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Research Article

Improved Workability and Strength of Rubberized Mortar Using Supplementary Cementitious Materials and Polypropylene Fibers

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Abstract: The recent past has shown that rubberized cementitious composites, despite their potential benefits such as improved ductility, impact resistance, and utilization of waste rubber, exhibit reduced workability and mechanical strength. This performance degradation is attributed to the lower density and higher elastic nature of rubber particles, which hinder compaction efforts and induce voids. Also, the hydrophobic nature of rubber particles repels water molecules and gives rise to pores. Present research focuses on improving the workability and strength of rubberized composites by using waste materials like silica fumes and fly ash and adding polypropylene fibers. A 1:4 cement-sand mortar was prepared as a control specimen. A systematic study was conducted in which the ingredients were added incrementally. First, 5% of the sand was replaced with crumb rubber. In the next group of samples, silica fume and fly ash were included as extra materials in the cement, replacing 2.5% of the cement's weight. Subsequently, a water reducer was introduced. Finally, in the last set of specimens, polypropylene fibers were added at a rate of 0.1% by volume of mortar. The results revealed that the incorporation of crumb rubber reduced the 28-day compressive strength from 8.5 MPa to 4.55 MPa, corresponding to a strength loss of 46%. The proposed modifications reduced this strength loss to only 7.4%, resulting in a 28-day compressive strength of 7.9 MPa. Similarly, the flow value increased from 80 mm to 100 mm after the incorporation of supplementary cementitious materials. It is concluded that the careful incorporation of supplementary cementitious materials and synthetic fibers can improve the mechanical strength and workability of rubberized mortar.

Keywords: Rubberized Mortar, Supplementary Cementitious Materials, Polypropylene Fibers, Workability, Strength.

1. INTRODUCTION

The rubberized cementitious composites are preferred in many situations, including sound insulation, impact resistance, shock absorption, repair and restoration, and where high flexibility is required. The drawbacks include lower workability and compressive strength, which hinder its applications in normal concrete construction. The rubberized particles are extracted from waste rubber tires. These tires are an important waste material because it is thought that rubber is not a biodegradable material, and its dumping requires space, which is already short due to population increase and urbanization [1, 2]. There is a need to recycle the waste tires so that they do not require dumping spaces for disposal. One safe method to dispose of the waste rubber tires is recycling them in building materials like mortar, concrete, bricks, and tiles [3]. Several researchers in the recent past have used rubber particles in cementitious composites.

Liu *et al.* [4] worked on rubberized concrete. The authors have reported that, with the addition of crumb rubber, the compressive strength of concrete decreased significantly. Other researchers, such as Qureshi *et al.* [5], Assaggaf *et al.* [6], and Youssf *et al.* [7], have also found that when sand is partially replaced with crumb rubber (between 5% and 25%), the compressive strength of concrete decreases, and this decrease becomes larger as more rubber is added. Similar studies are available

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about the reduction of tensile strength in concrete with the inclusion of rubber content [8]. There are numerous studies available that depict that the rubber content reduces the workability of concrete. It has been reported that the rubber particles have a rough surface and high water absorption. This discrepancy of rubber particles induces void spaces and reduces workability [9]. The past research shows that the workability and the mechanical strength of rubberized cementitious composites are reduced due to rough surface, more water absorption, and induced void content. Yet there are other situations where rubber content has positively impacted the cementitious composites. According to Khan *et al*. [10], when strength is not as important as toughness and deformability, rubberized concrete can be effectively used for road foundations and bridge barriers. Rubber-based concrete can be used to reduce vibrations in structural foundations since it has reversible elasticity. Eltayeb *et al*. [11] utilized crumb rubber as a partial replacement for sand in concrete mixtures, with substitution levels ranging from 0% to 50%. The findings indicated that rubberized concrete exhibited superior resistance to bullet impacts, blast loads, high-velocity impacts, and collisions compared to unreinforced concrete. Also, adding rubber greatly improved the ductility, energy absorption, and weakening of structural parts when they faced repeated and earthquake-related stresses. Kashani *et al*. [12] investigated the performance of lightweight cellular concrete (LCC) incorporating waste crumb rubber as a filler. In their study, the crumb rubber was pretreated with an NaOH solution to improve its interaction with the cement matrix. The findings indicated that the incorporation of crumb rubber improved the acoustic and thermal insulation characteristics of LCC while simultaneously decreasing its water absorption. Furthermore, the NaOH pretreatment improved the compressive strength of the LCC by promoting a stronger bond between the crumb rubber and cement paste, as evidenced by SEM analysis.

Previous studies [4, 5, 13] have found that rubberized cement mixtures usually have lower workability and strength but better performance in terms of dynamic, thermal, and sound insulation. Researchers primarily studied the enhancement of workability and strength by pretreating the rubber particles with a suitable alkaline solution. Although alkaline pretreatment has been reported to enhance the bond between rubber particles and the cementitious matrix and provide modest improvements in mechanical properties, the magnitude of improvement remains limited. Therefore, alternative approaches are still needed to further enhance the workability and strength of rubberized cement mixtures.The current research aims to improve the workability and strength of rubberized cement mixtures (mortar) by using industrial waste materials such as silica fumes, fly ash, polypropylene (PP) fibers, and a water reducer. The study used a step-by-step experimental method, trying out different combinations based on literature review to gradually improve the mix design while keeping scientific control. A systematic approach was adopted, and the parameters were examined by a stepwise addition/substitution for clearly watching the effect of each new addition or substitution. Mortar samples were tested for density, flowability, water absorption, and mechanical strength because these traits together determine the compaction behavior, durability, and structural viability of rubberized mortars.

2. MATERIALS AND METHODS

For this experimental investigation, a 1:4 cement–sand mortar was used as a reference material to ensure consistency and comparability in evaluating the effects of rubber incorporation and subsequent modifications. Grade 53 cement (OPC-Type I) and river sand were used as the ingredients. Recently, we have investigated the properties of rubberized cementitious mortar [14]; some of these results are used as reference materials in the present study. The characteristics of cement are presented in Table 1. The domination of CaO, together with sufficient

Table 1. Chemical composition of cement [14].

Compound	Percentage
CaO	63%
SiO_2	22%
Al_2O_3	5.5%
MgO	1.7%
SO_3	1.8%
Fe_2O_3	3.5%
Na_2O	0.2%
K_2O	1%
Loss of Ignition	0.6%

SiO_2 and Al_2O_3 contents, indicates the suitability of the cement for normal hydration and strength development. The Fe_2O_3 content falls within the typical range for ordinary Portland cement. The relatively low MgO (1.7%) and SO_3 (1.8%) contents suggest a low risk of unsoundness and appropriate control of setting time. The low alkali contents (Na_2O and K_2O) reduce the potential for alkali–silica reaction, while the very low loss on ignition (0.6%) indicates minimal pre-hydration or impurities. Overall, the composition reflects good chemical stability and suitability for mortar production [15].

Table 2 lists the key physical characteristics of sand. The specific gravity and fineness modulus indicate a well-graded sand suitable for mortar applications. The bulk and dry rodded bulk density values fall within typical ranges for natural sand, reflecting stable packing characteristics and enabling consistent mix proportioning. Furthermore, the moderate water absorption indicates limited moisture demand, which helps maintain adequate workability without requiring excessive water addition [16].

Waste rubber tires were collected from the local market and were converted into fine powder. The fine particles were sieved through sieve # 4 (4.75 mm). The material that passed through the sieve was further used as a partial replacement of sand. This practice was performed because the sand particles have a size range from 2.00 mm to 4.74 mm [17]. The characteristics of rubber particles are given in Table 3. The specific gravity of the crumb rubber was determined using the water-displacement method. The relatively high value obtained may be attributed to the heterogeneous nature of recycled tire rubber, which contains carbon black, fillers, and other constituents originating from end-of-life automobile tires.

Table 2. Physical properties of sand.

Parameter	Value
Specific Gravity	2.5
Fineness Modulus	2.6
Bulk Density (Kg/m^3)	1490
Dry rodded Bulk Density (Kg/m^3)	1780
Water absorption (%)	2

Table 3. Physical properties of crumb rubber [14].

Parameter	Value
Specific Gravity	1.66
Color	Dark Black
Surface	Rough
Fineness Modulus	3.9
Water absorption (%)	1.25

The crumb rubber exhibits a relatively low specific gravity than fine aggregates and a coarse particle size, as indicated by the high fineness modulus. These characteristics are expected to reduce the overall density of the mortar and affect its compaction behavior and fresh-state workability. In addition, the rough surface texture may enhance mechanical interlocking with the cementitious matrix, potentially improving the bond between rubber particles and the surrounding paste.

The characteristics of silica fume (SF) and fly ash (FA) are mentioned in Table 4. Silica fume has a high level of SiO_2, indicating a strong pozzolanic potential and the ability to react with calcium hydroxide to form additional cementitious products like calcium silicate hydrate gel (C-S-H) [18]. In contrast, fly ash exhibits a more balanced composition, with significant amounts of SiO_2 (33.5%), Al_2O_3 (13%), Fe_2O_3 (34.3%), and CaO (13%). Although the Fe_2O_3 content is relatively high, the combined content of SiO_2, Al_2O_3, and Fe_2O_3 exceeds 70%, satisfying the ASTM C618-19 requirement for Class F fly ash .This combination suggests that fly ash can contribute to both pozzolanic reactions and micro-filler effects,

Table 4. Chemical composition of silica fumes and fly ash [14].

Compound	Silica fumes (%)	Fly ash (%)
Al_2O_3	-	13
CaO	0.43	13
Fe_2O_3	-	34.3
SiO_2	95.73	33.5
K_2O	1.87	1.7
Na_2O	0.38	-
TiO_2	0.93	2.1
ZrO_2	0.11	0.41
V_2O_5	-	0.93
SrO	0.03	0.23

enhancing particle packing and long-term strength development in the mortar matrix [19].

The characteristics of PP fibers are mentioned in Table 5. The fibers have a low density and high tensile strength, making them effective for controlling microcracking and improving post-cracking behavior in mortar. Additionally, the high melting temperature indicates that the fibers remain stable under normal service conditions, ensuring reliable performance within the cementitious matrix [20].

A polycarboxylate ether (PCE)–based third-generation superplasticizer was also used along with the abovementioned materials. The plasticizer met ASTM C494 Type F/G requirements and is used to control the workability of the mortar mixtures [21]. All the ingredients except admixture are shown in Figure 1. Five types of mortars were prepared, and their compositions are mentioned in Table 6. In Table 6, all quantities are given in kg, except water and water reducer, which are in liters. It is reiterated that a systemic study (in steps) was conducted to improve the performance of the rubberized mortars.

Table 5. Characteristics of polypropylene fibers [14].

Parameter	Description
Density (g/cm^3)	0.9
Melting (ºC)	160
Tensile strength (MPa)	350
Color	White and translucent

As a first step, the rubber content was fixed at 5% by mass of sand. This lower amount of rubber was chosen on purpose to see how the material behaves with a small amount of rubber, giving a clear starting point to understand its effects before trying larger amounts for further studies. In all cases, the total binder content and the total filler content remained at 383 kg and 1755 kg, respectively. The water-to-binder ratio was kept constant at 0.6 in all cases, except M3 and M4, where the water content was reduced by 15% owing to the use of the superplasticizer (manufacturer recommendation). Silica fumes and fly ash were each used at 2.5% by mass of cement. The content was selected to maintain a moderate total cement replacement level of 5% while benefiting from their combined pozzolanic effects. A polypropylene fiber content of 1.2 kg/m³, corresponding to approximately 0.13% by volume, falls well within the commonly reported range for fiber-reinforced mortars and concretes [22]. In practice, PP fibers are usually added at 0.1–0.3% by volume to help control cracks, reduce shrinkage, and improve the material's response after cracking. Higher PP fiber content decreases workability and may lead to fiber agglomeration.

The mortar specimens were mixed and prepared according to ASTM standard ASTM C305-20 [23]. All the specimens were prepared in a Hobart mixer. After mixing, the specimens were molded in three-gang molds and prisms. After casting, the specimens were covered with a plastic sheet for 24 h to minimize moisture loss. The specimens were then demolded and submerged

Fig. 1. Raw materials used for producing control and rubberized cementitious mortars.

Table 6. Composition of one cubic meter of mortar.

ID	C	S	W	R	SF	FA	SP	PP
M0	383	1755	230	0	0	0	0	0
M1	383	1667	230	88	0	0	0	0
M2	364	1667	230	88	9.5	9.5	0	0
M3	364	1667	195	88	9.5	9.5	5.7	0
M4	364	1667	195	88	9.5	9.5	5.7	1.2

ID: Specimen identity, C: Cement, S: Sand, W: Water, R: Crumb Rubber, SF: Silica Fumes, FA: Fly Ash, SP: Superplasticizer, PP: Polypropylene Fibers.

in tap water until the specified testing ages (7 and 28 days). The fresh and hardened densities were determined in accordance with the ASTM C138-17 [24] and ASTM C642 [25] standard methods, respectively. The flowability was examined according to the ASTM C1437-20 standard method [26]. The standard ASTM C109/C109M-20 method was used to measure the compressive strength [27].

3. RESULTS AND DISCUSSION

Figure 2 illustrates the hardened specimens in the gang mold after one day of curing. M0 represents the control mortar containing only cement (C), sand (S), and water (W). In M1, 5% of the sand (by mass) was replaced with crumb rubber. This modification changed the aggregate grading and was expected to affect workability and packing density. M2 is a modification of M1; it includes silica fume and fly ash as supplementary cementitious materials. These materials partially replace cement to improve packing, pozzolanic activity, long-term strength, and permeability.

M3 is a modification of M2. A superplasticizer was added, and the mixing water was reduced while maintaining workability. This modification is expected to enhance strength and durability by reducing the water-to-binder ratio and improving the dispersion of fine particles. M4 is a further modification that incorporates polypropylene fibers in addition to all previous constituents. The fibers enhance crack resistance, toughness, and post-cracking behavior but may slightly reduce flowability due to mechanical interlocking.

Overall, moving from M0 to M4 shows a clear change in the mortar from a regular mix to a high-quality composite that includes mineral additives, chemical additives, and fibers. The

Fig. 2. Mortar casting process from three-gang mold to hardened cube specimens.

observable differences in fresh-state appearance and consistency during molding reflect the combined effects of particle size distribution, water content, and the action of the incorporated admixtures.

3.1. Density

Figure 3 shows the variations of density in the fresh state and at one day of age. For the density determination, six samples were tested for each mix type, and the reported values represent the average of six measurements. The results revealed that the mean fresh density of the reference mortar (M0) was 2.1 g/cm^3. As the sand was partially replaced by crumb rubber, the density was reduced by 20%. The incorporation of rubber particles reduced the density of cementitious composites, primarily because rubber is significantly lighter than natural sand. The sand particles have a specific gravity of 2.5 (Table 2), while the crumb rubber particles possess a specific gravity of 1.66 (Table 3). Also, because rubber doesn't mix well with water and fresh cement paste, it creates trapped air pockets, which makes the composite more porous [28]. Thus, the inclusion of pores due to rubber further reduced the density of the mortar specimens. Next, when silica fumes and fly ash were added, the loss of density caused by rubber particles was reduced from 20% to 17%. The addition of a water reducer further decreased the loss, from 17% to 13%. And lastly, when PP fibers were added, the loss was further reduced to 5%.

Fly ash and silica fume are very fine materials that help fill in the gaps in the cement matrix, making the mix denser [29]. At early ages, the improvement in density is primarily due to physical effects, including filler action and enhanced particle packing, rather than pozzolanic reactions. The fine particles occupy spaces between cement grains, reduce initial porosity, and refine the microstructure. This leads to a denser matrix and may improve early-age strength and reduce bleeding and permeability. A water reducer, also known as a plasticizer or superplasticizer, enhances the density of cementitious composites by reducing the water required to achieve the desired workability [30]. By lowering the water content while maintaining or improving flowability, it produces a more compact mixture with fewer voids. It was also observed that the inclusion of fibers reduced the loss in density from 13% to 5%. Polypropylene (PP) fibers are generally expected to decrease density because of their low specific gravity [31]. However, they can also improve density by increasing mixture cohesiveness and helping to hold the constituents together [32]. This improved cohesion reduces air entrapment and void formation within the composite, thereby decreasing the overall volume. Because density is inversely related to volume, a reduction in volume results in an increase in overall density [33]. Higher density leads to higher strength and vice versa. Previous studies on conventional cementitious systems have shown that mineral additives, plasticizers, and fibers can enhance

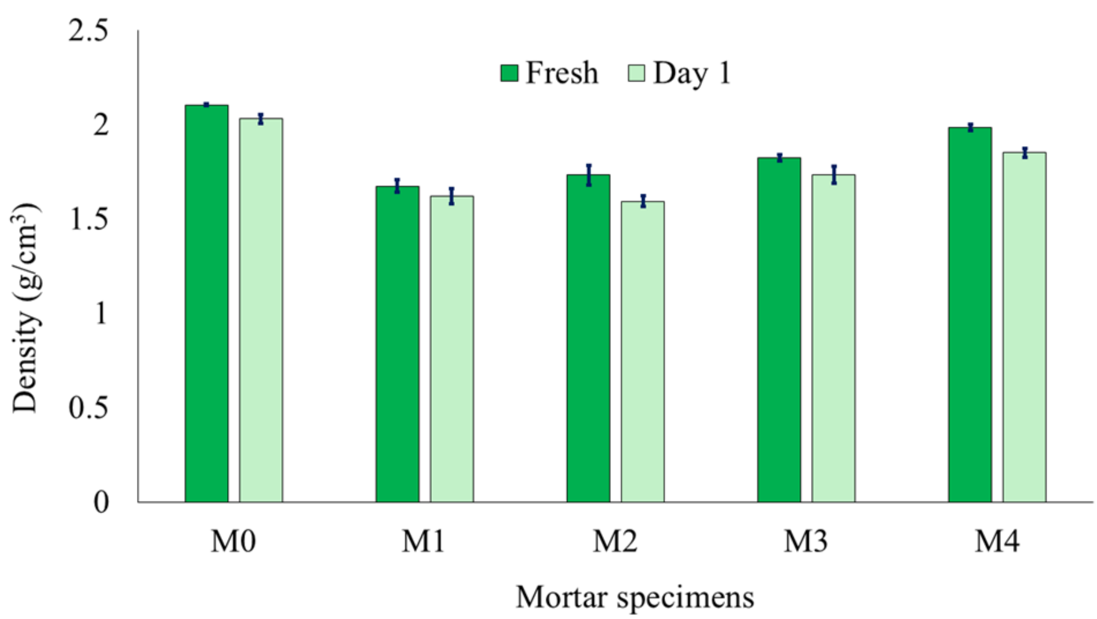

Fig. 3. Density of mortar specimens in the fresh state and after one day of curing.

material performance through improved packing, reduced water demand, and crack control [34-36].

3.2. Workability

The workability was examined by a flow table test. For each mix type, four specimens were tested and the mean flow was calculated from the recorded measurements. Figure 4 illustrates the experimental setup for assessing the flow value of mortar. The flow table test is a standard method for evaluating the workability and consistency of fresh mortars by measuring their ability to deform under controlled dynamic loading. The resulting flow value reflects the combined influence of water content, particle grading, and admixtures on the rheological behavior of the mix, thereby indicating ease of placement and compaction. It is especially useful for mortars containing SCMs or fibers, which can markedly alter cohesion and viscosity [26, 37].

Figure 5 presents the effect of the additives on workability. The workability, as presented by the flow value, varies across the specimens. It seems to be a function of the additive's content and the volume of fibers and plasticizer. The incorporation of fine mineral additives can modify the water demand and particle packing of the mortar, thereby influencing its flow characteristics. Fibers generally reduce workability due to mechanical interlocking and increased internal friction, which restricts the free movement of the mix. In contrast, the presence of a superplasticizer improves dispersion of cement particles and reduces yield stress, resulting in enhanced flow despite low water content. Therefore, the observed variations in flow values reflect the competing effects of filler action, fiber reinforcement, and chemical admixture on the rheological behavior of the fresh mortar [26, 37]. The flow value of the control specimens was 100 mm. The value decreased to 80 mm when rubber

Fig. 4. Setup for measuring mortar flow using a flow table.

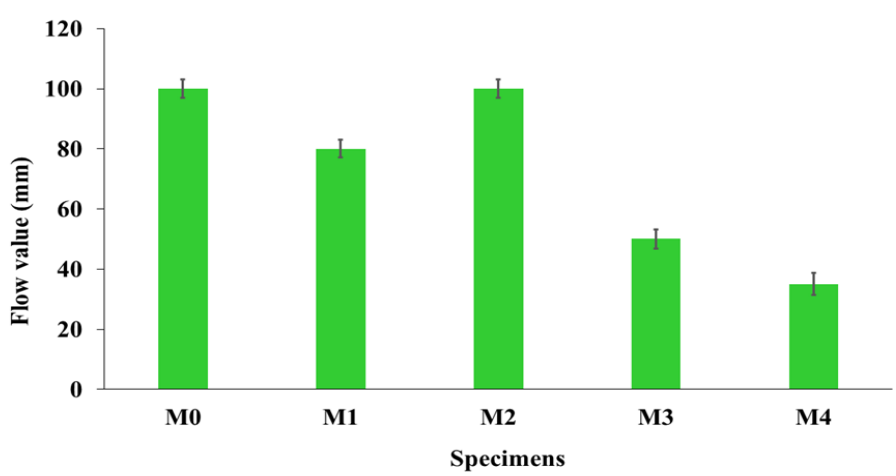

Fig. 5. Variation of flow value with additives.

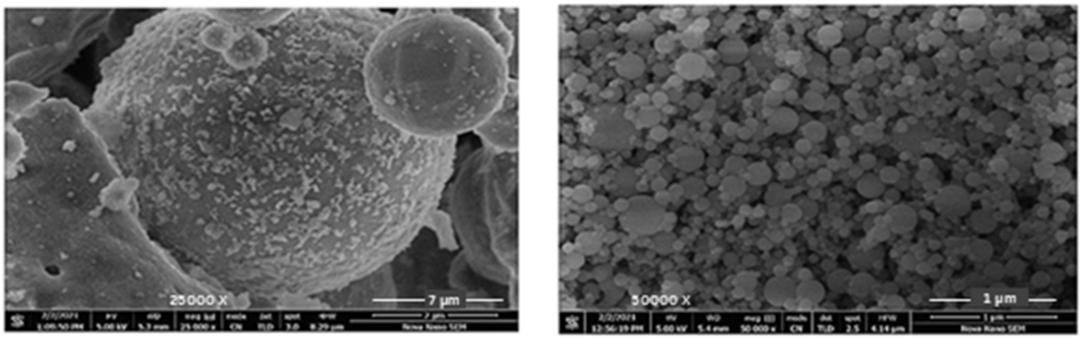

Fig. 6. SEM images of fly ash particles (on left) and silica fume particles (on right).

was incorporated. This reduction is attributed to several factors, including the rough surface texture of rubber particles, which impedes flow. In addition, rubber particles have a lower density, which causes them to float and segregate from the rest of the mix. Rubber particles also tend to entrap air, which resists movement of the mix. The entrapped air induces pores, leading to a reduction in overall density. Thus, the flowability is also linked to the density [38]. As silica fumes and fly ash were added, the loss in flow was substantially recovered. Figure 6 displays the silica fumes and fly ash particles used in this research work.

Fly ash particles are smooth and round, which makes them easier to flow and pack within the matrix. Silica fume particles, on the other hand, are very fine and uneven, which helps fill in gaps and make the mixture denser. Their contrasting morphologies highlight their complementary roles in modifying fresh and hardened properties of cementitious composites [29].

Fly ash is added at a rate of 15-35% by mass of cement, whereas silica fumes are added at a rate of 5-10% by mass of cement [39]. Silica fume is used in smaller amounts than fly ash because its extremely fine particles and high reactivity can produce significant effects even at low dosages. However, excessive use may adversely affect workability and increase shrinkage [40]. For the current study, lower levels were decided, i.e., 2.5% each. The literature survey shows that a lower level of fly ash particles significantly improves workability, whereas a lower level of silica fumes provides a good balance between strength and workability [41]. Thus, for improving the workability of rubberized cementitious composites, lower levels of silica fumes and fly ash are recommended.

Subsequently, a water-reducing admixture was incorporated into the mix, and the water content was decreased by 15% (Table 6) in accordance with the manufacturer's recommendations. Despite this adjustment, the expected improvement in workability was not achieved; instead, the flow value dropped from 100 mm to 50 mm. This indicates that the prescribed water reduction was not suitable for the specific composition of the mortar used in this study. The reduced flow may be attributed to the combined effects of a lower effective water content and the prevailing hot weather during casting, which likely accelerated moisture loss and early hydration, thereby increasing the stiffness of the mix. The specimens were cast during the month of July 2024. The average heat index was calculated to be 44 ºC, and the average humidity was 40% [42]. To ensure the consistency and comparability of the experimental results, all the mortar combinations were prepared and tested under identical environmental conditions.The dosage of the water reducer typically lies between 0.1 to 1.5% (by mass of cementitious binder) [43]. Thus, for this work, an average dosage was used. The lower humidity and high temperature enhance water demand. The substantial reduction in flow is primarily attributed to the 15% reduction in mixing water associated with the use of the water-reducing admixture. The high ambient temperature during casting may also have contributed to a greater water demand and accelerated moisture loss; however, this effect was not directly quantified in the present study. Thus, there is a need for an optimum water reducer content for maintaining the workability of the mix in hot weather conditions. Lastly, when PP fibers were added, the flow value further declined. PP fibers tend to hold the mix together, forming a cohesive network that restricts particle movement. In addition, these synthetic fibers can absorb or retain water on their surfaces, reducing the amount of free water available for lubrication [44]. Consequently, the flow value decreases. The overall study suggests that a careful selection of SCMs can enhance workability alone. The addition of fibers might enhance the strength but is not useful for the workability of the rubberized composites.

3.3. Compressive Strength

The compressive strength was determined at two ages: 7 and 28 days. The respective results are shown in Figure 7. All values represent an average of three measurments for each mix.The 7-day strength indicates early hydration and initial load-bearing capacity of the mortar. It reflects cement reactivity and the early effects of additives. The 28-day strength is the standard reference for structural performance and quality evaluation. It represents more complete hydration and microstructural development. Comparing these two ages helps assess both early performance and long-term strength gain [45, 46].

The 28-day compressive strength of control specimens is 8.5 MPa, which was reduced to 4.55 MPa when sand was partially replaced by rubber particles. The 28-day compressive strength of control specimens may appear modest compared with standard laboratory mortars, it falls within the range commonly reported for 1:4 cement–sand mortars with similar water-to-binder ratios. The mortar was prepared using locally available Mangla river sand, and comparable strength levels have been reported in studies employing similar materials and mix proportions [47]. Furthermore, the control mix serves as a reference mixture for comparative evaluation of the effects of crumb rubber, supplementary cementitious materials, water-reducing admixture, and polypropylene fibers. Therefore, the relative changes in strength are of primary significance in the present investigation. This decrease from 8.5 MPa to 4.555 MPa is attributed to void formation, weak interfacial bonding with the cement paste, and the low stiffness of rubber particles, which act as soft inclusions [48, 49]. These factors create stress concentration points and initiate microcracks, leading to reduced strength. When mineral additives were added, the strength further decreased from 3.18 MPa to 3.01 MPa at 7 days and from 4.55 MPa to 4.3 MPa at 28 days, corresponding to a reduction of about 5% at both ages. Supplementary cementitious materials such as silica fume and fly ash often show limited early-age benefits in rubberized systems because their pozzolanic reactions are time dependent. Higher strength gains are typically observed at later ages, such as 56 days and beyond [50].

The incorporation of a water-reducing admixture resulted in a 43% increase in compressive strength at both 7 and 28 days. This improvement can be attributed to the 15% reduction in the water-to-cement ratio, which produced a denser microstructure with improved particle packing and stronger interfacial bonding within the matrix. Water-reducing admixtures or plasticizers enhance strength by reducing water-to-cement ratio, resulting in a denser and less porous cementitious matrix. This reduction in excess water decreases

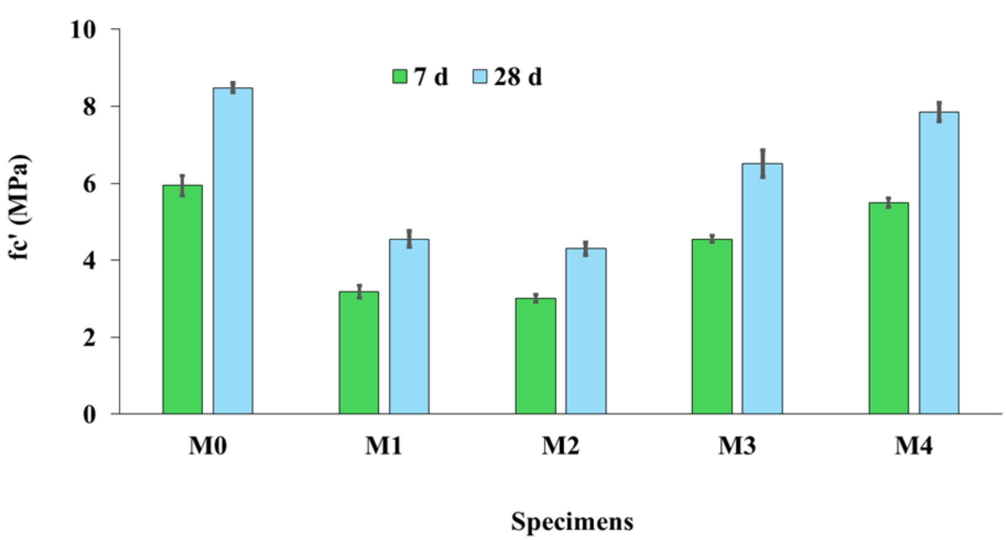

Fig. 7. Compressive strength of control and rubberized mortars after 7 and 28 days of curing.

the formation of capillary voids within the hardened matrix. It also improves particle packing, allowing the solid constituents to occupy the available space more efficiently. In addition, the lower water content promotes more effective cement hydration. Furthermore, it strengthens the bond between the cement paste and aggregates. Collectively, these effects lead to higher compressive strength [51, 52]. The addition of polypropylene fibers resulted in a 73% strength increase compared with M1 (rubberized specimens without mineral additives, fibers and plasticizer). Fibers help bridge microcracks and improve stress transfer, partially compensating for the weakness introduced by rubber particles [53]. At 28 days, rubberized specimens (M1) showed a 46% reduction in strength compared with control specimens (M0), but this reduction decreased to 7.4% after incorporating silica fume, fly ash, water reducer, and PP fibers. Similar synergistic improvements from combined mineral and fiber modifications have been reported in recent studies [54, 55]. The next section further elaborates on the effects of additives, fibers, and plasticizers.

3.4. Relation between Density and Compressive Strength

Figure 8 illustrates the relationship between density and compressive strength. This relationship is important because density strongly influences load-bearing performance, structural weight, and material efficiency. Higher density usually means fewer pores, voids, and defects. In materials like concrete, this generally leads to higher strength because the load is carried through a more continuous solid matrix [33]. The results indicate a strong positive correlation, with higher-density mixes exhibiting greater compressive strength. The reduction in density and strength in rubberized mortars is attributed to the low stiffness and lightweight nature of crumb rubber particles. On the other hand, adding silica fume, fly ash, and PP fibers helped to better arrange the particles and make the mixture denser, which improved its strength. A strong positive trend was observed between density and compressive strength (R^2 = 0.92). However, the relationship was derived from a limited dataset comprising five mix types and should therefore be interpreted as indicative rather than conclusive. Many studies have reported a positive relationship between density and compressive strength because denser materials contain fewer voids and can distribute applied loads more effectively [56, 57]. This benefit is attributed to the addition of finer particles of silica fumes and fly ash as well as a reduced water content. Extra water is a source of voids formation. The addition of fibers results in stronger bonds between particles, enhancing the material's ability to withstand compressive forces. Thus, using lower dosages of SCMs, a water reducer, and PP fibers can enhance the density and strength of a rubberized cementitious composite.

3.5. Effect of Fibers on Crack Formation

The crack formation was carefully observed during the compressive strength test. The difference of crack formation in the specimens M1 and M4 can be seen in Figure 9. Visual assessment of crack patterns provides valuable insight into the failure mode and internal integrity of cementitious materials. The width, orientation, and distribution of cracks indicate the brittleness or ductility of the specimen. Localized and wide cracks typically suggest weak bonding and sudden failure, whereas multiple fine cracks reflect improved stress redistribution and energy absorption. Such observations complement compressive strength results by revealing the influence of additives and fibers on crack resistance and post-peak behavior [45, 46]. The control mortar (M0) showed brittle failure with sudden rupture and a large crack. This indicates low energy absorption capacity. In contrast, M4, which contained fibers and mineral additives, developed only fine hairline cracks. Another notable observation was the reduction in delamination due to the additives and fibers. Severe delamination was observed in M1 (rubberized mortar). However, M4 maintained strong internal cohesion. Overall, the additives and

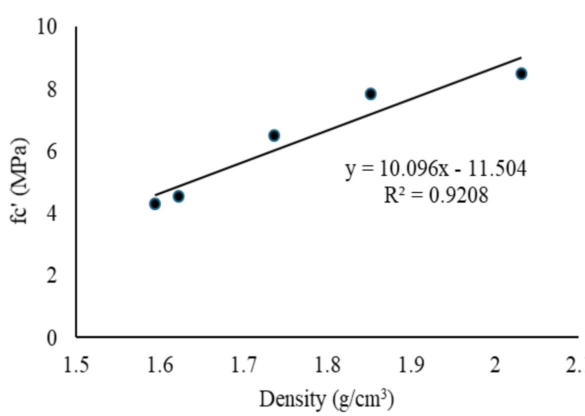

Fig. 8. Variation of compressive strength with density.

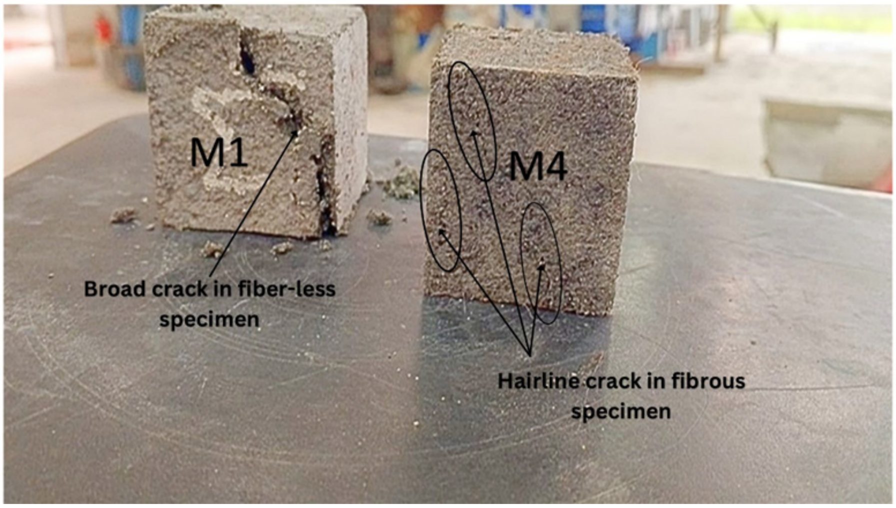

Fig. 9. Comparison of crack patterns in specimens M1 (left) and M4 (right).

fibers effectively controlled crack propagation and improved structural integrity. Fibers acted as crack bridges and restricted crack widening [58]. This prevented sudden fracture and helped maintain the integrity of the specimen. Mineral additives densified the matrix and reduced internal voids. The improved microstructure enhanced the bond among the constituents [59]. Consequently, the material was able to sustain higher deformation before failure. In contrast, the rubberized mortar exhibited weak interfacial bonding, which led to layer separation. The modified mortar therefore showed a more stable and damage-tolerant failure mode.

4. CONCLUSIONS

This study was conducted to improve the performance of rubberized cementitious mortar for subsequent application to concrete specimens. The addition of 5% silica fume and fly ash (combined), along with 0.1% polypropylene (PP) fibers, significantly increased the density of the rubberized mortar. The one-day hardened density increased from 1.60 to 1.90 g/cm³ following the incorporation of SCMs and PP fibers. This value approaches the one-day hardened density of the control 1:4 cement–sand mortar (2.03 g/cm³). The same 5% SCM combination also improved the flow value from 80 mm to 100 mm, which is comparable to the workability of the control mix. In contrast, the inclusion of PP fibers alone markedly reduced the flow value from 80 mm to 35 mm. This reduction is attributed to fiber-induced interlocking and volumetric restriction within the matrix. The incorporation of rubber particles reduced the compressive strength from 8.5 MPa to 4.5 MPa, representing a loss of 46%. However, this reduction was substantially mitigated when silica fume, fly ash, a water-reducing admixture, and PP fibers were used together. Under these conditions, the strength loss was limited to only 7%. Rubberized cementitious composites generally exhibit reduced workability and mechanical strength but improved dynamic properties. These characteristics limit their use in structural applications. Nevertheless, workability can be effectively enhanced using SCMs with ball-bearing effects, such as fly ash and silica fume. The observed increase in flow from 80 mm to 100 mm was achieved through the incorporation of SCMs alone. In contrast, the addition of a water-reducing admixture with reduced mixing water and polypropylene fibers resulted in lower flow values but contributed to strength recovery. Mechanical performance can therefore be partially restored through the combined use of SCMs, water-reducing admixture, and fiber reinforcement.

5. ETHICAL STATEMENT

All experimental work was conducted on laboratory-prepared cementitious materials. No experiments involving human participants or animals were performed; hence, ethical approval was not applicable.

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7. CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

8. DECLARATION

The authors declare that the results presented in this manuscript are original and have not been published previously, nor are they under consideration for publication elsewhere. All authors have reviewed and approved the final version of the manuscript and agree to its submission. All data and figures presented in this work are original and generated by the authors; therefore, no copyright permission from other sources was required. In the event that the article is accepted for publication, the authors agree to assign the copyright of the manuscript to the Pakistan Academy of Sciences.

9. AI Statement

No AI tools were used for data generation, analysis, or figure preparation. All scientific interpretations remain the sole responsibility of the authors. Artificial intelligence–based tools were used only to assist with language editing and formatting.

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