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Comparative Study on Mechanical Properties of Fiber-Reinforced Cement Mortars Using Fly Ash and Manufactured Sand

Abdul Raheem.K [1], Chethan K [2], Akash Babu L.A[3], Ashwini Joish [4], Sadath Ali Khan Zai [5]
[1]Research Scholar, Department of Civil Engineering, UVCE, Bangalore University, Bangalore, India, arkhazi63@gmail.com
[2]Associate Professor, Department of Civil Engineering, UVCE, Bangalore University, Bangalore 560056, Karnataka,India
[3]Research Scholar, Department of Civil Engineering, UVCE, Bangalore University, Bangalore 560056, Karnataka, India
[4]Post Graduate Department of Civil Engineering, UVCE, Bangalore University, Bangalore 560056, Karnataka, India
[5]Professor, Department of Civil Engineering, UVCE, Bangalore University, Bangalore-56, Karnataka, India.

Abstract: *The depletion of river sand and the high carbon footprint of cement production makes it essential to use sustainable alternatives in mortar design. This study experimentally evaluates the influence of partial cement replacement with fly ash and substitution of river sand with manufactured sand (M-sand) on the compressive and flexural strength of fiber-reinforced cement mortars. Two mortar mix proportions, 1:3 and 1:4 (cement:sand), were considered and twelve mixes for each proportion were designed, cast and tested as per IS 2250:1981. For 1:3 mixes, cement was partially replaced with 6% fly ash (mixes 3,4,7,8,11,12). River sand was replaced with 50% M-sand (mixes 9,10,11,12) and 100% (mixes 5,6,7,8). Polypropylene fibers (0.25% by cement weight) were incorporated in mixes 2,4,6,8,10,12. For 1:4 mixes, 4% fly ash replacement was used in mixes 3,4,7,8,11,12 with the same M-sand replacement scheme and fiber additions with a constant water to cement ratio of 0.5. Compressive and flexural strengths were tested at 28, 56, and 90 days. Results revealed that mixes with fly ash, River sand, M-sand, and fibers improved mechanical properties, with best performance for 1:3 and 1:4 mixes containing 6% and 4% fly ash, blended sands, and fibers. The 1:3 mixes outperformed 1:4 blends, showing the viability of these sustainable materials.*
Keywords: *Cement mortar; Fly ash; Manufactured sand; Polypropylene fibers; Compressive strength; Flexural strength; Sustainable construction materials.*

1. INTRODUCTION:

According to the United Nations Environment Program (2019), increased sand mining has led to the depletion of accessible river sand resources by over 20% in the past decade, while the International Energy Agency (2022) reports that cement production contributes nearly 8% of global anthropogenic CO_2 emissions, together emphasizing the urgent need to develop sustainable mortar systems that integrate industrial by-products and engineered materials [16][29]. The construction industry heavily depends on natural sand and cement; resources whose extraction and production have serious environmental consequences [17][25]. With rising construction demands, there is an urgent need for alternative materials that can meet structural requirements without compromising sustainability [19][28].

Cement mortar, a mixture of cement, sand, and water, is indispensable in masonry and plastering works [32,33]. However, excessive river sand extraction disrupts ecosystems by lowering water tables, causing soil erosion, and affecting agricultural productivity [21][27]. Similarly, cement manufacturing contributes significantly to global CO_2 emissions [14][23]. To counteract these issues, manufactured sand (M-sand) and supplementary cementitious materials such as fly ash are increasingly adopted [31][15]. M-sand, produced by crushing rocks, offers controlled particle grading and consistency [18]. Fly ash, a by-product of coal combustion, can partially replace cement, improving workability and durability while reducing environmental impact [22][26].

Incorporating fibers, particularly polypropylene fibers, has been found to enhance the mechanical properties of mortars by improving tensile capacity and reducing shrinkage cracks [24][30]. Despite

significant research on M-sand and fly ash individually, limited studies systematically combine these materials with fibers in mortar mixes of different ratios [20][13]. Understanding the mechanical behavior of such composite mortars is vital to promote eco-friendly construction practices [28][17]. Most studies have focused on concrete mixes or single mortar ratios. Few have investigated both 1:3 and 1:4 mortar proportions together, while simultaneously examining combined effects of fly ash, M-sand, and polypropylene fibers on compressive and flexural strength [27][19].
This study aims to evaluate the effect of partial replacement of cement with fly ash and river sand with M-sand on the compressive and flexural strengths of fiber-reinforced mortars [23][15]. To compare the mechanical performance of 1:3 and 1:4 mortar mixes. To identify the optimal combination of materials for enhanced strength and sustainability [30][25]. This research encompasses laboratory testing of 24 different mortar mixes under controlled conditions, measuring compressive and flexural strengths over a 90-day curing period [18][29].

2. LITERATURE REVIEW

Recent research has extensively explored the influence of supplementary materials and fibers on the mechanical and durability performance of mortars and concretes, with a focus on enhancing sustainability [17][25]. Balamurugan and Perumal (2013) demonstrated that partial replacement of natural sand with quarry dust improves strength owing to better particle packing [13], while Habib et al. (2013) showed that synthetic fibers enhance mortar tensile capacity and crack resistance [27]. Akid et al. (2021) reported that combining 15–30% fly ash with polypropylene fibers improves compressive and splitting tensile strengths at 28 and 90 days, despite minor reductions in workability [19][30], whereas Wu et al. (2022) highlighted that hybrid fibers in fly ash–rich mortars significantly refine microstructure, increase flexural capacity, and reduce wear [22][28].
Similarly, NematianJelodar et al. (2022) found that nano-silica and PVA fibers together improved the strength and shrinkage behavior of repair mortars [15]. Studies on high-flowing mixed-sand concretes (Materials, 2020) and self-compacting concrete with fiber and fly ash (Materials, 2023) further confirmed the positive synergy between alternative fine aggregates, mineral admixtures, and fibers in improving strength and workability [24][31]. In addition, Zhao et al. (2025) demonstrated that PVA fibers combined with nano SiO_2 in high-volume fly ash mortar yielded significant early strength gains and matrix densification [20][26].
While these studies clearly confirm the benefits of using manufactured or mixed sand, fly ash, and fibers for enhancing mechanical properties and durability, most have been carried out either on concrete rather than mortar, or have focused on individual or dual combinations of materials, and often at a single mix proportion [16][23]. There remains a notable research gap in systematically evaluating the combined effects of fly ash, manufactured sand, and polypropylene fibers on the compressive and flexural strength development of cement mortars in both 1:3 and 1:4 mix ratios over 28, 56, and 90 days, which forms the unique focus of the present study [14][18][29].

3. MATERIALS AND MIX DESIGN

The materials used in the present study were as follows: Ordinary Portland Cement of 43 grade conforming to IS 269:2015 [18][25]; Class F fly ash, used as 20% partial replacement by weight of cement [21]; fine aggregates used were river sand and manufactured sand (M-sand) conforming to IS 2116:1970 [14][27]. Recron polypropylene fibers (0.25% by weight of cement) were incorporated to enhance mechanical performance [22][30], and potable water was used throughout the mixing process [17].
Two mortar mix proportions—1:3 and 1:4 (cement: sand)—were considered, and a total of twelve mixes for each proportion were designed, cast, and tested for mechanical performance as per IS 2250:1981 [20][26]. A constant water-to-cement ratio of 0.5 was used throughout the study [16][28].

Table 1 Mix Proportions for 1:3 Cement mortar mix

Mix1	30% Cement + 70% River sand
Mix2	30% Cement + 70% River sand + 0.25%PPF
Mix3	24% Cement + 6% Fly ash + 80% River sand
Mix4	24% Cement + 6% Fly ash+70% River sand+ 0.25%PPF

Mix5	30% Cement + 70% M-sand
Mix6	30% Cement +70 % M sand + 0.25%PPF
Mix7	24% Cement + 6% Fly ash + 70% M sand
Mix8	24% Cement + 6% Fly ash + 70% M sand + 0.25%PPF
Mix9	30% Cement + 35% M-sand+ 35% River sand
Mix10	30% Cement + 35% River sand + 35% M sand+0.25%PPF
Mix11	24% Cement + 6% Fly ash + 35% River sand + 35% M sand
Mix12	24% Cement + 6% Fly ash + 35% River sand + 35% M sand +0.25 PPF

Table 2 Mix Proportions for 1:4 Cement mortar mix

MIXES	COMBINATIONS
MIX-1	20%Cement+80%River sand
MIX-2	20%Cement+80%River sand+0.25%PPF
MIX-3	16%Cement+4% Fly ash+80% River sand
MIX-4	16 %Cement+4% Fly ash + 80% River sand+0.25%PPF
MIX-5	20%Cement+80% M-Sand
MIX-6	20%Cement+80%Msand+0.25%PPF
MIX-7	16%Cement+4% Fly ash + 80% M Sand
MIX-8	16%Cement+4%Flyash+80% M-sand+0.25%PPF
MIX-9	20%Cement+40% River sand+40%M-sand
MIX-10	20% Cement +40% river Sand+ 40% M-sand + 0.25% PPF
MIX-11	16% Cement +4% Fly ash + 40% River sand + 40% M Sand
MIX-12	16%Cement+4%Flyash+40% River Sand + 40%Msand + 0.25% PPF

4. Methodology

4.1 Compressive Strength

For compressive strength determination, mortar specimens were prepared in the form of standard cubes of 70.6 × 70.6 × 70.6 mm [16]. The cement, fly ash, manufactured sand, river sand, and polypropylene fibers, as per the designated mix proportions, were first dry mixed to achieve a uniform blend [24][27]. Potable water was then added gradually, maintaining the prescribed water-to-cement ratio, and the materials were thoroughly mixed to produce a homogeneous and workable mortar [15][28]. The fresh mortar was placed into pre-oiled steel cube moulds in three uniform layers, and each layer was compacted carefully using a tamping rod to eliminate entrapped air and ensure uniform density [20][31].

After the moulds were filled and the top surface was leveled with a trowel, the specimens were stored under ambient laboratory conditions for 24 hours [19][29]. Following this initial setting period, the cubes were demoulded carefully and transferred to a curing tank containing clean water maintained at room temperature, where they remained submerged until the day of testing [18][30]. Compressive strength was assessed at 28, 56, and 90 days of curing using a calibrated Universal Testing Machine (UTM) in accordance with IS 4031 [21][25].

Each cube was positioned centrally on the loading platform, and a gradually increasing load was applied until failure occurred [22]. The maximum load sustained by each specimen was recorded, and the compressive strength was computed as the ratio of the failure load to the cross-sectional area of the cube [14][17].

4.2 Flexural Strength

Flexural strength was evaluated on prismatic mortar specimens of size 160 × 40 × 40 mm prepared in a manner similar to that of the compressive strength specimens [14][25]. After proportioning and mixing the dry ingredients to a uniform consistency, water was added to achieve the required workability, and the fresh mortar was filled into the prism moulds in two layers [18][27]. Each layer was compacted using the standard tamping procedure to ensure the absence of air voids [30][19]. The top surface was finished with a trowel, and the specimens were left undisturbed for 24 hours at ambient conditions [16][29]. After demoulding, the prisms were cured under water at room temperature until testing [17][26].

Flexural testing was carried out after 28, 56, and 90 days of curing using the three-point bending method described in IS 1607 [23][31]. The test was performed on a Universal Testing Machine equipped with a flexural testing attachment [15][20]. During testing, the prism was placed on two supporting rollers, and a gradually increasing load was applied at the midspan until failure [21]. The maximum load recorded at failure was used to calculate the modulus of rupture (flexural strength) using the standard formula [22][28].

The equipment used for these experiments included steel moulds for cubes and prisms, calibrated digital weighing balances for accurate batching, a Universal Testing Machine with appropriate compressive and flexural testing fixtures, and a water-curing tank maintained under controlled laboratory conditions [13][24].

5. RESULTS AND DISCUSSIONS

5.1 Compression test

Table 3 Compressive strength for 1:3 Cement mortar mix

Compressive Strength			
01:03			
	28 Days	56 Days	90 days
Mix 1	44.91	45.57	45.71
Mix 2	46.66	46.98	47.13
Mix 3	45.15	47.01	47.26
Mix 4	47.19	47.64	47.79
Mix 5	44.06	44.74	44.82
Mix 6	46.57	46.94	47.19
Mix 7	44.62	47.05	47.30
Mix 8	46.84	47.58	47.83
Mix 9	46.98	47.63	47.88
Mix 10	47.19	47.90	48.16
Mix 11	47.56	48.11	48.37
Mix 12	48.15	48.93	49.19

From Table 3, it is evident that the compressive strength of all 1:3 mixes increases steadily from 28 days to 90 days, showing the beneficial effect of continued hydration. At 28 days, Mix 12, which combines 16 % cement, 4 % fly ash, 40 % river sand, 40 % M-sand, and 0.25 % polypropylene fibers, records the highest strength (48.15 MPa), clearly outperforming the control mix (44.91 MPa). By 56 days and 90 days, the same mix continues to lead, reaching 48.93 MPa and 49.19 MPa, respectively. These results demonstrate the positive synergy of partial replacement and fibers, with the hybrid Mix 12 exhibiting approximately 9 % higher compressive strength than the control by 90 days.

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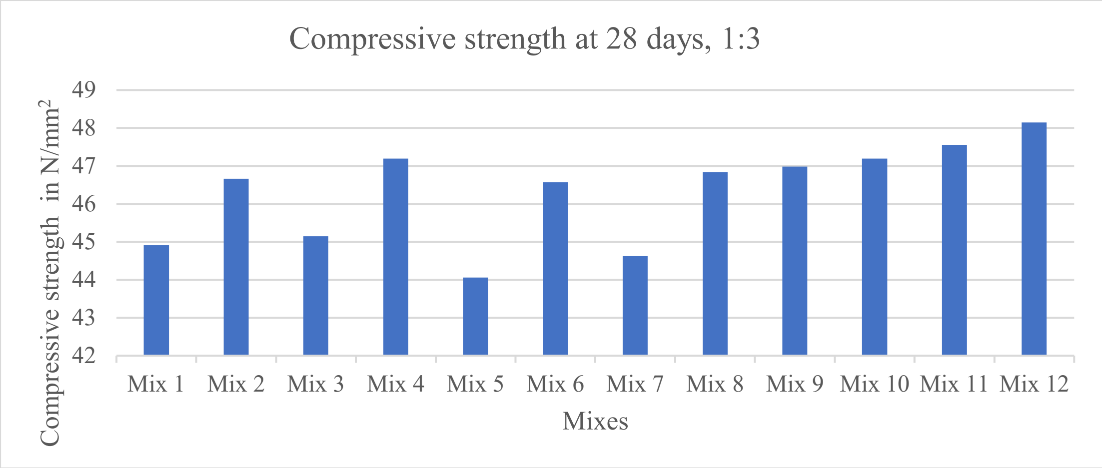

Fig. 1 Compressive strength at 28 days for different mixes for 1:3

Figure 1 (28-day results) shows that Mix 12, which combines 16 % cement, 4 % fly ash, 40 % river sand, 40 % M-sand, and polypropylene fibers, achieved the highest strength (48.15 MPa) while the control mix (Mix 1) recorded 44.91 MPa.

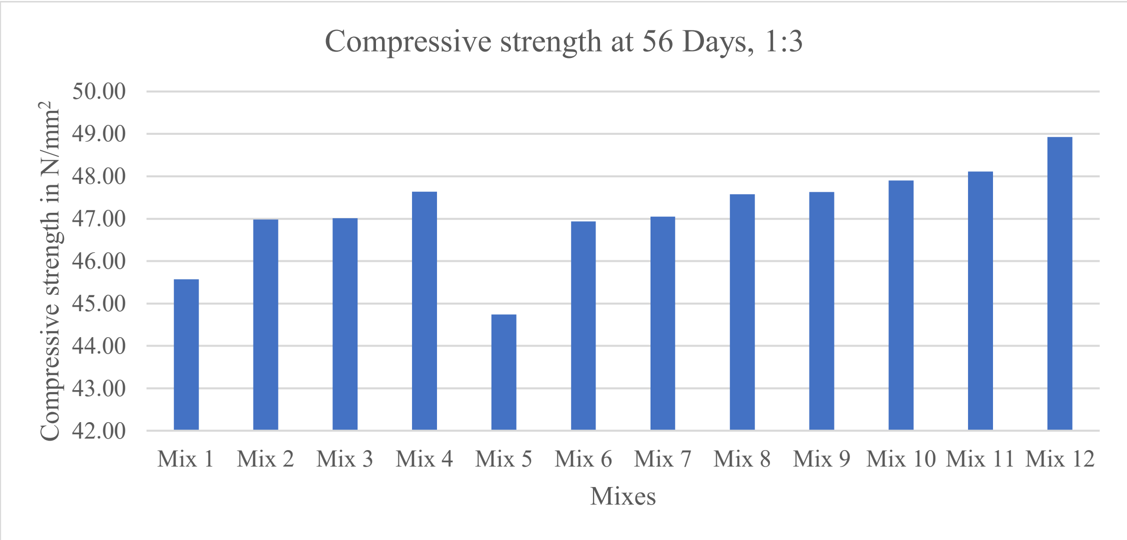

Fig. 2 Compressive strength at 56 days for different mixes for 1:3

Figure 2 illustrates that by 56 days, the strength gap widens further, confirming the role of fly ash in long-term strength gain.

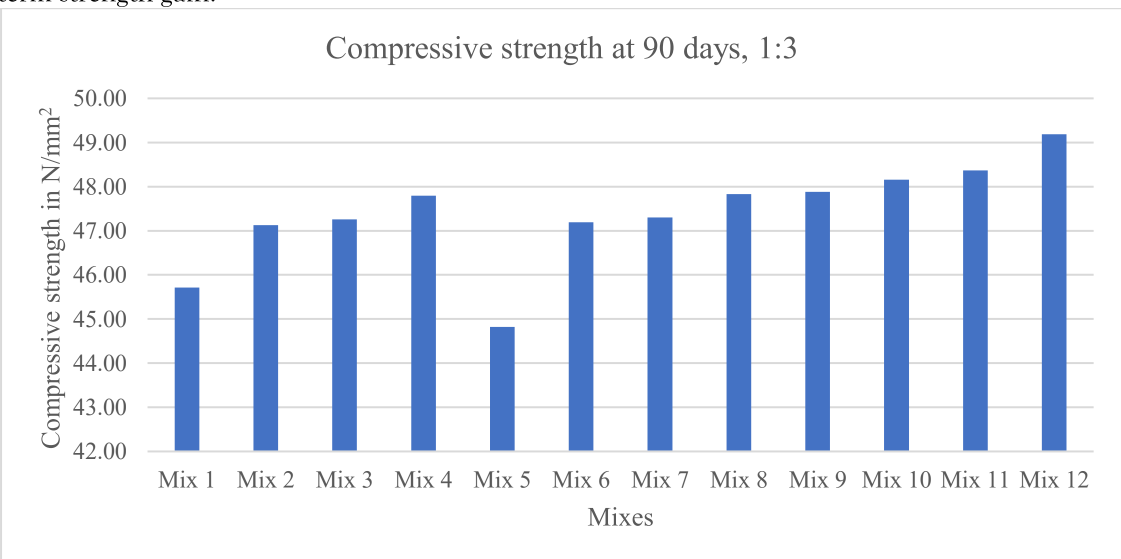

Fig. 3 Compressive strength at 90 days for different mixes for 1:3

Figure 3, at 90 days, shows Mix 12 reaching 49.19 MPa, outperforming all other mixes.

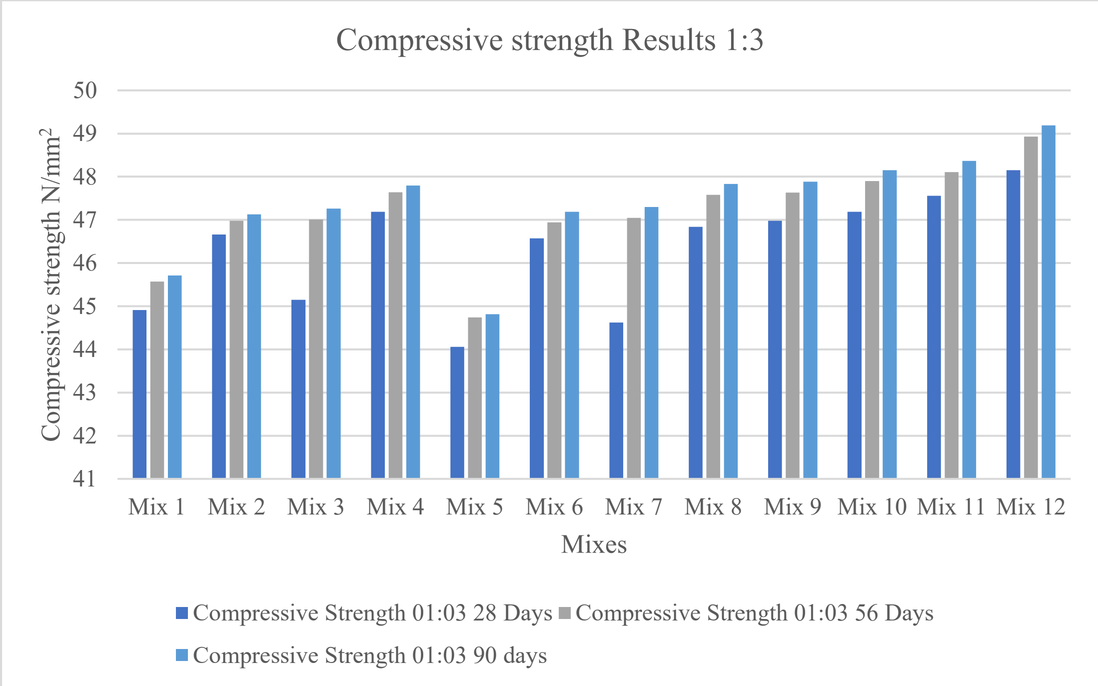

Fig. 4 Compressive strength of the mortar mixes at 28,56 And 90 days for 1:3

Figure 4 (trend of all ages) highlights that mixes containing both M-sand and fibers consistently remain superior throughout the curing period.

Table 4 Compressive strength for 1:4 Cement mortar mix

Compressive Strength			
01:04			
	28 Days	56 Days	90 days
Mix 1	41.89	42.52	42.66
Mix 2	43.47	43.69	43.83
Mix 3	42.31	43.81	43.95
Mix 4	44.03	44.28	44.42
Mix 5	41.22	41.87	42.00
Mix 6	43.24	43.38	43.52
Mix 7	41.62	43.46	43.60
Mix 8	43.78	44.09	44.23
Mix 9	43.99	44.23	44.37
Mix 10	44.26	44.55	44.69
Mix 11	44.81	44.89	45.13
Mix 12	45.06	45.57	45.82

Table 4 shows a similar trend for 1:4 mixes, with compressive strength improving as curing progresses. Mix 12 once again achieves the best performance, with strengths of 45.06 MPa, 45.57 MPa, and 45.82 MPa at 28, 56, and 90 days, respectively. Although these values are slightly lower than those of the 1:3 series due to the leaner mix, the improvement over the control mix is clear. Even in 1:4 mortars, the combined use of fly ash, M-sand, and fibers enhances strength development compared to mixes with only one modified parameter.

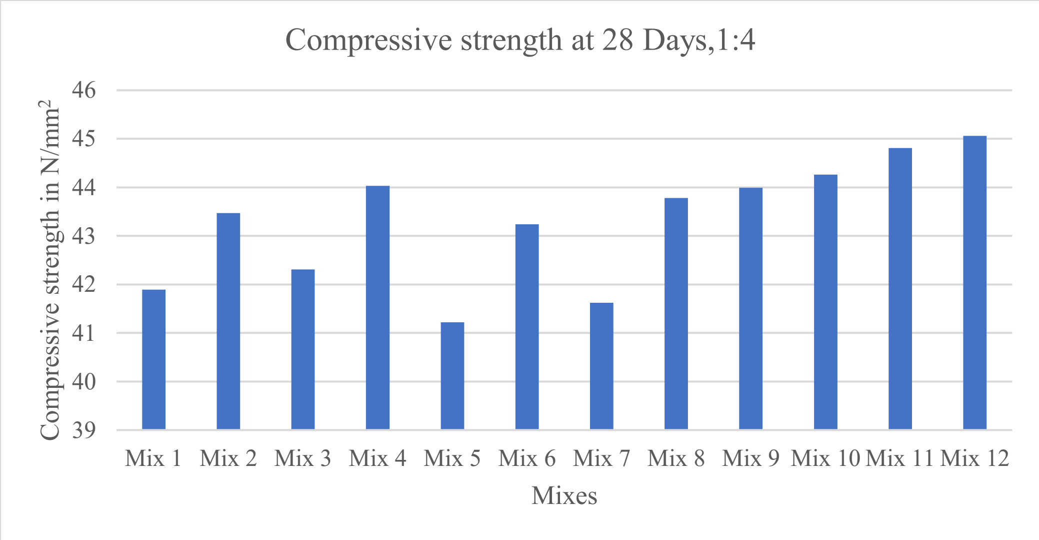

Fig. 5 Compressive strength at 28 days for different mixes for 1:4

Figure 5 illustrates that at 28 days, Mix 12 again delivers the best performance (45.06 MPa) compared to the control (41.89 MPa).

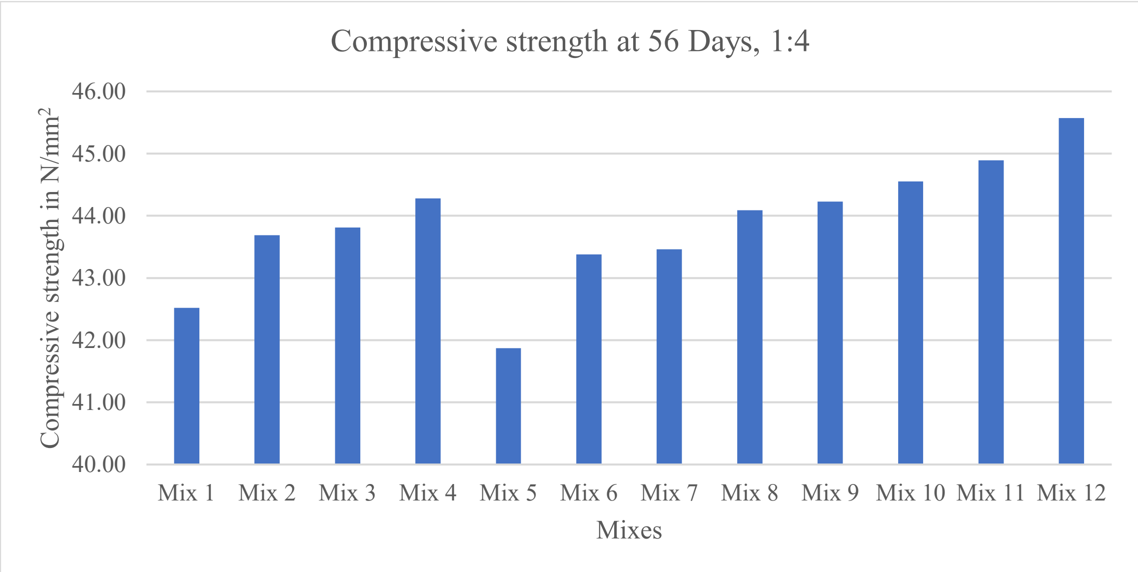

Fig. 6 Compressive strength at 56 days for different mixes for 1:4

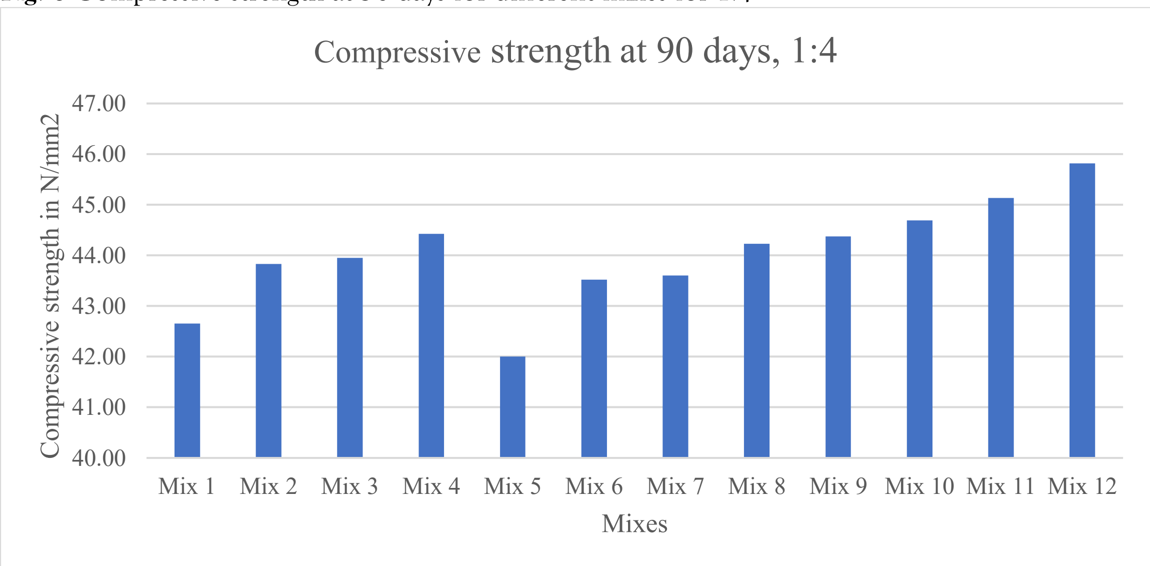

Fig. 7 Compressive strength at 90 days for different mixes for 1:4

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Figures 6 and 7 (56 and 90 days) confirm that hybrid mixes continue to gain strength, with Mix 12 reaching 45.82 MPa at 90 days.

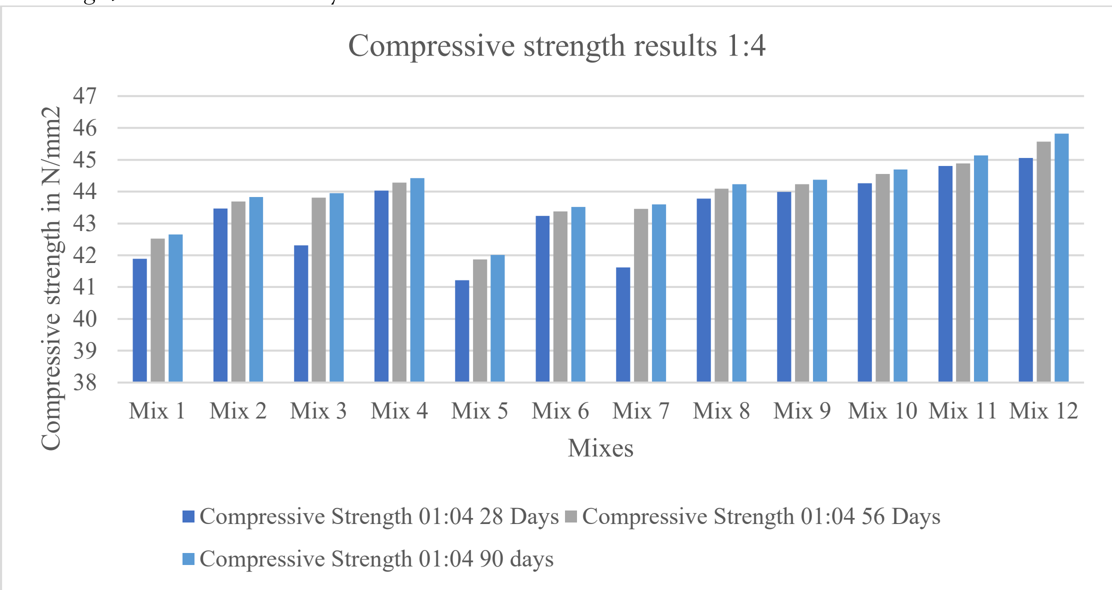

Fig. 8 Compressive strength of the mortar mixes at 28,56 And 90 days for 1:4

Figure 8, summarizing all curing periods, clearly shows that the combination of fly ash, M-sand, and fibers consistently enhances performance compared to mixes with single modifications.

5.2 Flexural Strength Test

Table 5 Flexural strength for 1:3 Cement mortar mix

Flexural Strength			
01:03			
	28 Days	56 Days	90 days
Mix 1	8.27	8.40	8.47
Mix 2	8.59	8.53	8.62
Mix 3	8.32	8.66	8.75
Mix 4	8.69	8.83	8.92
Mix 5	8.12	8.25	8.34
Mix 6	8.55	8.49	8.50
Mix 7	8.22	8.59	8.69
Mix 8	8.63	8.78	8.88
Mix 9	8.73	8.87	9.01
Mix 10	8.78	8.92	9.06
Mix 11	8.81	9.01	9.16
Mix 12	9.05	9.20	9.31

Table 5 illustrates that flexural strength follows a similar growth pattern as compressive strength, with results increasing slightly from 28 to 90 days. For example, Mix 12 improves from 9.05 MPa at 28 days to 9.31 MPa at 90 days, while the control mix increases from 8.27 MPa to 8.47 MPa over the same period. Blends that include polypropylene fibers exhibit higher flexural values, highlighting the crack-bridging action of fibers that delays crack propagation.

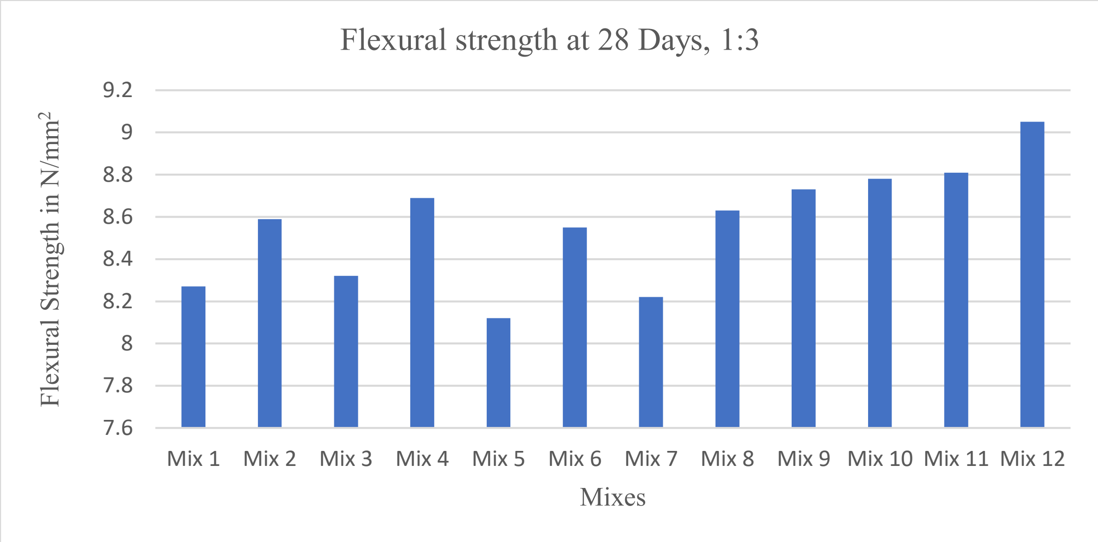

Fig. 9 Flexural strength at 28 days for different mixes for 1:3

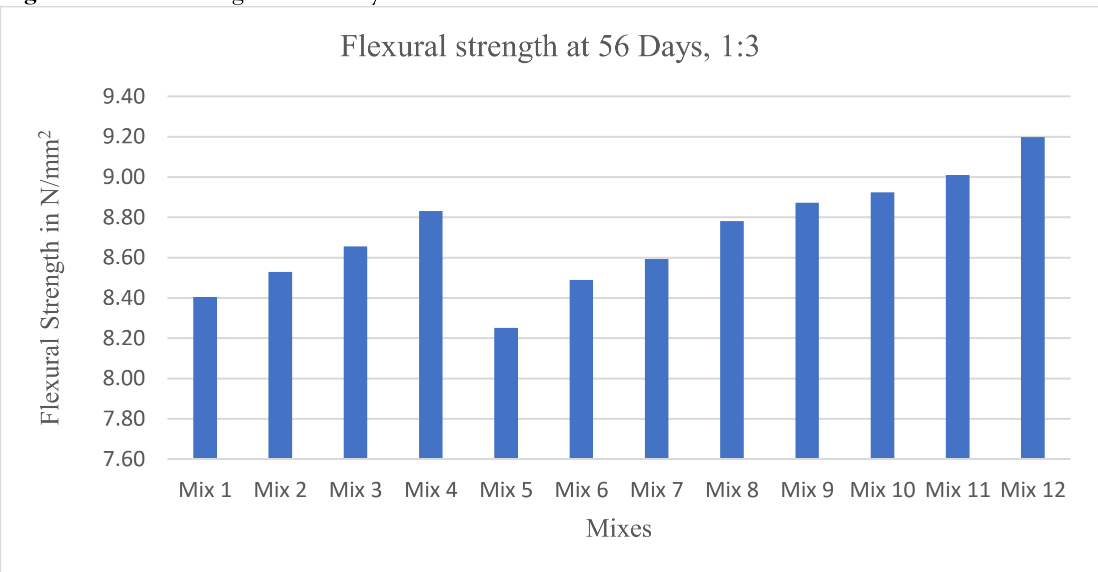

Fig. 10 Flexural strength at 56 days for different mixes for 1:3

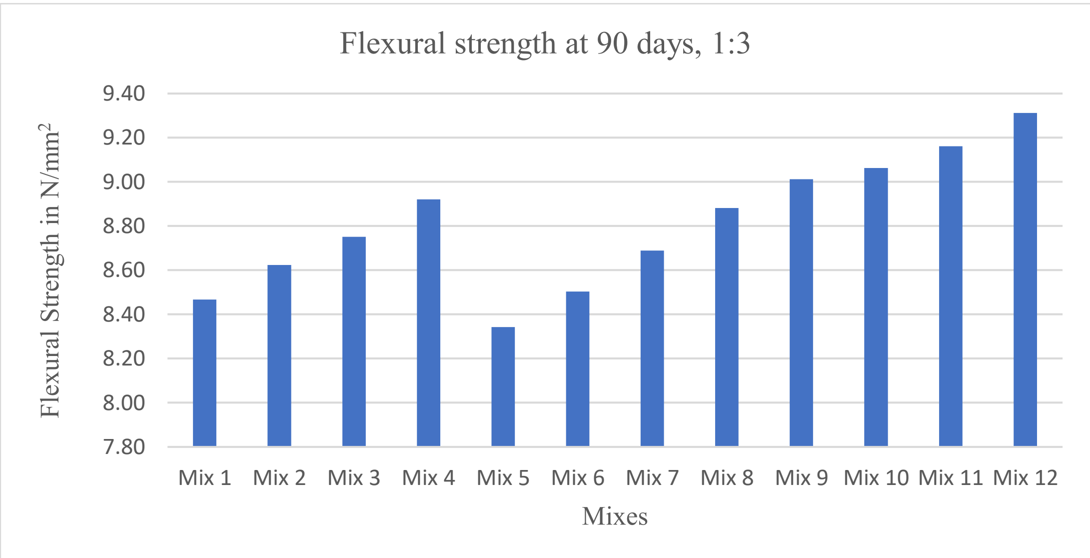

Fig. 11 Flexural strength at 90 days for different mixes for 1:3

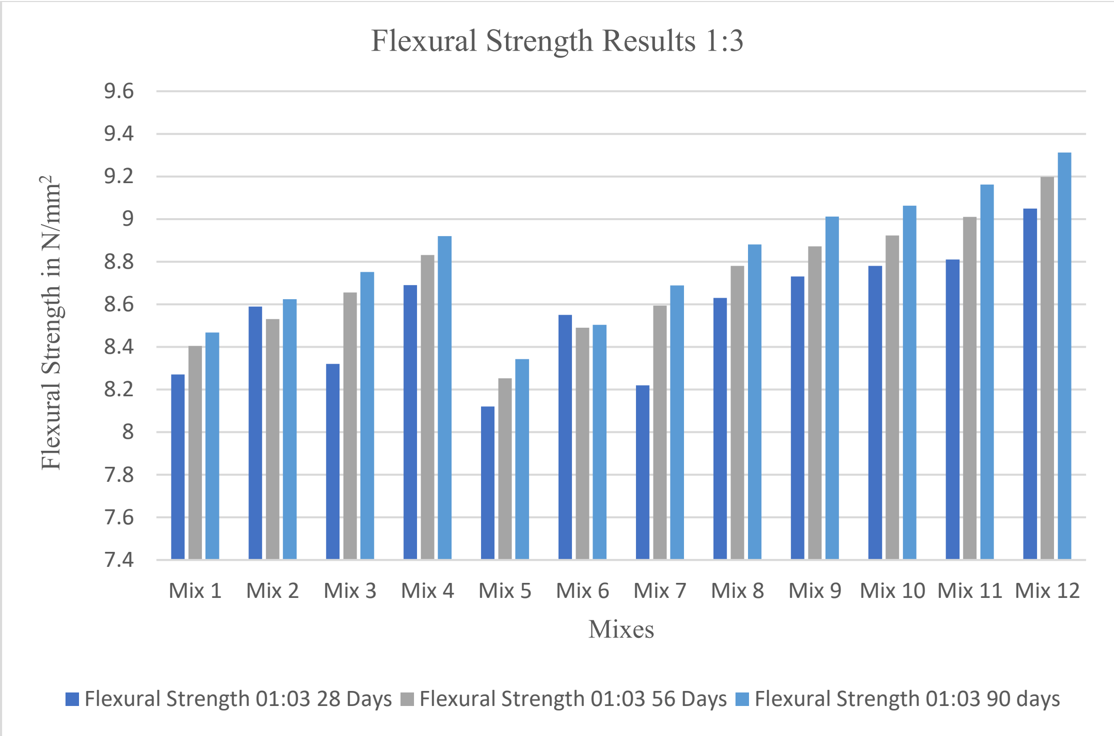

Fig. 12 Flexuralstrength of the mortar mixes at 28,56 And 90 days for 1:3

Figure 9 shows that at 28 days, Mix 12 has the highest value (9.05 MPa), while the control mix records 8.27 MPa. By 56 days (Figure 10), the effect of fibers becomes evident as fiber-containing mixes rise above 9.0 MPa. Figure 11 (90 days) shows Mix 12 attaining 9.31 MPa, and Figure 12 summarizes the trend, showing a steady performance improvement from early to later ages for all fiber-reinforced and hybrid mixes.

Table 6 Flexural strength for 1:4 Cement mortar mix

Flexural Strength			
01:04			
	28 Days	56 Days	90 days
Mix 1	7.72	7.80	7.84
Mix 2	8.02	8.10	8.15
Mix 3	7.79	7.87	7.91
Mix 4	7.96	8.04	8.09
Mix 5	7.61	7.68	7.72
Mix 6	8.01	8.09	8.14
Mix 7	7.68	7.76	7.80
Mix 8	7.91	7.99	8.04
Mix 9	8.02	8.10	8.15
Mix 10	8.09	8.17	8.22
Mix 11	8.12	8.20	8.25
Mix 12	8.33	8.41	8.48

From the table 6, the 1:4 series also shows incremental gains in flexural strength as curing progresses. Mix 12 again stands out, showing an improvement from 8.33 MPa at 28 days to 8.48 MPa at 90 days. Compared to the control mix (7.72 MPa at 28 days and 7.84 MPa at 90 days), there is a clear benefit from the inclusion of supplementary materials and fibers.

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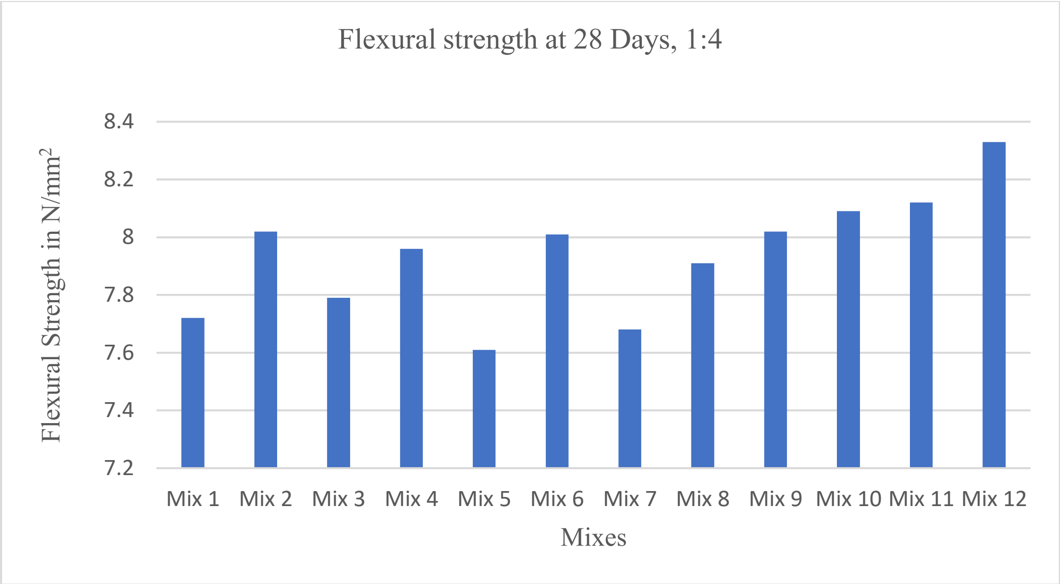

Fig. 13 Flexural strength at 28 days for different mixes for 1:4

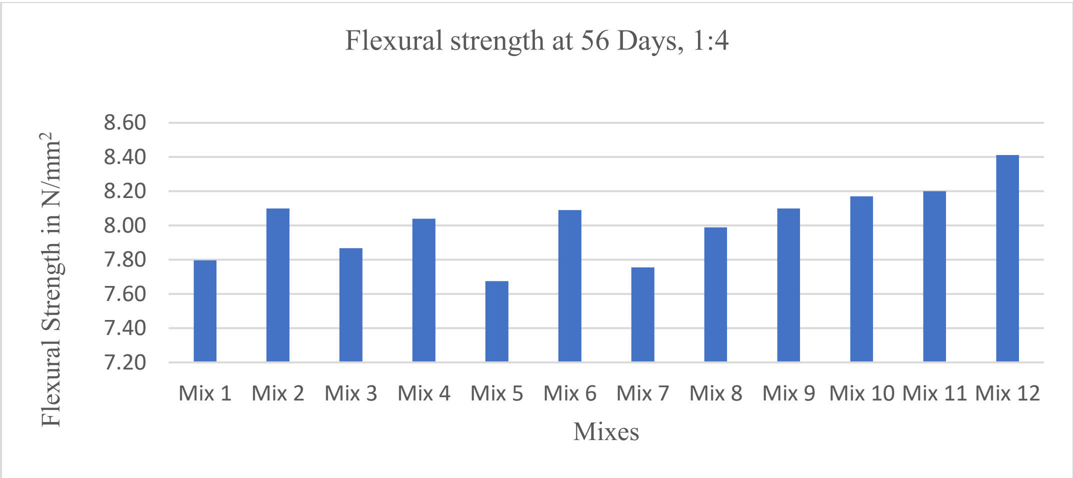

Fig. 14 Flexural strength at 56 days for different mixes for 1:4

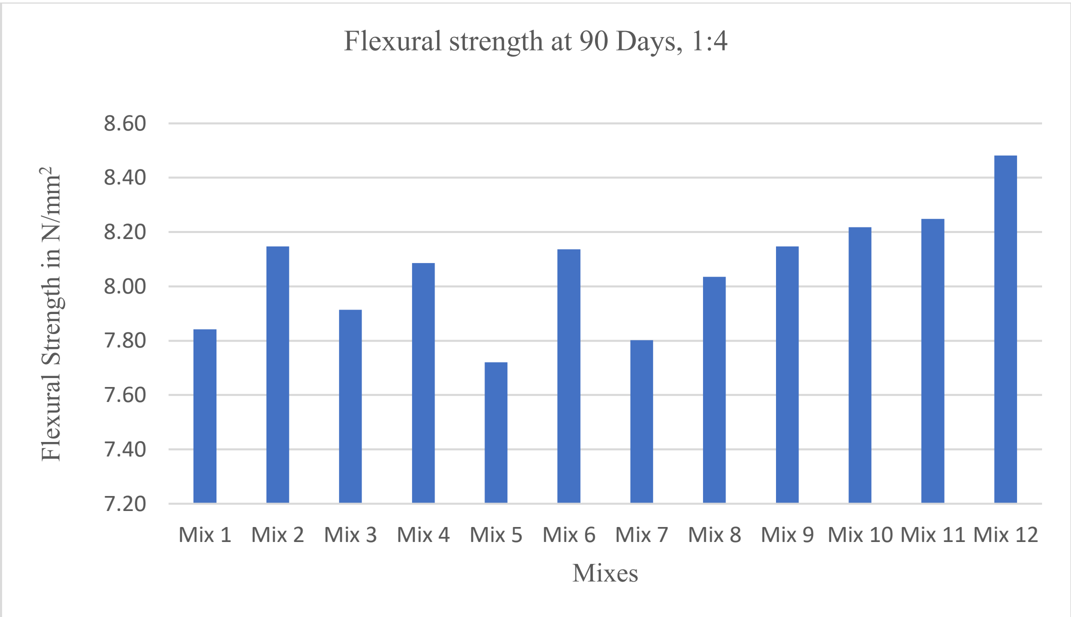

Fig. 15 Flexural strength at 90 days for different mixes for 1:4

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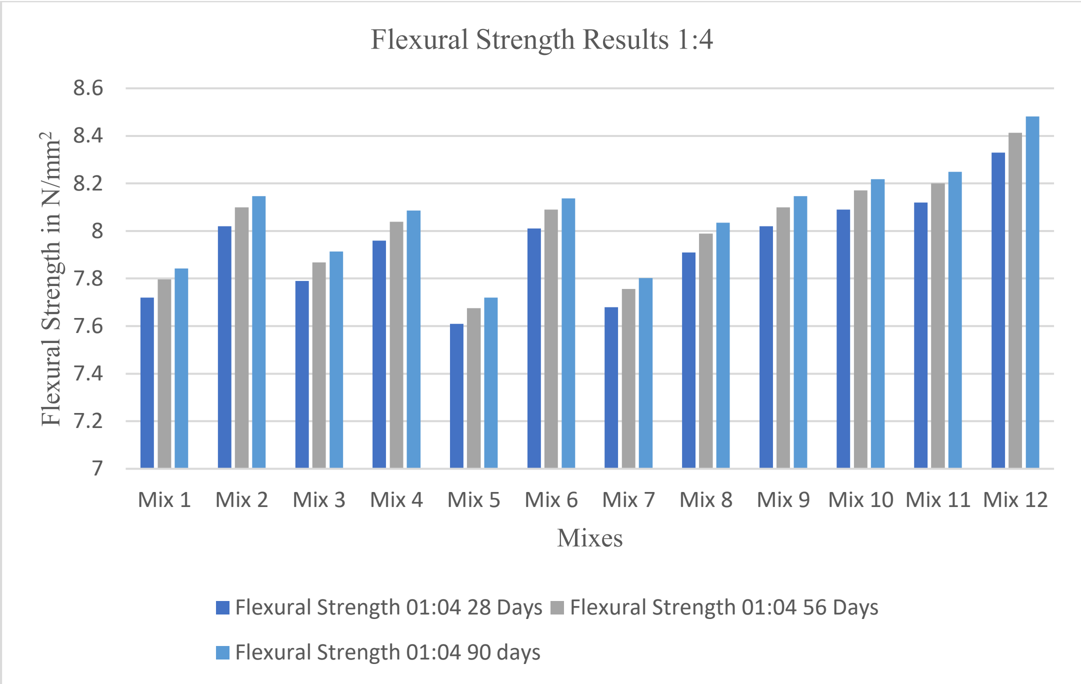

Fig. 16 Flexuralstrength of the mortar mixes at 28,56 And 90 days for 1:4

Figure 13 (28 days) shows Mix 12 with 8.33 MPa, higher than the control (7.72 MPa). Figures 14 and 15 display incremental gains at 56 and 90 days, respectively. By 90 days (Figure 15), Mix 12 achieves 8.48 MPa. Figure 16 presents the overall pattern, reinforcing the benefit of using fibers with M-sand and fly ash.

Discussion of Compressive Strength Trends: we observe that theintegration of fly ash, manufactured sand, and fibers improves long-term compressive strength. Fly ash contributes pozzolanic activity, M-sand enhances packing density, and fibers reduce micro-crack formation. The rate of strength gain slows after 56 days, but hybrid mixes maintain a consistent lead. Comparing mix ratios, 1:3 mortars consistently produce higher values due to the richer binder content, yet the 1:4 mixes show parallel trends, confirming the robustness of the observed effects [34,35]. Discussion of Flexural Strength Trends: it can be seen that fiber incorporation is particularly influential in flexural behavior, as it enhances post-cracking resistance, resulting in better load-bearing capacity at later stages. The gain in flexural strength over time is more gradual than compressive strength but consistent across all modified mixes. The combined mix design (Mix 12) shows the most balanced and superior performance, confirming the importance of material synergy.

5.3 Comparative Analysis of 1:3 vs. 1:4 Ratios

Across all test results, 1:3 mortars consistently outperform 1:4 mortars because of their higher cementitious content. However, the pattern of strength enhancement due to material modifications remains the same for both mix ratios. This implies that even leaner mixes (1:4) benefit substantially from optimized combinations of fly ash, M-sand, and polypropylene fibers.

6. CONCLUSIONS

Based on the compressive and flexural strength results obtained at 28, 56, and 90 days, the following conclusions can be drawn: all mixes exhibited a progressive increase in strength with curing time; mixes containing partial cement replacement with fly ash, partial replacement of river sand with M sand, and polypropylene fibers showed significant improvements in both compressive and flexural strength compared to control mixes; Mix 12, incorporating fly ash,River sand, M sand, and fibers, consistently produced the highest strength in both 1:3 and 1:4 mortars; 1:3 mortars demonstrated higher strength values overall than 1:4 mortars, but the percentage gains from the material modifications were similar in both; these results confirm that incorporating industrial by-products and fibers into mortar is an effective way to produce more sustainable and stronger mortars, reducing reliance on natural sand and cement without compromising structural performance.

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