Enhancing Concrete Performance with Crumb Rubber and Waste Materials: A Study on Mechanical and Durability Properties

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Abstract: In addressing the dual challenges of sustainable waste management and environmental conservation in the construction industry, particularly the disposal of waste tire crumb rubber (CR) and the demand for eco-friendly building materials, this study explores a novel solution. It examines the sustainable incorporation of waste tire crumb rubber and mineral additions—namely silica fume (SF), marble slurry powder (MSP), and fly ash (FA)—as partial substitutes for natural fine aggregates and cement in concrete. Through comprehensive testing of seventeen concrete samples, the study reveals that the specific mix of R10S5M10F15 that contained 10% crumb rubber as replacement of fine aggregates, and 5% silica fume, 10% marble slurry powder and 15% fly ash as replacements of cement, not only achieves compressive and split tensile strength comparable to the control mix, while the 90 days flexural strength was improved by 4.48%; credited to SF’s pozzolanic action and the filler effects of MSP and FA, but also that the inclusion of CR, while reducing compressive strength due to material variations, enhances ductility and improves resistance to sulfate and acid attacks, despite increasing water absorption. The primary goal of this research is to investigate the feasibility and effectiveness of using waste materials in concrete to foster more sustainable construction practices. The objectives include a detailed assessment of the mechanical properties and durability of concrete incorporating these waste materials, aiming to determine the optimal mix proportions for their effective utilization. This study’s novelty lies in its detailed analysis of the synergistic effects of combining CR, SF, MSP, and FA in concrete, contributing to the field by offering a sustainable alternative approach to traditional concrete formulations and highlighting the delicate balance required for optimized concrete performance.

Keywords: rubberized concrete; crumb rubber; mineral additions; sustainable construction; waste material utilization; eco-friendly concrete

1. Introduction

As urbanization has increased globally, concrete, a ubiquitous material in construction, is utilized in significant quantities annually [1]. However, the production of concrete has a significant environmental impact as a result of the high energy consumption and the emission of greenhouse gases associated with cement manufacturing [2,3]. Cement production contributes significantly to carbon emissions. The process involves subjecting limestone and other raw materials to high temperatures resulting in the release of carbon dioxide (CO₂) as a byproduct [4]. Roughly 0.9 tonnes of CO₂ are released into the atmosphere for every tonne of cement produced [5]. According to the International Energy Agency [6] the cement industry is responsible for 7% of CO₂ emissions. Consequently, there is an increasing interest in developing eco-friendly concrete by incorporating waste materials from various industrial sectors.

To reduce the environmental impact of concrete, various strategies have been proposed, such as the utilization of alternative materials during the manufacturing of cement, making cement production processes more efficient, minimizing the transportation of raw materials...
and finished products, and embracing sustainable construction practices that prioritize energy conservation [7,8].

Sustainable concrete development involves using environmentally friendly and socially responsible methods to make and utilize concrete. The goal is to reduce the environmental impact of concrete manufacturing, optimize natural resource use, and boost its social and economic benefits. Using recycled aggregates and additional cementitious ingredients, optimizing manufacturing techniques to reduce waste and energy consumption, and designing concrete buildings to improve durability and resilience can achieve the goal. Sustainable growth in the concrete sector is crucial for the building industry’s existence and environmental protection. This approach aligns with the findings of recent studies, which emphasize the use of recycled materials like bone china ceramic waste powder and stone cutting waste in self-compacting concrete, demonstrating both environmental and economic advantages [9,10] contributing to waste reduction and environmental sustainability.

Keeping the above in view, this study envisaged to prepare the concrete by partially replacing cement and fine aggregates with some alternative materials. The admixture materials chosen for the present study are crumb rubber (CR), silica fume (SF), marble slurry powder (MSP), and fly ash (FA).

The rapid growth in the automotive sector has resulted in an increased demand for passenger vehicles, and thus an increased use of tires, and thus there is a significant amount of tire waste that needs to be disposed of [11]. In India, around 1.5 million tons of end-of-life tires (ELT) are generated per annum out of which only 450,000 tons is recycled [12]. These ELT can be crushed and used as construction materials [13]. Two significant benefits come from adding waste rubber particles to concrete: it is a viable way to combat the overuse of natural resources, and it recycles waste tires for long-term sustainability [14]. This crushed crumb rubber has a particle size ranging from 0.1 mm to 4.76 mm, which makes it suitable for replacing typical fine aggregates in concrete [15]. The workability of rubberized concrete diminishes as the quantity of CR (crumb rubber) and particle size rise. Nevertheless, the quality of the material may be enhanced by using additives such as superplasticizers, silica fume, and supplementary cementitious materials such fly ash, slag, and metakaolin [16]. Rubber concrete absorbs more water than typical concrete because it has pores and capillaries. The rubber component gradually boosts concrete absorption and permeability. Increased rubber particle size lowers concrete impermeability [17].

The processing waste from the cutting and polishing of marble comes out in the form of a slurry. When this slurry dries, it is known as marble slurry powder (MSP). MSP contains fine material and can help fill voids between other larger particles in the mix, leading to improved particle packing. MSP can also enhance lubrication within the mix and contribute to better workability [18–21]. It is also interesting to note that MSP can exhibit effects similar to pozzolanic materials like FA at ordinary temperatures. Hence, in the presence of moisture, MSP can react with calcium hydroxide produced during cement hydration, resulting in the formation of cementitious material with long-term strength. Thus, it can be safely interpreted that MSP requires low water demand and exhibits better workability.

Fly ash is produced by the combustion of pulverized coal in power plants. FA is a pozzolanic substance. These substances combine with lime to generate hydrates. Tiny and spherical granules of FA help in the particle packing of concrete and its lubrication, thereby improving the cohesion and workability of the concrete mix [22–25]. The large surface area of fine FA particles also interacts with cement hydration byproducts to save water consumption and enhance workability [26–31]. Fine FA also helps in reducing the bleeding and segregation to prepare a fresh homogeneous concrete.

Silica fume (SF), or microsilica, is an ultrafine powder composed of spherical particles that are a byproduct of the manufacturing of silicon and ferrosilicon alloys. High pozzolanic reactivity in SF increases concrete compressive strength, lime-consuming activity, narrow pore size distribution, and reduced heat release [32].
Further, it may be noted that all the undertaken materials are wastes, environmentally friendly, and their disposal is always a concern to their respective authorities [18,22,23]. Thus, their usage as a replacement to cement and fine aggregate will provide a concrete mix with better strength and workability.

The innovative aspect of this investigation lies in its approach to integrating waste tire crumb rubber (CR) and specific mineral additions—namely silica fume (SF), marble slurry powder (MSP), and fly ash (FA)—into concrete, to enhance sustainability in construction practices. This research goes beyond traditional usage by meticulously analyzing the synergistic effects of these materials when combined in concrete, offering insights into alternative sustainable building materials. The methodology employed involves a systematic evaluation of seventeen distinct concrete mixes, with varying proportions of CR, SF, MSP, and FA. Each mix was carefully designed to understand the impact of these additions on the mechanical properties and durability of concrete. The study’s approach included comprehensive testing for compressive, flexural, and tensile strength, as well as assessments of water absorption and resistance to environmental degradation such as sulfate and acid attacks. This methodology not only provides a quantitative analysis of the performance of these innovative concrete mixes but also helps in identifying the optimal combination of materials to achieve a balance between environmental sustainability and the maintenance of key structural properties. Through this approach, the study aims to contribute to the field of sustainable construction, presenting a novel, eco-friendly solution to the challenges of waste management and material sustainability in the construction industry.

2. Materials, Equipment, and Mix Proportioning

2.1. Materials

For this research we utilized Ordinary Portland Cement (OPC) 43 grade, as the binding material. The OPC obtained from M/s Ultratech Cement Limited, Bhopal, India, was in accordance with the BIS 269 [33] standards. To conduct the study, we sourced natural sand granules from the Narmada River. Additionally, we acquired crushed basalt rock of sizes 10 mm and 20 mm from Dhakad Traders also located in Bhopal, India. The fine aggregate falls under Zone II categorization and both the fine and coarse aggregates have been found to meet the requirements set by BIS 383 [34].

A sample of wet marble slurry powder (MSP) (Figure 1b) was collected from a local stone-cutting facility, M/s Taj Stone Company, Bhopal, India. The MSP obtained was first dried under the sunlight and sieved through 75 µm. Fly ash (FA) was obtained from the thermal power plant M/s Sarni Thermal Power Plant, Sarni, India. As per the BIS 3812 [35], 82% of the weight of the FA sample was finer than 45 µm.

Crumb rubber (CR) was obtained from a local tire processing and remolding unit, M/s Sai Tires, Bhopal, India. CR was free from metallic contaminants and had a rough surface texture with an irregular shape.

Silica fume (SF) was obtained from local wholesaler and manufacturer M/s Metro Chemicals, Bhopal, India. SF was found to be complying with BIS 15388:2003 [36] and ASTM C1240-20 [37] as 99.2% of the sample was finer than 45 µm in size.

For preparation of the concrete mix, municipal tap water (pH = 7) and polycarboxylate ether (PCE) based Superplasticizer SikaPlast-5202 NS (pH ≥ 6) [38] were used.

Physical appearances of MSP, FA, SF, and CR can be observed in Figure 1.

2.2. Equipment

To determine various physical parameters of the OPC and other materials, instruments manufactured by M/s Zeal International (New Delhi, India) were used. The specific gravity was calculated using the Le Chatelier flask. The standard consistency, beginning setting time, and final setting time were obtained using Vicat’s apparatus. The soundness was assessed using the Le Chatelier apparatus [39–42]. For the characterization of materials—OPC, Sand, MSP, FA, SF and CR, X-Ray Diffractometer AXS D2 Phaser (M/s Bruker Corp., Billerica, MA, USA) with CuKα radiation of wavelength 1.54 Å at 10°–110° scanning range
was used. The Slump Cone Apparatus, manufactured by M/s Zeal International, was employed to assess the workability of newly mixed concrete. Tests on cube and cylindrical specimens were conducted using a Compression Testing Machine (M/s Enkay Enterprises, New Delhi, India) with 2000 kN of capacity while beam specimens were tested using 100 kN capacity flexural strength testing machine.

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2.3. Mix-Proportioning

The standard concrete mix, designated as ‘R0S0M0F0’, was prepared in accordance with BIS 456-2000 [43] specifications to achieve a minimum compressive strength of 30 MPa. Figure 2 shows the overview of conventional and modified concrete mix ingredients. The conventional mix consisted of Ordinary Portland Cement (OPC), water, and coarse and fine aggregates in specified proportions. The coarse aggregate, comprising 20 mm and 10 mm sizes, was used in a 60:40 ratio. Following standard procedures, the aggregates were first mixed dry, followed by the addition of OPC and water to achieve the desired consistency.

Figure 1. Different replacement materials used in the present study.

(a) Marble Slurry Powder  (b) Fly Ash  (c) Silica Fume  (d) Crumb Rubber
For the modified concrete samples, crumb rubber (CR) and silica fume (SF) replacements were fixed at 10% and 5%, respectively, whereas the replacement levels of marble slurry powder (MSP) and fly ash (FA) varied from 5% to 15% as per the different mix designs detailed in Table 1. For instance, in mix R10S5M15F15, 10% of the fine aggregates were replaced by CR, and the cement was substituted by 5% SF, 15% MSP, and 15% FA by weight. The mixing process for these modified samples followed a similar sequence to the standard mix but included the additional step of incorporating the respective proportions of CR, SF, MSP, and FA. These materials were added to the dry mix of aggregates and cement, ensuring thorough blending before the gradual addition of water. The mixing was performed meticulously to ensure a homogeneous mix and to accurately assess the impact of the varied proportions of CR, SF, MSP, and FA on the concrete’s properties.
Table 1. Mix–proportion quantities.

<table>
<thead>
<tr>
<th>Mix Label</th>
<th>Cementitious Materials</th>
<th>Fine Aggregates</th>
<th>Coarse Aggregates</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OPC</td>
<td>Fly Ash</td>
<td>Silica Fume</td>
<td>Marble Slurry Powder</td>
</tr>
<tr>
<td></td>
<td>kg/m³</td>
<td>%</td>
<td>kg/m³</td>
<td>%</td>
</tr>
<tr>
<td>R0S0M0F0</td>
<td>540</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>R10S5M0F0</td>
<td>513</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>R10S5M0F5</td>
<td>486</td>
<td>5</td>
<td>27</td>
<td>5</td>
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<td>10</td>
<td>54</td>
<td>5</td>
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<tr>
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<td>15</td>
<td>81</td>
<td>5</td>
</tr>
<tr>
<td>R10S5M5F0</td>
<td>486</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>R10S5M5F5</td>
<td>459</td>
<td>5</td>
<td>27</td>
<td>5</td>
</tr>
<tr>
<td>R10S5M5F10</td>
<td>432</td>
<td>10</td>
<td>54</td>
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<tr>
<td>R10S5M5F15</td>
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<td>15</td>
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<td>5</td>
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<tr>
<td>R10S5M10F0</td>
<td>459</td>
<td>0</td>
<td>0</td>
<td>5</td>
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<tr>
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<td>432</td>
<td>5</td>
<td>27</td>
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<td>432</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>R10S5M15F5</td>
<td>405</td>
<td>5</td>
<td>27</td>
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<tr>
<td>R10S5M15F10</td>
<td>378</td>
<td>10</td>
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<td>5</td>
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<tr>
<td>R10S5M15F15</td>
<td>351</td>
<td>15</td>
<td>81</td>
<td>5</td>
</tr>
</tbody>
</table>

Abbreviations for Table 1: R—Rubber, S—Silica Fume, M—Marble Slurry Powder, F—Fly Ash.
3. Properties of Concrete

The characteristics of recently mixed concrete, such as its workability, and the attributes of solidified concrete blends, including mechanical and durability properties, have been assessed.

3.1. Fresh Concrete Properties

Freshly prepared concrete mix is plastic in nature and can be molded into any shape. Workability is a property of concrete in the fresh stage. The workability of concrete can be defined as the ease with which concrete can be mixed, handled, and compacted.

Workability

The workability of all the 17 freshly prepared concrete mixes was evaluated by the Slump Cone Test as per specifications of BIS 1199:1959 [44]. The parameters of the cone used were a top diameter of 10 cm, a bottom diameter of 20 cm, and a height of 30 cm. The concrete of each sample was poured into a slump cone in three layers of about equal volume. In order to prevent the trapping of air, each layer was compacted about 25 times using a typical tamping rod that was 60 cm long and had a diameter of 16 mm.

3.2. Mechanical Properties

This study involved the assessment of mechanical properties, including compressive strength, flexural strength, split tensile strength, and elastic constants, for solidified concrete of various mixes.

3.2.1. Compressive Strength

After casting, the specimens were placed in a temperature-controlled curing tank with a constant temperature of 27 ± 2 °C. The compressive strength according to BIS 516 [45] was measured at curing ages of 7, 28, and 90 days. For each mix, three 150 mm-sized cubes were used, and a 2000 kN capacity compressive testing machine (CTM) was employed to evaluate their compressive strength.

3.2.2. Split Tensile Strength

Split tensile strength is of more significance than compressive strength in structures such as concrete dams, pavements, and runways where reinforcing is absent [1]. Split tensile strength for cylindrical specimens of a size of 150 × 300 mm was determined at curing ages of 7, 28, and 90 days as per ASTM C496 [46] and BIS 5816 [47]. Each test was performed on three different specimens for each mix, and the results of the average test were presented for all 51 samples that were tested.

3.2.3. Flexural Strength

Flexural or bending strength is the ability of a material to resist applied vertical forces on its longitudinal axis [48]. The test for the flexural strength of concrete was carried out as per BIS 516 [41] and ASTM C78 [49]. Beam specimens of a size of 500 × 100 × 100 mm (length × width × height) were used after curing for 7, 28 and 90 days. A three-point loading setup was used to perform the test. Three specimens per mix were tested and their average value was evaluated.

3.3. Durability Properties

Durability properties such as water absorption, sorptivity, sulfate attack and acid attack have been evaluated for hardened concrete mixes.

3.3.1. Water Absorption

Water absorption in concrete relates to total open porosity, and it is influenced by pore size distribution. The test evaluates capillary water rise, which is inversely proportional to
pore diameter. Smaller pores absorb water more quickly. In summary, absorption refers to a material’s water-holding capacity, while capillarity measures the rate of water penetration.

The water absorption test for concrete cube specimens was conducted according to ASTM C642-06 [50]. At first, the specimens were fully immersed with water for complete saturation. Afterwards, every fully soaked cube was placed inside an oven that was adjusted to a precise temperature of 105 °C for a drying period of 24 h. Subsequently, the specimens were cooled in a dry air atmosphere, and their initial weights (W1) were documented. Subsequently, the cubes were submerged in water, ensuring that there was a consistent water level of approximately 50 mm over their top surfaces. Following a 48 h period of complete submersion, the specimens were extracted from the water and given 1 min to drain, after which their ultimate weights (W2) were measured.

The water absorption percentage was determined by dividing the difference between the weight of the specimen after immersion (W2) and the weight of the oven-dried specimen (W1) by the weight of the oven-dried specimen, and then multiplying the result by 100%. The Expression (1) for water absorption is given as follows:

\[
\text{Water absorption(\%)} = \left( \frac{(W_2 - W_1)}{W_1} \right) \times 100\% \tag{1}
\]

3.3.2. Sulfate Attack

A sulfate attack involves a series of chemical interactions between sulfate ions and the constituents of hardened concrete, potentially leading to issues such as concrete cracking, spalling, or a reduction in structural strength.

The ASTM C1012 [51] standard test is designed to evaluate the expansion of mortar prisms submerged in a sodium sulfate solution and mandates that the expansion remains within a specific limit. This test primarily focuses on the ettringite form of sulfate attack. However, it is worth noting that the ASTM C1012 test, which takes between 6 months and 1 year to complete, has limitations.

Bucea et al. [52] argued that the expansion alone might not always indicate specimen failure, as instances of low expansion could still be associated with signs of crumbling, suggesting early failures. Therefore, they proposed that a reduction in strength could be a more suitable parameter for assessing sulfate resistance. Mehta and Gjorv [53] introduced an accelerated test method using strength loss as the key indicator of sulfate resistance. The formation of cracks due to ettringite or gypsum and the expansion of ettringite, along with the loss of C-S-H, adversely impact compressive strength. As such, when evaluating damage incurred during sulfate exposure, both external and internal forms of sulfate attack are considered when using loss in strength as a measure [54].

Therefore, in this study, to evaluate concrete’s resistance to sulfate attack, a test was conducted using sodium sulfate (Na₂SO₄). This test entails dissolving 150 g of sodium sulfate per liter of water, and concrete cubes are immersed in this solution for a period of 90 days. The residual compressive strength of these cubes is then assessed, serving as a crucial indicator of their ability to withstand sulfate attack and maintain their structural integrity.

3.3.3. Acid Attack

The acid attack test, following ASTM C 267-97 [55], was carried out over a 90 day period to assess the chemical resistance of concrete under anticipated service conditions. This test utilized a 3% sulfuric acid solution to estimate the concrete’s resistance to acidity. To begin, oven-dried concrete cubes were weighed and then completely immersed in the sulfuric acid (H₂SO₄) solution. The change in weight was subsequently compared to the initial measurement. Additionally, the compressive strength of the acid-cured specimens was determined using CTM, in accordance with IS: 516 [45] standards. The results obtained were then compared to the compressive strength of concrete cubes cured with water for 90 days.
4. Results and Discussion

The results obtained for different tests performed are as follows:

4.1. Properties and Characterization of Materials

The standard consistency, initial setting time, final setting time, and soundness of OPC are determined 29%, 126 min, 240 min, and 1 mm, respectively. Physical specifications of materials used are shown in Table 2 and chemical composition are shown in Table 3.

Table 2. Physical specifications of materials used.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>OPC</th>
<th>MSP</th>
<th>FA</th>
<th>SF</th>
<th>CR</th>
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</thead>
<tbody>
<tr>
<td>Form</td>
<td>Powder</td>
<td>Powder</td>
<td>Powder</td>
<td>Powder</td>
<td>Granules</td>
</tr>
<tr>
<td>Grain Size (µm)</td>
<td>100% &lt; 90 µm</td>
<td>92% &lt; 75 µm</td>
<td>82% &lt; 45 µm</td>
<td>100% &lt; 600 µm</td>
<td>75–4750 µm</td>
</tr>
<tr>
<td>Colour</td>
<td>Dark Grey</td>
<td>Off-white</td>
<td>Light Grey</td>
<td>Grey</td>
<td>Black</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>3.16</td>
<td>2.7</td>
<td>2.45</td>
<td>2.23</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Table 3. Chemical composition of materials used.

<table>
<thead>
<tr>
<th>Compounds</th>
<th>OPC</th>
<th>MSP</th>
<th>FA</th>
<th>SF</th>
<th>CR</th>
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</thead>
<tbody>
<tr>
<td>SiO₂ (%)</td>
<td>30.59</td>
<td>6.11</td>
<td>55.94</td>
<td>94.83</td>
<td>2.19</td>
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<tr>
<td>CaO (%)</td>
<td>48.24</td>
<td>45.86</td>
<td>2.90</td>
<td>0.91</td>
<td>17.21</td>
</tr>
<tr>
<td>Al₂O₃ (%)</td>
<td>3.65</td>
<td>0.94</td>
<td>23.81</td>
<td>0.65</td>
<td>-</td>
</tr>
<tr>
<td>Fe₂O₃ (%)</td>
<td>3.49</td>
<td>0.80</td>
<td>6.10</td>
<td>0.74</td>
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<tr>
<td>K₂O (%)</td>
<td>0.61</td>
<td>0.24</td>
<td>1.02</td>
<td>0.41</td>
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<tr>
<td>MgO (%)</td>
<td>0.89</td>
<td>6.59</td>
<td>1.34</td>
<td>0.70</td>
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</tr>
<tr>
<td>Na₂O (%)</td>
<td>0.05</td>
<td>-</td>
<td>0.60</td>
<td>0.15</td>
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<tr>
<td>P₂O₅ (%)</td>
<td>0.21</td>
<td>0.09</td>
<td>0.38</td>
<td>0.48</td>
<td>-</td>
</tr>
<tr>
<td>ZnO (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>55.68</td>
</tr>
<tr>
<td>TiO₂ (%)</td>
<td>0.34</td>
<td>0.08</td>
<td>1.52</td>
<td>0.12</td>
<td>0.50</td>
</tr>
<tr>
<td>MnO (%)</td>
<td>0.09</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
<td>-</td>
</tr>
<tr>
<td>Loss on Ignition (%)</td>
<td>3.10</td>
<td>36.25</td>
<td>0.47</td>
<td>0.51</td>
<td>4.5</td>
</tr>
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</table>

The X-ray diffractograms for the OPC, CR, SF, MSP, and FA are exhibited in Figure 3 and explain the chemical compositions of these materials. In the case of OPC (Figure 3a) the characteristic diffractogram peaks at exhibited 2θ values 32.2458, 32.26, 34.3896, 29.4981, 11.6767, 29.4749, 41.3269, 51.7227, 56.5767, 60.015, 62.4421 representing peak 1, indicating the presence of alite (Ca₃SiO₅); peaks 2 at 12.2025, 32.3469, 38.819, 47.3136 for belite (Ca₂SiO₄); peaks 3 at 20.7578, 32.9941, 46.99, 59.9341, 66.7298 for C₃A (Ca₃Al₂O₆); peaks 4 at 34.511, 41.1853 for C₄AF (Ca₄Al₂Fe₂O₁₀); and peaks 5 at 14.9329, 22.9826 for gypsum (CaSO₄·2H₂O). The results clearly indicate presence of prominent amounts of oxides of lime, silica and alumina and corroborate with earlier studies [56,57].

In the XRD of river sand (Figure 3b), peaks 1 denoting quartz (SiO₂) are obtained at 2θ values 21.1667, 26.9511, 28.1646, 50.4124, 55.1451, 60.2419; as major crystalline material. Crystalline silicate phases may help concrete produce calcium silicate hydrate (CSH) gel or calcium aluminum silicate hydrate (CASH). The presence of quartz and mica corroborates with other studies [58].

XRD analysis of CR (Figure 3c) suggested presence of calcite (CaCO₃) from peaks 1 obtained at 2θ values 20.0745, 21.0859, 23.2386, 27.5825, 31.6204, 32.8428, 42.1417, 51.7826, 57.9927, 69.2793; and zinc oxide (ZnO) from peaks 2 obtained at 2θ values 30.4478, 35.0541, 37.5693, 39.7619, 48.3752, 60.915. Zn-based chemicals are likely linked to tire de-molding agents added during manufacturing and processing phase [59]. The diffractogram also shows amorphous components of tire carbon black as corroborated by others [60].
XRD analysis of CR (Figure 3c) suggested presence of calcite (CaCO₃), obtained at 2θ values 20.0745, 21.0859, 23.2386, 27.5825, 31.6204, 32.8428, 42.1417, 51.7826, 57.9927, 69.2793; and zinc oxide (ZnO), obtained at 2θ values 30.4478, 35.0541, 37.5693, 39.7619, 48.3752, 62.0915. Zn-based chemicals are likely linked to tire de-molding agents added during manufacturing and processing phase [59]. The diffractogram also shows amorphous components of tire carbon black as corroborated by others [60].

In the XRD of SF (Figure 3d), appearances of crystalline peaks obtained at 2θ values 22.0364, 24.5848, 26.8298, 30.6928, 31.7445, 35.9109, 44.5875 show the presence of quartz as the major crystalline material and rest is amorphous phase; suggesting that the main component of SF is quartz, as presented elsewhere [23].

A careful examination of XRD obtained in the case of MSP (Figure 3e) confirms the presence of components calcite (CaCO₃), dolomite (CaCO₃·MgCO₃), silica (SiO₂) and sodium acetate (CH₃COONa). The presence of calcite was ascertained on the basis of characteristic peaks obtained at 2θ values at 22.2949, 27.7962, 31.275, 35.6032, 39.7493, 47.8799, 51.3789, 68.5501; peaks 2 representing dolomite at 26.9467, 29.7783, 42.7224, 60.2173; peaks 3 at 10.807, 21.2028, 24.9444; and peak 4 at 12.5261. The majority mineral phases in MSP were calcite (CaCO₃) and dolomite (CaCO₃·MgCO₃). MSP contains small amounts of impurities, such as magnesium carbonate (MgCO₃), iron oxide (Fe₂O₃), silica (SiO₂), and other trace elements [56,61,62].

In the XRD of FA (Figure 3f), peaks denoting quartz (SiO₂) are obtained at 2θ values 21.1421, 25.7737, 31.6795, 38.9605, 41.1247, 48.9923, 52.5924, 61.087; while mullite (3Al₂O₃·2SiO₂) is shown as peaks at 2θ values 18.4521, 23.286, 25.6726, 29.6974, 36.6549, 56.0307, 62.5836. Thus, it can be deduced that predominant phases of quartz and mullite were discovered in FA. The primary constituents of FA consist of silicon and aluminum oxides, together with other metallic oxides and residual carbon, as described in other sources [56,63,64].

Figure 3. Cont.
Figure 3. XRD patterns of (a) OPC, (b) River Sand, (c) CR, (d) SF, (e) MSP and (f) FA.

In the XRD of SF (Figure 3d), appearances of crystalline peaks 1 obtained at 2θ values 22.0364, 24.5848, 26.8298, 30.6928, 31.7445, 35.9109, 44.5875 show the presence of quartz
as the major crystalline material and rest is amorphous phase; suggesting that the main component of SF is quartz, as presented elsewhere [23].

A careful examination of XRD obtained in the case of MSP (Figure 3e) confirms the presence of components calcite (CaCO₃), dolomite (CaCO₃·MgCO₃), silica (SiO₂) and sodium acetate (CH₃COONa). The presence of calcite was ascertained on the basis of characteristic peaks 1 obtained at 2θ values at 22.2949, 27.7962, 31.275, 35.6032, 39.7493, 47.8799, 51.3789, 68.5501; peaks 2 representing dolomite at 26.9467, 29.7783, 42.7224, 60.2173; peaks 3 at 10.807, 21.2028, 24.9444; and peak 4 at 12.5261. The majority mineral phases in MSP were calcite (CaCO₃) and dolomite (CaCO₃·MgCO₃). MSP contains small amounts of impurities, such as magnesium carbonate (MgCO₃), iron oxide (Fe₂O₃), silica (SiO₂), and other trace elements [36,61,62].

In the XRD of FA (Figure 3f), peaks 1 denoting quartz (SiO₂) are obtained at 2θ values 21.1421, 25.7737, 31.6795, 38.9605, 41.1247, 48.9923, 52.5924, 61.087; while mullite (3Al₂O₃·2SiO₂) is shown as peaks 2 at 2θ values 18.4521, 23.286, 25.6726, 29.6974, 36.6549, 56.0307, 62.5836. Thus, it can be deduced that predominant phases of quartz and mullite were discovered in FA. The primary constituents of FA consist of silicon and aluminum oxides, together with other metallic oxides and residual carbon, as described in other sources [36,63,64].

4.2. Fresh Concrete Properties

The workability results for freshly prepared concrete mixes are discussed as follows:

Workability

The Slump Cone Test results of all 17 samples are displayed in Figure 4. These findings assess the workability of the freshly made concrete mixes. It should be emphasized that mix ‘R0S0M0F0’ does not contain any admixtures and has the lowest level of workability compared to all the other samples. Conversely, sample ‘R10S5M15F15’, which contains the largest quantities of CR, SF, MSP, and FA, demonstrates the highest slump value and more workability compared to all the other mixes.

![Figure 4. Workability of freshly prepared mixes.](image)

The slump obtained in control mix R0S0M0F0 is 145 mm. The addition of crumb rubber into concrete decreases the workability of the mix. This can be attributed to the irregular shape and size of rubber particles that can increase friction within the mix, leading to reduced flow and increased difficulty in placement. Additionally, the water absorption
characteristics of rubber particles contribute to an increased water demand in the mix, further influencing the overall workability of the concrete. The addition of silica fume negatively affects the workability of the concrete mix. This is because SF is very fine and reactive, which leads to a significant reduction in workability. It results in a stiff, less flowable mix.

Considering the above facts in view, workability-improving admixtures were added to concrete in different proportions in order to balance the workability of mixes containing CR and SF. MSP positively influences concrete workability. This is due to the fact that the fine particles in marble slurry act as effective fillers, enhancing workability by improving particle packing. This results in a more cohesive mix, potentially reducing the water demand and contributing to the overall ease of mixing, placing, and compacting the concrete. Similarly, the addition of fly ash improves workability as FA acts as a filler and reduces the heat of hydration, which results in better workability by enhancing the flow and reducing the risk of cracking. The highest slump obtained was for mix R10S5M15F15. This can be attributed to a 30% replacement of cement by workability enhancing admixtures MSP and FA.

4.3. Mechanical Properties

The results obtained for mechanical properties, i.e., compressive strength, flexural strength and split tensile strength have been discussed as follows:

4.3.1. Compressive Strength

The values of compressive strength of the 17 mixes after curing periods of 7, 28 and 90 days are given in Figure 5.

![Figure 5. Compressive strength of mixes.](image)

During the test, the conventional concrete specimens exhibited brittle fracture, but the rubberized concrete remained resistant to brittle failure. The conventional concrete specimens had vertical fractures, whereas the rubberized specimens showed horizontal cracks.

The compressive strength findings demonstrated that the mix R10S5M10F15 exhibited near-identical compressive strength to the conventional mix (R0S0M0F0) across all curing durations. The increase in compressive strength was ascribed to the pozzolanic activity and filler impact of SF. The 90 days compressive strength test results (shown in Figure 5) showed that incorporating SF in OPC-based concrete improved compressive strength due
to SF’s filler effect and pozzolanic activity, enhancing formation of C-S-H in the cement matrix. These results align with those of Khodabakhshian et al. [2].

Initially, the incorporation of MSP (5–10%) enhanced the compressive strength of concrete mixes. However, an increased replacement of MSP (15%) resulted in a decline in compressive strength as a consequence of the diluting effect of cement and lower binder concentration. The increased compressive strength observed with up to 10% MSP substitution was linked to pore-filling action, corroborated by Tennich et al. [65] and Khodabakhshian et al. [2]. MSP served as a catalyst, enhancing the hydration process of OPC. The addition of FA initially decreased compressive strength due to slower hydration, but the combined use of SF, MSP, and FA, along with CR at replacement levels of 5%, 10%, 15%, and 10% (referred to as mix R10S5M10F15), yielded a near-identical compressive strength to the control specimen R0S0M0F0. This enhancement was attributed to MSP’s pore-filling accomplishment and FA’s pozzolanic effect.

A general decrease in compressive strength is observed in rubberized concrete mixes as compared to the control concrete. In their study, Ganjian et al. [66] identified key factors contributing to the decline in compressive strength in rubberized concrete. First, the presence of rubber particles in the cement paste creates a softer matrix, leading to rapid crack development around rubber particles during loading and subsequent premature failure of specimens. Second, insufficient bonding between rubber particles and the cement paste, compared to the bond between cement paste and natural aggregates, results in non-uniform stress distribution and crack formation.

4.3.2. Flexural Strength

Figure 6 shows the variations in flexural tensile strength of different mixes for curing ages 7, 28 and 90 days.

The results showed improved 90 days flexural strength of R10S5M10F15 by 4.48% compared to the control mix R0S0M0F0. It was noted that the control specimens had brittle failure and fractured into two separate pieces when subjected to loading. In contrast, the rubberized concrete did not display brittle failure when subjected to flexural tensile stress. Fly ash (FA) serves as an addition in cement to improve the mechanical characteristics of concrete. Its pozzolanic nature contributes to increased strength during extended curing...
periods but may lead to decreased early age strengths [67]. Substituting higher percentages of cement with mineral admixture MSP at each curing stage resulted in a reduction in flexural tensile strength due to diminished binder content. However, the synergistic utilization of SF, MSP, and FA created a compact paste medium within the concrete, thereby enhancing flexural strength. The result findings corroborated with previous studies [22,65].

4.3.3. Split Tensile Strength

Figure 7 shows the variations in flexural tensile strength of different mixes observed at 7, 28 and 90 days.

The addition of rubber caused a reduction in the tensile strength of concrete. The decrease in strength mostly stems from the insufficient adhesion between the rubber particles and the cement paste. The replacement of 5% silica fume resulted in an improvement in split tensile strength. The addition of SF enhanced the adhesive properties of the binder material, resulting in the rise in split tensile strength.

The split tensile strength was further enhanced by substituting 10% of cement with MSP. Furthermore, increasing the substitution of cement with MSP (15% of the total cement) leads to a reduction in split tensile strength. Nevertheless, the additional replacement of cement with FA led to a reduction in split tensile strength. This might be attributed to the spherical morphology of the FA particles.

4.4. Durability Properties

The results for water absorption, sulfate attack, and acid attack are discussed below:

4.4.1. Water Absorption

The weight of oven-dried specimen is taken as W1 and the weight after water immersion for 48 h is taken as W2. The water absorption is calculated as expressed in Equation (1). The results for different mixes are shown in Figure 8.
Through the immersion of the samples in water, the interconnected pores in the concrete mixes were filled by the ingress of water. The water absorption for the control concrete R0S0M0F0 was evaluated to be 3.53%. Rubberized concrete mixes showed relatively increased water absorption that may be attributed to the lack of internal packing of the concrete. It can be observed that with the addition of MSP and FA, the water absorption increases gradually. This can be attributed to higher water retention capacity of concrete.

Though, there is a marginal reduction in water absorption observed in R10S5M10F15 when compared to R10S5M10F10. This could be attributed to the pore refinement in the cement paste matrix facilitated by FA. The fine particles of SF were effective in occupying the available space between cement and sand particles.

### 4.4.2. Sulfate Attack

The results for residual compressive strength for concrete cubes submerged in Na$_2$SO$_4$ solution for 90 days in comparison with compressive strength before the exposure (refer to Figure 5) are given in Figure 9.

![Figure 8. Water absorption (%) of mixes.](image)

Figure 8. Water absorption (%) of mixes.

![Figure 9. Comparison of compressive strength of mixes after sulfate attack.](image)

Figure 9. Comparison of compressive strength of mixes after sulfate attack.
Concrete permeability significantly influences sulfate attack, with the extent of damage often governed by factors such as pore size, connectivity, and void distribution. Initially, sulfate ions primarily react with the aluminate phases, particularly tricalcium aluminate (C₃A), in the cement paste to form ettringite. Ettringite is a type of sulfoaluminate mineral known for its needle-shaped crystals. This formation contributes to expansion and creates voids within the concrete matrix early in sulfate exposure. Over time, or with continued exposure to sulfate ions, secondary ettringite, another form of sulfoaluminate, may continue to form, further contributing to expansion and potential cracking. Concurrently, sulfate ions can also react with calcium hydroxide (portlandite) to form gypsum. This gypsum deposition can lead to softening and mass loss of concrete, especially noticeable as a white paste on concrete surfaces and within voids. Rubber particles, when included in the concrete mix, provide some level of resistance to sulfate ingress due to their chemical resistance and hydrophobic nature, which can reduce permeability and improve the overall resilience of the concrete against sulfate attack [68].

The loss of compressive strength after 90 days sulfate attack for R0S0M0F0 was 21.83%. There was a reduced loss in compressive strength for rubberized concrete compared to the control concrete; it ranged from 18.4 to 19.8%. This can be attributed to the crumb rubber in rubberized concrete that prevents constituent particles from breaking away by impeding crack formation and material separation. In contrast, control concrete experiences increased crack formation, leading to easy separation of constituent materials. Additionally, the refined pore structure facilitated by SF and improved grain interlocking through the filler effect of FA and MSP contributed to this effect.

4.4.3. Acid Attack

The results for variation in weight due to acid attack for concrete cubes submerged in 3% sulfuric acid solution for 90 days are given in Figure 10.

Figure 10. Variation in weight due to acid attack for concrete cubes.

A discernible trend is noticeable in the weight variation of specimens submerged in a 3% sulfuric acid solution. The decrease in weight can be ascribed to the concrete deterioration process in these mixtures induced by acid attack.

Acid attack completely deteriorated all six surfaces of the control specimen. Conversely, in rubberized concrete, all six surfaces were impacted by acid, but the deterioration
of the top surface layer was less than 100%. Also, the crack formation in rubberized concrete mixes were less compared to R0S0M0F0.

Furthermore, the comparison of residual compressive strength after 90 days acid attack was performed with the compressive strength of 90 days water cured concrete specimens (Refer Figure 5). It has been shown in Figure 11.

Figure 11. Comparison of compressive strength of mixes after acid attack.

The loss of compressive strength after 90 days acid attack for R0S0M0F0 was 21%. The maximum reduced loss in compressive strength for rubberized concrete was found to be 26.31% for the mix R10S5M15F15.

The presence of crumb rubber particles effectively prevented the constituent particles of concrete from separating by securely binding them together. Consequently, concrete with a balanced proportion of CR, SF, MSP, and FA exhibited increased resistance to both loss in compressive strength and weight. Replacement of more than 20% cement by MSP and FA resulted in decreased residual compressive strength.

5. Summary of Research Findings

This study presents pivotal insights into enhancing concrete properties through sustainable methods. Key findings include the improved workability of concrete when marble slurry powder (MSP) and fly ash (FA) are incorporated, with MSP enhancing particle packing and FA reducing hydration heat. Notably, the mix R10S5M10F15, integrating crumb rubber (CR), silica fume (SF), MSP, and FA, achieves comparable compressive strength to the control mix, highlighting the beneficial pozzolanic action of SF and filler effects of MSP and FA. However, the inclusion of CR reduces compressive strength, primarily due to material variability and uneven distribution.

In terms of durability, rubberized concrete exhibits increased ductility and enhanced resistance to sulfate and acid attacks, attributed to the protective role of crumb rubber and the microstructural refinement induced by SF, FA, and MSP. While the addition of rubber impacts tensile strength negatively, SF at a 5% replacement rate improves it. Water absorption in rubberized concrete is higher, yet marginally reduced in the R10S5M10F15 mix due to pore refinement. Overall, the study underscores the viability of using waste materials in concrete, offering a path toward more sustainable and resilient construction practices.

This study embarked on a comprehensive investigation into the use of various sustainable materials—crumb rubber (CR), silica fume (SF), marble slurry powder (MSP), and
fly ash (FA)—to enhance the properties of concrete. We observed that the incorporation of MSP and FA significantly improved the workability of the concrete mixtures, with MSP enhancing particle packing and FA reducing the heat of hydration. Notably, the mix labeled R10S5M10F15, which integrates CR, SF, MSP, and FA, demonstrated compressive strength comparable to the control mix, thereby affirming the effective pozzolanic action of SF and the filler effects of MSP and FA. However, the inclusion of crumb rubber tended to reduce compressive strength, primarily due to material variability and its impact on the concrete matrix.

In evaluating the durability aspects, the study revealed that rubberized concrete generally exhibited increased ductility and enhanced resistance to sulfate and acid attacks, attributed to the protective role of CR and the microstructural refinement induced by the combined use of SF, FA, and MSP. While the addition of crumb rubber generally impacted tensile strength negatively, the incorporation of 5% silica fume was found to improve it. Water absorption was higher in rubberized concrete mixes, but a marginal reduction was observed in the R10S5M10F15 mix, suggesting the beneficial effect of pore refinement. These findings emphasize the potential for using waste materials in concrete to achieve more sustainable and resilient construction practices while highlighting the importance of balanced mix design and consideration of material interactions.

6. Conclusions

This experimental study focused on incorporating waste tire crumb rubber (CR) as a partial replacement for natural fine aggregates, and silica fume (SF), marble slurry powder (MSP), and fly ash (FA) as partial substitutes for cement in cement concrete. Seventeen samples were cast with different proportions of these materials. The concrete properties, including workability, compressive strength, flexural strength, split tensile strength, water absorption, resistance to acid attack, and sulfate attack, were tested. Based on the outcomes and discussions from this study, the following conclusions can be drawn:

1. MSP improves workability by acting as fillers, enhancing particle packing, while FA enhances flow and reduces cracking risk.
2. The R10S5M10F15 mix achieves similar compressive strength to the control mix, due to the synergistic effects of SF, MSP, and FA.
3. Using rubber in place of traditional aggregates lowers compressive strength, primarily due to its physical and mechanical properties.
4. Rubberized concrete shows more ductility under load, with CR, SF, MSP, and FA collectively improving flexural tensile strength.
5. The addition of rubber lowers tensile strength, but 5% SF replacement and 10% MSP substitution improve it, while higher MSP levels and FA substitution reduce it.
6. Rubberized concrete absorbs more water than control concrete, but the R10S5M10F15 mix shows a marginal decrease due to pore refinement from FA and SF.
7. Rubberized concrete offers better resistance than control concrete, thanks to crumb rubber preventing material separation and the pore refining and grain interlocking effects of SF, FA, and MSP.
8. Rubberized concrete shows a lower loss in compressive strength after acid exposure, benefitting from crumb rubber’s protective properties and the pore structure refinement from SF, and grain interlocking from FA and MSP.

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Abbreviations
The article used the following abbreviations:

BIS Bureau of Indian Standards
CR Crumb Rubber
CTM Compression Testing Machine
FA Fly Ash
MSP Marble Slurry Powder
OPC Ordinary Portland Cement
RCC Reinforced Cement Concrete
SF Silica Fume
XRD X-ray Diffraction

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