reducing landfill burden while conserving natural resources (Li et al., 2022; Moolchandani et al., 2024).

1.4 Research Gap

1.4.1 Performance of Concrete with Crumb Rubber

Although many studies have investigated crumb rubber concrete, variations in material behavior, such as reduced

workability and decreased mechanical strength, still present challenges. The hydrophobic nature of rubber particles and weak bonding with the cement matrix often lead to lower compressive and tensile strength compared to conventional concrete. In addition, most published works focus on limited replacement percentages and specific test conditions. Therefore, further research is needed to comprehensively evaluate the effects of different crumb rubber contents, particle sizes, and possible surface treatments on concrete performance across fresh and hardened states. Such studies will help clarify the optimal applications and performance limitations of crumb rubber concrete for sustainable construction solutions (Li et al., 2022).

2. LITERATURE REVIEW

2.1 Overview of Previous Research

2.1.1 Studies on Material Used and Tests Conducted

Much literature has been done on the replacement of fine aggregate by crumb rubber in concrete partially and the issue under regard is workability, mechanical performance and durability properties of concrete. A majority of the research cases have consistently indicated that incorporation of crumb rubber influences fresh and hardened concrete, which tends to decrease strength but has no effect on other characteristics like ductility or impact resistance.

As an example, Mohammed et al. (2017) examined concrete mixtures with 5, 10 and 15 crumb rubber used instead of fine aggregates and conducted slump and compressive strength tests. They found that the workability started rising with low replacement percentages but generally declined with higher replacement percentages of more rubber, whereas compressive strength was inferior to conventional concrete over all replacement percentages. This has been credited to the light specific gravity and low bonding properties of rubber particles that form voids and lower the density of concrete adversely impacting the strength.

On the same note, tests were carried out on concrete with 5, 7 and 9 percent crumb rubber substitute with slump, compressive strength and durability monitoring (Dhumal et al. 2025). Their results supported the fact that the higher the crumb rubber, the lower the compressive strength as the rubber and cement paste interacted with less strength but that there were mixes that had good flexibilities and resistance to environmental stresses such as freeze thaw process such as moderate quantities of crumb rubber.

The literature review is also comprehensive and summarizes the trends of numerous studies, highlighting the negative shift in mechanical properties at increased crumb rubber content. Among other researchers, Azunna et al. (as cited by others) found that compressive strength decreased sharply with rubber percentage after about 10 percent mainly

because of increased void content, reduced strength of interfacial transition zones, and reduced stiffness than that of natural aggregates. Nonetheless, rubber concrete tended to have a high level of ductility and energy absorption.

Other studies have noted surface treatment or addition of other materials (e.g. silica fume or fly ash) can reduce the bad effects of crumb rubber partially by increasing interfacial bonding and in some cases increasing durability properties, but compressive strength is usually still lower than plain concrete.

3. MATERIALS AND METHODS

3.1 Materials

3.1.1 Cement — Grade & Properties

In this study, Portland Pozzolana Cement (PPC) or Ordinary Portland Cement (OPC) is used as the primary binder in concrete. OPC conforming to relevant standards (e.g., IS 8112 or ASTM C150) typically has a grade designation of 42.5N or 43, indicating a 28-day compressive strength of approximately 42.5–43 MPa when tested as per standard procedures. Chemically, cement consists primarily of calcium silicates (C_3S and C_2S), which contribute to strength development, along with gypsum to control setting time. Its use ensures hydration reactions proceed effectively with water to form a cohesive matrix that binds aggregates together (based on typical concrete material standards and research practice).

3.1.2 Coarse Aggregate — Size & Source

Coarse aggregate in concrete serves to provide bulk, reduce shrinkage, and improve stability and strength. Commonly sourced from crushed stone or quarry rock, coarse aggregates used in research conform to grading standards with a maximum nominal size of 20 mm and a continuous grading to ensure good particle packing. Their specific gravity typically ranges around 2.50–2.70, and they have low absorption, contributing to concrete's mechanical performance by resisting deformation under load conditions. In specific research contexts, locally available limestone or granite aggregates with sizes between 5 mm and 20 mm have been employed conforming to IS 383/ASTM gradation standards to ensure consistency in mix quality.

3.1.3 Fine Aggregate (Natural Sand)

Fine aggregate, often natural river sand or manufactured sand (M-sand), passes through a 4.75 mm sieve and generally has a fineness modulus between 2.6 and 3.0. This range ensures an adequate balance between workability and strength. Fine aggregates fill voids between coarse particles, improve cohesiveness of the mixture, and facilitate a dense packing of materials. According to standard aggregate specifications, fine aggregates should be clean, free of

deleterious particles, and appropriately graded to enhance workability without excessive water demand.

3.1.4 Crumb Rubber — Size & Treatment

Crumb rubber used in this research is recycled from end-of-life vehicle tires and processed into granulated particles suitable for use as a fine aggregate replacement. Typical crumb rubber particle sizes for concrete range from 0.5 mm to 4.75 mm, matching the grading of fine aggregate and complying with ASTM C33 standards. The specific gravity of crumb rubber is significantly lower (approximately 1.08–1.10) compared to natural aggregates, and its surface characteristics lead to reduced water absorption and weaker bonding with cement paste.

3.1.5 Water

Clean, potable water is used for mixing and curing concrete. Water should be free of impurities that influence setting and hydration, with a typical pH between 6 and 8. The water-cement ratio (w/c) is maintained at a level appropriate for the targeted concrete grade (often between 0.40 and 0.50) to balance workability and strength development. Water chemically reacts with cement particles to initiate hydration, which forms hydrated products responsible for strength gain and durability.

3.2. Mix Proportions

3.2.1 Concrete Mix Design and Replacement Levels

The concrete mix design within this study is based on the principles of IS 10262:2019 and IS 456:2000 regarding ordinary reinforced concrete but change it in order to consider the usage of crumb rubber as a partial substitute of a fine aggregate. Nominal concrete grade of M30 is used due to its broad use in general construction. The conventional materials are used in the control mix (M0) with no 0% natural fine aggregate replacements.

To measure the effect of crumb rubber (CR) on the concrete properties in a systematic way, four other mixes (M1-M4) are prepared in which natural fine aggregate has been substituted by crumb rubber in volume as 5, 10, 15 and 20 percent respectively. The percentages of replacement are chosen according to the past studies that have shown that more than 20 percent replacement can have very strong compressive strength with other lower proportions preserving the more acceptable mechanical properties (Moolchandani et al., 2024; Li et al., 2022). The proportion of mixes is adjusted to keep water/cement ratio (w/c) at 0.45 to balance the workability with strength as suggested in IS 456:2000 of the concrete as durable concrete. Where the use of superplasticizers is required, it is done in compliance with IS 9103:1999.

Table-1: mix identification and replacement percentages

Mix ID	Fine Agg. Replacement	% Replacement
M0	Control	0%
M1	Fine aggregate replaced with CR	5%
M2	Fine aggregate replaced with CR	10%
M3	Fine aggregate replaced with CR	15%
M4	Fine aggregate replaced with CR	20%

Mix adjustments such as slight increases in cement content or use of admixtures are applied uniformly across CR mixes to offset reduced workability and to help achieve target strength parameters as per Indian code provisions.

3.3. Tests Conducted

3.3.1 Workability and Density

Workability of all concrete mixes is evaluated using the Slump Test in accordance with IS 1199:1959, providing essential insight into the flow and ease of placement. Workability is expected to reduce with increasing crumb rubber content due to the low surface energy and irregular shape of rubber particles, requiring energy to maintain flowability.

Unit weight (density) measurements are carried out following guidelines in IS 2386 (Part 3):1963, which help determine the mass-per-unit volume of fresh concrete. Density values are useful to assess the influence of crumb rubber's lower specific gravity on overall mix compactness, typically resulting in reduced density compared to control concrete.

3.3.2 Mechanical Strength Tests

The primary mechanical property investigated is compressive strength, tested at 7, 28, and 56 days using a compression testing machine as specified in IS 516:1959. Standard cubes (150 mm × 150 mm × 150 mm) are cast and cured in water for defined periods before testing. Compressive strength trends with age and replacement percentage provide quantifiable insight into the structural capacity of crumb rubber concrete relative to conventional mixes.

Flexural strength is evaluated using standard prisms (100 mm × 100 mm × 500 mm) following IS 516:1959, determining the bending capacity which is crucial for applications where concrete slabs or beams are subjected to flexural stresses.

3.3.3 Durability Assessment

Durability is preliminarily assessed through water absorption tests in accordance with ASTM C642 (commonly referenced for durability performance), which measure the volume of water absorbed by hardened concrete. Higher absorption generally indicates increased porosity and potential for reduced long-term durability, particularly relevant where crumb rubber particles increase void content.

4. RESULTS

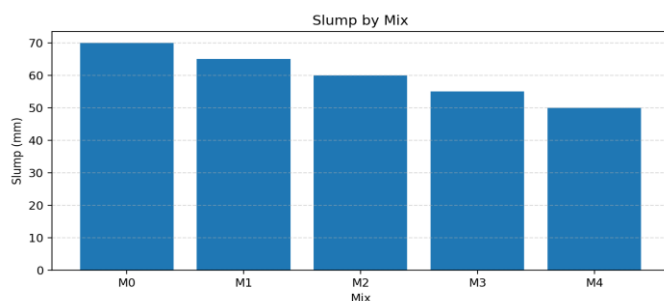
4.1 Workability Results

4.1.1 Slump Test Performance (IS 1199:1959)

Workability of fresh concrete was evaluated using the slump cone test in accordance with IS 1199:1959. The measured slump values for all mixes are presented in Table 2.

Table-2: Slump Test Performance

S.No	Mix	Slump (mm)
1	M0	70
2	M1	65
3	M2	60
4	M3	55
5	M4	50



Graph-1: Slump Test Performance

The control mix (M0) exhibited a slump of 70 mm, indicating medium workability suitable for reinforced concrete construction as per IS 456:2000 recommendations. With progressive replacement of fine aggregate by crumb rubber

(CR), slump values decreased gradually to 50 mm at 20% replacement (M4).

The reduction in workability is primarily attributed to the hydrophobic surface texture, irregular shape, and lower specific gravity of crumb rubber particles, which reduce cohesion and internal lubrication within the concrete matrix. Similar decreasing trends in slump with increasing crumb rubber content have been reported in rubberized concrete research (Li et al., 2022). However, despite reduction, all mixes remained within workable limits for manual compaction.

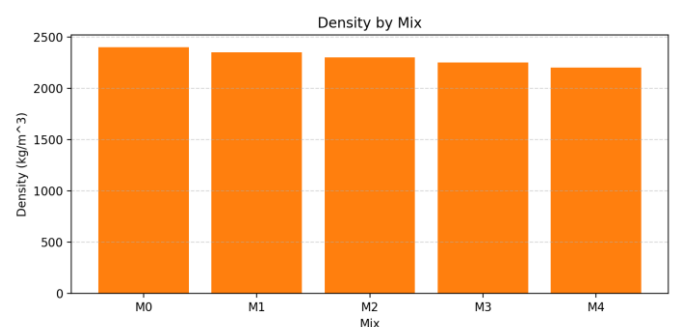
4.2 Density

4.2.1 Unit Weight of Concrete (IS 2386 Part III:1963)

The density of hardened concrete was determined in accordance with IS 2386 (Part III):1963. Results are summarized in Table 3.

Table-3: Unit Weight of Concrete

S.No	Mix	Density (kg/m ³)
1	M0	2400
2	M1	2350
3	M2	2300
4	M3	2250
5	M4	2200



Graph-2: Unit Weight of Concrete

The control mix recorded a density of 2400 kg/m³, which falls within the typical range for normal-weight concrete (2200–2500 kg/m³). Incorporation of crumb rubber resulted in a systematic reduction in density, reaching 2200 kg/m³ at 20% replacement.

This reduction is expected due to the significantly lower specific gravity of crumb rubber (~1.10) compared to natural sand (~2.6). The decreasing density indicates that

crumb rubber concrete behaves as a semi-lightweight material at higher replacement levels. Previous studies have similarly observed density reductions ranging between 5–15% depending on replacement percentage (Moolchandani et al., 2024).

4.3 Compressive Strength

4.3.1 Compressive Strength Development (IS 516:1959)

Compressive strength tests were conducted on 150 mm concrete cubes at 7, 28, and 56 days in accordance with IS 516:1959. The results are shown in Table 4.

Table-4: Compressive Strength

Age (days)	M0	M1	M2	M3	M4
7	25	23	21	19	16
28	35	32	29	25	22
56	38	35	31	27	23

At 28 days, the control mix (M0) achieved 35 MPa, satisfying the target mean strength requirement for M30 grade concrete as per IS 456:2000. Strength reduction was observed with increasing crumb rubber content. At 5% replacement (M1), the reduction was approximately 8.6%, while at 20% replacement (M4), the reduction reached nearly 37% relative to the control mix.

The decrease in compressive strength is primarily due to:

- Weak interfacial transition zone (ITZ) between rubber particles and cement paste
- Increased entrapped air content
- Lower stiffness and elastic modulus of rubber compared to mineral aggregates

However, mixes up to 10% replacement (M2) still achieved 29 MPa at 28 days, which may be acceptable for certain non-structural or secondary structural applications. Comparable strength reduction trends have been widely reported in crumb rubber concrete research (Li et al., 2022).

4.4 Flexural Strength

4.4.1 Flexural Behaviour (IS 516:1959)

Flexural strength was determined using prism specimens in accordance with IS 516:1959. The results are presented in Table 5.

Table-5: Flexural Behaviour

S.No	Mix	Flexural Strength (MPa)
1	M0	5.2
2	M1	4.9
3	M2	4.5
4	M3	4.1
5	M4	3.8

Flexural strength decreased progressively with crumb rubber inclusion. At 20% replacement, strength reduced by approximately 27% compared to control. The reduction mirrors compressive strength behavior due to weaker bonding and reduced stiffness.

However, crumb rubber concrete often exhibits improved ductility and crack resistance, as rubber particles help bridge microcracks and delay sudden brittle failure (Moolchandani et al., 2024). This characteristic may be advantageous in applications subjected to vibration or impact loading.

5. DISCUSSION

5.1 Interpretation of Fresh Concrete Behaviour

5.1.1 Influence of Crumb Rubber on Workability

The experimental results clearly indicate a progressive reduction in workability as crumb rubber (CR) content increases. This behavior is consistent with the physical characteristics of rubber particles, which possess an irregular geometry and hydrophobic surface that limits proper wetting by cement paste. Unlike natural sand, crumb rubber does not absorb water or contribute to internal lubrication, resulting in reduced flowability and higher resistance to compaction. From a practical standpoint, the observed slump values remain within acceptable limits for medium-workability concrete as per Indian practice, but additional plasticizer dosage may be required at higher replacement levels to maintain placement efficiency. Similar observations have been reported in rubberized concrete research, where slump reductions of 10–30% were associated with increasing rubber content due to particle morphology and surface chemistry (Li et al., 2022).

5.2 Hardened Concrete Characteristics

5.2.1 Density Reduction and Lightweight Behaviour

The decrease in density with increasing crumb rubber replacement reflects the intrinsic material properties of rubber, whose specific gravity is significantly lower than that

of mineral aggregates. The gradual drop in unit weight indicates that crumb rubber concrete transitions toward a semi-lightweight material at higher replacement percentages. This reduction can be beneficial in applications where dead load minimization is desirable, such as non-load-bearing panels or architectural components. However, lower density also correlates with increased entrapped air and reduced packing efficiency, which influence strength development. Comparable density reductions have been documented in experimental investigations, reinforcing that rubber inclusion systematically lowers the mass per unit volume of concrete while preserving structural integrity at modest replacement levels (Moolchandani et al., 2024).

5.3 Mechanical Performance

5.3.1 Strength Reduction and Interfacial Bonding Mechanism

Compressive and flexural strength reductions observed in this study are primarily linked to the weak interfacial transition zone (ITZ) between crumb rubber particles and the cement matrix. Rubber is elastic and chemically inert compared to mineral aggregates, leading to poor adhesion and stress transfer. Under loading, these weak interfaces become sites for microcrack initiation, resulting in reduced load-bearing capacity. Additionally, the inclusion of rubber increases void content and lowers stiffness, further contributing to strength loss. Despite this reduction, strength gain with curing age follows normal hydration trends, indicating that cementitious reactions remain unaffected. These mechanisms align with established findings in rubberized concrete literature, where interfacial bonding and elastic mismatch are identified as the dominant causes of strength decline (Li et al., 2022).

5.4 Optimum Replacement Range

5.4.1 Performance Balance at Lower Replacement Levels

A critical observation from the results is that mixes containing 5–10% crumb rubber demonstrate a favorable balance between mechanical performance and material sustainability. At these levels, reductions in strength and workability remain moderate while density benefits become noticeable. Such mixes may be suitable for secondary structural elements, pavement layers, vibration-resistant components, or architectural applications where enhanced ductility and energy absorption are advantageous. Beyond 15–20% replacement, strength degradation becomes more pronounced, limiting structural applicability. This threshold behavior closely matches trends reported in prior investigations, which identify low replacement levels as the practical optimum for maintaining engineering performance while achieving environmental benefits (Moolchandani et al., 2024).

5.5 Comparison with Published Research

5.5.1 Alignment with Literature Trends

The experimental trends observed — decreasing workability, reduced density, and gradual strength loss with increasing crumb rubber content — are consistent with the broader body of rubberized concrete research. Published studies consistently demonstrate that crumb rubber inclusion alters fresh and hardened concrete behavior due to its low stiffness, hydrophobicity, and poor interfacial bonding. Importantly, many researchers emphasize that controlled replacement levels can produce concrete with acceptable performance and improved ductility, supporting its role in sustainable construction. The agreement between present findings and existing literature strengthens the reliability of the experimental observations and confirms that crumb rubber concrete behaves predictably within established material science frameworks (Li et al., 2022; Moolchandani et al., 2024).

6. CONCLUSION

This study evaluated the performance of concrete incorporating crumb rubber as a partial replacement for natural fine aggregate at levels ranging from 5% to 20%. Experimental results demonstrate that crumb rubber significantly influences both fresh and hardened concrete properties. Workability showed a gradual reduction with increasing rubber content, primarily due to the hydrophobic nature and irregular particle geometry of crumb rubber, which reduce internal lubrication within the mix. Density decreased consistently as replacement levels increased, indicating the production of lighter concrete that may be advantageous for applications where reduced dead load is beneficial.

Mechanical performance revealed a proportional decline in compressive and flexural strength with increasing crumb rubber content, attributed to weak interfacial bonding and increased void formation. However, mixes containing 5–10% crumb rubber retained strength values close to the target design requirements, suggesting their suitability for non-structural and semi-structural applications. Strength development with curing age remained consistent, confirming that cement hydration was not adversely affected.

The findings indicate that controlled incorporation of crumb rubber can produce environmentally sustainable concrete with acceptable engineering performance. The study supports the practical feasibility of low-level crumb rubber replacement as a strategy for waste tire utilization while maintaining functional concrete properties.

6.1. Limitations of the Study

This research is limited to evaluating mechanical and fresh concrete properties under controlled laboratory conditions and does not fully represent long-term field performance. Durability aspects such as freeze–thaw resistance, chemical attack, shrinkage, creep, and fatigue behavior were not extensively investigated. The study also focused on untreated crumb rubber, whereas surface-modified rubber may improve bonding and performance. Only a single concrete grade and fixed water–cement ratio were examined, which restricts broader generalization of results. Variability in crumb rubber particle size distribution and source characteristics may also influence outcomes. Additionally, economic feasibility and large-scale production challenges were beyond the scope of this work. Future research should incorporate durability studies, treatment methods, and life-cycle assessment to validate practical implementation.

REFERENCES

1. Das, S.K., Shiuly, A. and Mahato, S.K., 2025. Sustainable concrete innovation: crumb rubber as a partial fine aggregate replacement. *Journal of Materials and Engineering Structures*, 12(2), pp.xx-xx.
2. Dhupal, C.H., Keskar, S.S., Aiwale, K.A., Lawate, P.H. and Gawade, R.S., 2025. Replacement of fine aggregate with crumb rubber. *International Journal for Research in Applied Science and Engineering Technology*, pp.xx-xx.
3. Indian Standards Institution, 1959a. IS 1199:1959 — Methods of Sampling and Analysis of Concrete. New Delhi: Bureau of Indian Standards.
4. Indian Standards Institution, 1959b. IS 516:1959 — Method of Tests for Strength of Concrete. New Delhi: Bureau of Indian Standards.
5. Indian Standards Institution, 1963. IS 2386 (Part III):1963 — Methods of Test for Aggregates for Concrete. New Delhi: Bureau of Indian Standards.
6. Indian Standards Institution, 1999. IS 9103:1999 — Specification for Concrete Admixtures. New Delhi: Bureau of Indian Standards.
7. Indian Standards Institution, 2000. IS 456:2000 — Plain and Reinforced Concrete — Code of Practice. New Delhi: Bureau of Indian Standards.
8. Indian Standards Institution, 2019. IS 10262:2019 — Concrete Mix Proportioning — Guidelines. New Delhi: Bureau of Indian Standards.
9. Khan, M.M., Sharma, A. and Panchal, S., 2017. Use of crumb rubber as replacement over aggregate in concrete. *International Journal of Civil Engineering and Technology*, 8(2), pp.148–152.
10. Li, Y., Zhang, S. and Du, Y., 2022. Crumb rubber as partial replacement of fine aggregate in concrete: A review. *Construction and Building Materials*, 343, 128049.
11. Moolchandani, K., Sharma, A. and Kishan, D., 2024. Enhancing concrete performance with crumb rubber and waste materials: A study on mechanical and durability properties. *Buildings*, 14(1), 161.
12. Azunna, S.U., et al., 2023. Implementation of crumb rubber in construction materials: A comprehensive review. *Infrastructures*, pp.xx-xx.
13. Batayneh, M., Marie, I. and Asi, I., 2008. Use of crumb rubber to improve fatigue resistance of concrete. *Construction and Building Materials*, 22(5), pp.875–882.
14. Corinaldesi, V., Moriconi, G., and Cosenza, E., 2011. Mechanical and durability properties of concretes containing shredded rubber tire. *Construction and Building Materials*, 25(6), pp.2981–2988.
15. Oikonomou, N., 2005. Use of waste tire rubber particles in concrete. *Cement and Concrete Composites*, 27(2), pp.158–169.
16. Ganjian, E., Mobasher, B. and Maghsoudi, A., 2009. Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Construction and Building Materials*, 23(5), pp.1828–1836.
17. Aiello, M.A. and Leuzzi, F., 2010. Influence of recycled tire rubber on mechanical properties of concrete. *Journal of Clean Production*, 19(2011), pp.2045–2053.
18. Huang, B., et al., 2004. Properties of rubberized concrete containing polyester fiber. *Cement and Concrete Research*, 34(1), pp. 97–102.
19. Neville, A.M., 1995. *Properties of Concrete*. 4th ed. Harlow: Longman Scientific & Technical (cited in rubber concrete reviews).
20. Sicakova, A., et al., 2017. Evaluation of crumb rubber concrete after thermal loading. *Construction and Building Materials*, 137(2017), pp.381–393.
21. Mohammadi, J., et al., 2014. Fatigue life assessment of rubberized concrete with crude rubber aggregates. *Materials and Design*, 53, pp.456–464.
22. Saberian, M., et al., 2019. Thermal effects on mechanical properties of crumb rubber concrete. *Journal of Materials in Civil Engineering*, 31(7), 04019188.

23. Li, Y., Zhang, S. and Du, Y., 2022. Crumb rubber as partial replacement for fine aggregate in concrete: An overview. *Construction and Building Materials*, 343, p.128049.
24. Fadiel, A., et al., 2023. Review on the characteristic properties of crumb rubber concrete. *Materials Today: Proceedings*, 2023.
25. Moolchandani, K., Sharma, A. and Kishan, D., 2024. Enhancing concrete performance with crumb rubber and waste materials: mechanical and durability properties. *Buildings*, 14(1), p.161.
26. Abd-Elaal, S.K., 2019. Effect of thermal treatment on crumb rubber concrete strength properties. *Journal of Sustainable Construction Materials*, 2019.
27. Agrawal, R., 2023. Effect of rubber crumb treatments on concrete mechanical properties. *Journal of Advanced Concrete Research*.
28. Youssf, O., et al., 2016. Effect of chemical pre-treatment on crumb rubber concrete behaviour. *Construction and Building Materials*, 2016.
29. Emam, K. and Yehia, S., 2018. Carbon disulfide treated rubber mortar performance. *Journal of Materials Science*, 2018.
30. Pham, et al., 2018. Styrene-butadiene copolymer treated crumb rubber mortar properties. *Cement and Concrete Composites*, 2018.
31. Al-Tayeb, T., et al., 2017. Microstructural study of crumb rubber concrete. *Material Characterization*, 130, pp.460–470.
32. Wang, et al., 2017. Mechanical performance of crumb rubber concrete with 10-40% rubber. *Cement and Concrete Composites*, 78, pp.215–224.
33. Oikonomou, N. and Mauridou, A., 2005. Workability of rubber aggregate concrete. *Materials and Structures*, 38(5), pp.480–486.
34. Saberian, M., et al., 2019. Effect of ageing on crumb rubber concrete properties. *Journal of Materials in Civil Engineering*, 31(3), 04019029.
35. Yasser, et al., 2023. Effect of rubber aggregate size on compressive strength of concrete. *Journal of Concrete Technology*, 2023.
36. MDPI Materials study (2019). Rubber treated concrete durability investigation. *Materials*, 12(13), 2019.
37. Evaluation of mechanical and durability properties of recycled aggregate concrete with crumb rubber — *Materials*, 15(5), 2022.