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Sustainable concrete modified with industrial waste and natural fibre

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Original research paper

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Sustainable concrete modified with industrial waste and natural fibre

This study aims to develop a sustainable concrete with partial replacement of fine aggregate with 70% waste foundry sand (WFS) and 30 % manufactured sand (M-sand), along with 10 % replacement of cement with metakaolin and a constant 0.5% addition of banana fibre. Fresh properties such as the slump value and mechanical properties such as the compressive strength, split tensile strength, and flexural strength of the mixes were examined. The modified concrete mix, F70S30MB, exhibited comparable mechanical properties, achieving 55.6 % higher flexural strength than the control mix, while reducing the embodied energy and embodied carbon by 7.39 % and 7.16 %, respectively. It was concluded that modifying concrete with industrial waste and natural fibres enhances its mechanical properties and reduces the environmental impact, thereby promoting sustainable construction.

Key words:
waste foundry sand, M-sand, metakaolin, natural fibre, mechanical properties, sustainable concrete

Izvorni znanstveni rad

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Održivi beton modificiran industrijskim otpadom i prirodnim vlaknima

Cilj ovog istraživanja jest razvoj održivog betona u kojemu je sitni agregat djelomično zamijenjen sa 70 % otpadnoga ljevaoničkog pijeska iz ljevaonica (WFS) i 30 % umjetnog pijeska (M-sand), dok je cement zamijenjen s 10 % metakaolina i stalnim dodatkom od 0,5 % vlakana banane. Ispitana su svojstva svježeg betona, uključujući slijeganje, te mehanička svojstva, uključujući tlačnu čvrstoću, vlačnu čvrstoću cijepanjem i savijanjem. Modificirana smjesa za beton, oznake F70S30MB, pokazala je usporediva mehanička svojstva u odnosu na referentnu mješavinu, pri čemu je ostvarena savojna čvrstoća bila za 55,6 % veća. Istodobno su utvrđena smanjenja utjelovljene energije i emisije ugljika za 7,39 %, odnosno 7,16 %. Zaključeno je da primjena industrijskog otpada i prirodnih vlakana u betonskim mješavinama doprinosi poboljšanju mehaničkih svojstava te smanjenju negativnog utjecaja na okoliš, što taj pristup čini pogodnim za održivu gradnju.

Ključne riječi:
otpadni ljevaonički pijesak, umjetni pijesak, metakaolin, prirodna vlakna, mehanička svojstva, održivi beton

1. Introduction

Concrete is a widely utilised and user-friendly material in the construction industry that provides excellent strength, durability, and adaptability [1, 2]. Consequently, it is widely used in all types of construction activities [3]. Concrete is composed of cement, aggregates, water, and admixtures. Cement binds to other concrete components and forms a dense matrix through a hydration reaction. Unfortunately, cement production results in huge CO_2 emissions into the environment and is a cause of global warming [4, 5]. It was reported that approximately 8 % of the total CO_2 emissions is caused by cement production [6]. Similarly, the costs associated with cement production increase daily. Accordingly, various alternative materials have been explored, and their suitability for concrete applications has been investigated. Such materials include fly ash [7], Alccofine [8], slag [9], electronic waste [10], silica fume [11], and rice husk ash [12]. Researchers are conducting experiments on the utilisation of these materials as partial replacements for cement to minimise cement production from environmental and economic perspectives. In addition to cement consumption, the utilisation of natural resources in construction projects has increase significantly since 1900 [13]. The overexploitation of natural resources such as gravel and river sand in construction projects is the primary cause of their depletion [14]. River sand, as a raw material for concrete production, is on the verge of disappearance. Furthermore, the dumping of waste in landfills due to industrialisation has a detrimental effect on the environment [15]. In most countries, the consumption of various types of aggregate has increased at a rate far higher than the growth rates of their economies or construction sectors. Hence, artificial or recycled aggregates such as manufactured sand (M-sand) are being widely used [16-18]. M-sand is produced by crushing hard granite stones into fine particles to create a sand-like material. M-sand has been broadly utilised as an alternative to natural river sand in construction projects, particularly in concrete production, masonry, and plastering. M-sand is a well-known and viable alternative to fine aggregates in concrete. It enhances the concrete strength and provides advantages such as decreased pollution and easy accessibility. Despite the numerous advantages of using M-sand in concrete, it has several drawbacks. M-sand concrete usually has lower workability than natural aggregate concrete, and thus, it requires superplasticisers for better workability [19]. Because the production cost of artificial aggregates such as M-sand is relatively high, and their production sites may be located far from construction areas, the added transportation expenses further increase the overall cost [20]. However, the foundry sector generates a large quantity of byproduct during the casting process. Approximately 70 % of the byproduct consists of sand because moulds are typically created using moulding sand, which is inexpensive, easily accessible, and bonds well with binders and other organic elements in the mould [21]. For moulding and casting processes, the foundry industry utilises high-quality silica sand of a specific size. After the sand is successfully recycled and reused several times, foundries remove it from the production process and call it foundry sand, which is no longer usable in their operations. It is also called waste foundry sand (WFS). It is a byproduct of ferrous and non-ferrous metal casting industries. It has been reported that the quality of foundry sand used in construction projects is typically superior to that of river sand. Approximately 100 to 700 foundry units are available in various parts of India, including Howrah, Rajkot, Agra, Jamnagar, Belagavi, Kolhapur, Coimbatore, and Hyderabad [22]. Numerous studies [19, 23-28] have examined the fresh and hardened properties of concrete made with WFS to determine its viability as an alternative to fine aggregates. They concluded that replacing fine aggregates with WFS is possible; however, the replacement level varies. Mehta [28] reported that the utilisation of WFS at replacement levels of 20 %–30 % significantly improved the voids, density, and specific gravity of concrete. This study concluded that a replacement level above 30 % resulted in increased carbonation and reduced resistance to sulphur trioxide. Bhardwaj and Kumar [19] reported that the addition of WFS caused a reduction in compressive strength when compared with that of the reference concrete because of the reduced availability of paste for binding. They concluded that the addition of WFS up to a 20 % replacement level was optimal for a compressive strength comparable to that of conventional concrete. Bilal et al. [27] found that the utilisation of WFS beyond a 30 % replacement level increased the demand for water to achieve the necessary workability of concrete. They found that a replacement level of 40 % with WFS resulted in a 31 % decrease in the slump value compared with that of conventional concrete. Prabhu et al. [23] found that the utilisation of WFS as a fine aggregate in a concrete mix at a replacement level of 20 % resulted in a split tensile strength comparable to that of conventional concrete, whereas beyond a 20 % replacement level, a slight decrease in the split tensile strength was observed. A maximum decrease of approximately 19.32 % in the split tensile strength was observed for a 50 % replacement level with WFS in the concrete. Kavitha et al. [29] concluded that using WFS as a fine aggregate in concrete reduced its compressive strength. This reduction is primarily due to the higher porosity and weaker bond formation of untreated WFS compared with those of natural fine aggregates, such as river sand or M-sand. Supplementary cementitious materials (SCMs), such as ground granulated blast furnace slag (GGBS), fly ash, metakaolin, and silica fume, can induce strength development in WFS-added concrete through secondary hydration reactions. SCMs contain high levels of alumina and silica, which interact with calcium hydroxide to form calcium–silicate–hydrate (C-S-H) gel, which is the primary bending agent that enhances the durability and strength of concrete. The use of WFS combined with SCMs in concrete has been extensively studied. Reshma et al. [30] tested the properties of M40-grade concrete containing 30 % of fly ash as a partial replacement for cement, along with a 0 %–40 % replacement level of fine aggregate with WFS. It was concluded that the optimum replacement level for better fresh and mechanical properties was 30 %, and slight decreases in strength were observed at 40 % replacement level. Karumanchi et al. [31]

reported that optimum mechanical properties were achieved for a mixture with 30 % fly ash and 60 % WFS replacement. However, they concluded that increasing the fly ash content reduced workability, indicating a trade-off between strength and ease of use. Ashish and Verma [32] examined concrete mixes in which metakaolin was used instead of cement and WFS replaced 50 % of the fine aggregate. They found that the presence of alumina in the metakaolin accelerated hydration, resulting in strength improvement. They concluded that the need for a superplasticiser increased to maintain workability. Gholampour et al. [33] studied the properties of concrete made with GGBS and fly ash as cement supplements, along with the inclusion of recycled fine aggregate and WFS as replacement for natural sand. They discovered that the compressive strength of concrete decreased as the replacement levels with recycled fine aggregate and foundry aggregate increased to 100 %. In addition, the strength decreased when fly ash was used instead of cement. However, the combined replacement of cement with 23 % fly ash and 47 % GGBS increased the strength. Shahbaz and Lalotra [34] discovered that, while maintaining the fly ash concentration at 5 %, the compressive strength increased as the amount of foundry sand increased. However, the strength peaked at a 15 % replacement level, with an increase of 24 %, and diminished at a 20 % replacement level. Parashar et al. [35] demonstrated that the higher the GGBS content in the concrete mix, the harder the mix became. Therefore, the optimum mix was made with 30 % WFS and 15 % GGBS. However, its poor tensile properties and ductility are major issues that affect its application. The emergence of fibre-reinforced concrete (FRC) resolved these issues. The impact of the replacement rates of WFS (20 %, 40 %, and 60 %), fly ash (10 %, 20 %, and 30 %), and the addition of steel fibres (1 %, 2 %, and 3 %) on various properties of concrete was examined by Liu et al. [36]. They found that the steel fibre content primarily affected the density, tensile strength, flexural strength, and elastic modulus of the concrete, whereas the WFS content had the most significant effect on the workability and compressive strength. Selvarani and Prabhavathy [37] investigated the mechanical properties of C 25/30 (M30)-grade concrete with the inclusion of 1 kg/m^3 polypropylene fibres and the replacement of fine aggregate with 0 % to 30 % WFS. They observed that a 10 % replacement level with foundry sand, along with the addition of polypropylene fibres, increased the flexural and compressive strengths. Prasath et al. [38] conducted an experiment on glass-fibre-reinforced concrete with foundry sand as a 10 % to 30 % replacement for fine aggregates. DurgaDevi and Chandrasekaran [39] studied the impact of WFS and carbon fibre (CF) on the mechanical and durability properties of C 30/37 (M40)grade concrete. The compressive strength was found to increase by 8.05 % at 7 days and 4.13 % at 28 days upon the addition of 0.5 % CF. However, at higher CF levels (0.75 % and 1.0 %), poor bonding caused by fibre clustering led to decreased strength. Deore et al. [40] concluded that an optimal mix of 30 % WFS and 0.75 % CF improved the mechanical properties with reduced crack formation compared with those of non-fibre specimens. However, a higher CF content resulted in decreased bonding in concrete, ultimately decreasing its overall strength. Abhishekh Soratur et al. [41] explored the mechanical properties of concrete with a 10 % to 30 % replacement level of fine aggregates with WFS and a 0.5 % addition of glass fibres. However, no studies have been performed on the combined use of WFS and metakaolin in natural-fibre reinforced concrete. Studies have been conducted on the combined utilisation of WFS as replacement for fine aggregate and metakaolin as replacement for cement [32], as well as the combined utilisation of WFS as replacement for fine aggregate with the addition of banana fibre [42]. No study has reported the combined utilisation of WFS and M-sand as replacement for fine aggregate and of metakaolin as replacement for cement, along with the addition of banana fibres. To address the insufficient studies on the aforementioned concrete properties, this study aimed to develop a sustainable concrete modified with industrial waste and natural fibre containing WFS and M-sand as replacement for fine aggregate and metakaolin as partial replacement for cement with a constant 0.5 % addition of banana fibre.

2. Material and methodology

2.1. Materials

In this study, materials such as cement, coarse aggregate, WFS, M-sand, metakaolin, and banana fibres were used as the composition for concrete production.

2.1.1. Cement

Ordinary Portland cement (OPC) 53-grade cement manufactured by Ultratech, which complies with IS: 12269-1987 [43] specifications, was used to produce the concrete samples. The fineness of the cement was 309 m^2/kg, which promoted faster hydration and strength development [44]. The physical properties of the cement are listed in Table 1. The chemical composition of the cement is listed in Table 2.

2.1.2. Metakaolin

In this study, commercially available metakaolin was utilised as a mineral admixture to prepare concrete samples as a partial replacement for cement. The replacement level of cement in

Table 1. Physical properties of cement

Properties	Fineness [m^2/kg]	Normal consistency [%]	Setting time		Compressive strength [MPa]		
			Initial [min]	Final [min]	7 days	14 days	28 days
OPC53	309	32	37	460	35.4	45.7	62.4

the concrete mix with metakaolin was approximately 10 %. Many studies [45, 46] have reported that a 10 % replacement level with metakaolin significantly improves the performance of concrete. The metakaolin sample was oven-dried at 100–110 °C to remove moisture. It was then finely ground and sieved to ensure a uniform particle-size distribution. A small amount of the sample was mounted on an aluminium stub using double-sided carbon tape to ensure stability. A thin gold or carbon coating was applied to achieve conductivity. Finally, the sample was placed in the chamber of a scanning electron microscope (SEM) and imaging was performed under high-vacuum conditions. The SEM image of metakaolin (Figure 1) shows that it has an angular, multi-layered, and microporous surface, which exhibits a high surface area and thus promotes high pozzolanic reactivity. The various properties of the metakaolin were determined according to IS: 4031-1985 [47] recommendations. The chemical composition of the metakaolin is presented in Table 2.

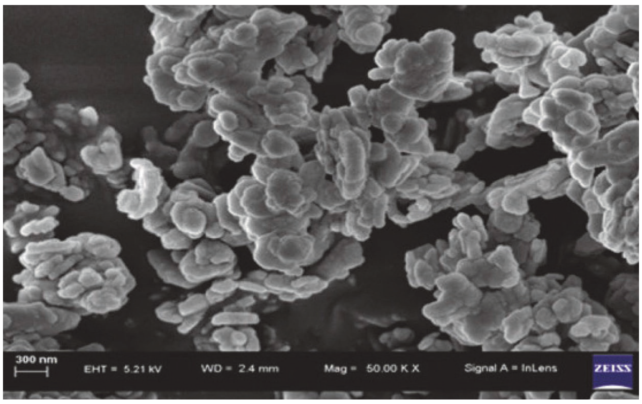

Figure 1. SEM image of metakaolin

Table 2. Chemical compositions of cement and metakaolin

Composition	Cement [%]	Metakaolin [%]
SiO_2	19.35	53.79
Al_2O_3	4.79	40.03
MgO	1.39	0.34
Na_2O	0.05	0.09
SO_3	3.34	-
CaO	68.64	0.14
Fe_2O_3	1.21	1.45
K_2O	-	0.69
TiO_2	-	2.21
P_2O_5	-	0.05
LOI	1.23	1.21

2.1.3. Waste foundry sand (WFS)

WFS is a byproduct of the nonferrous and ferrous metal casting processes, and it is usually sub-angular or round. The WFS utilised in the concrete mix replaced M-sand with a replacement level of approximately 70 %. Nearly 50,000 foundries worldwide produce approximately 69 million metric tons of castings each year [49]. The WFS used in this concrete mix was collected from foundry units in Coimbatore, Tamil Nadu, India. Its particle size ranged from 4.75 mm to 150 μ, corresponding to zone-III grading, and was used as per IS: 383-2016 [48]. The particle size distribution of the WFS samples was analysed as per IS 2386 (Part-2)-1963 [50], as presented in Figure 2. Table 4 lists the properties of the WFS determined according to IS: 2386 (Part-2)-1963 [50] and IS: 2386 (Part-3)-1963 [51] recommendations. The chemical composition of the WFS is presented in Table 3.

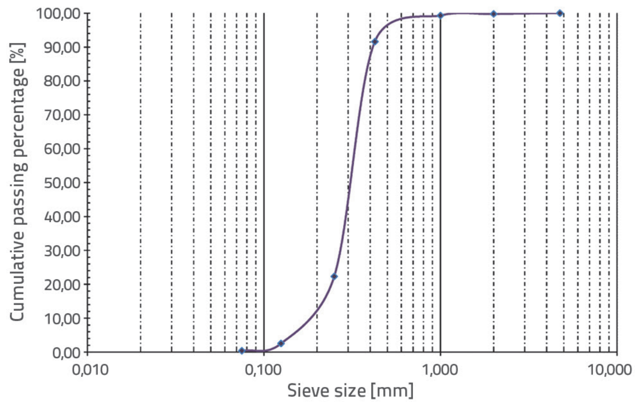

Figure 2. Particle size distribution of waste foundry sand (WFS)

Table 3. Chemical composition of WFS

Components	Composition [%]
SiO_2	98
Al_2O_3	1.18
Fe_2O_3	0.5
CaO	0.26
MgO	0.01
SO_3	0.01
Na_2O	0.04

The waste foundry sand (WFS) sample was oven-dried at 100 to 110 °C to remove moisture. It was then sieved to ensure a uniform particle size distribution. A small amount of the sample was mounted on an aluminium stub using double-sided carbon tape to ensure stability. The prepared WFS sample was then placed in an SEM chamber, and imaging was performed using secondary electron (SE) or backscattered electron (BSE) detectors to analyse the surface morphology and particle characteristics.

The SEM image of the WFS illustrated in Figure 3 reveals that the WFS particles are angular and irregular, which may be due to wear and thermal stress during the casting process. This angularity may affect the packing and binding properties of sand in applications such as concrete. The presence of a rough, uneven surface with pores or voids indicates that the sand particles were subjected to thermal fracturing [52]. This rough texture can facilitate better bonding with cement when used in concrete and increase mechanical interlocking.

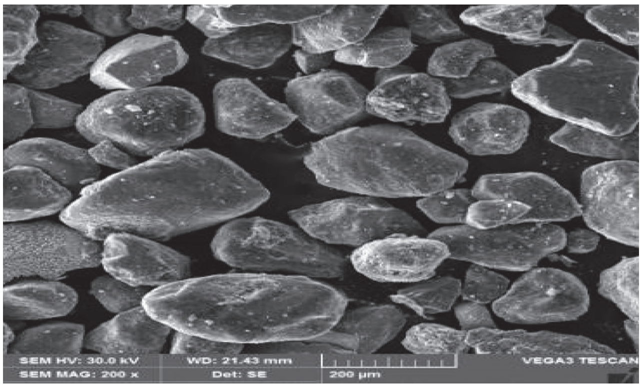

Figure 3. SEM image of WFS

2.1.3. M-Sand

Locally available M-sand was used as the fine aggregate for concrete production. The particle size of M-sand ranges from 4.75 mm to 150-micron size and falls under zone-III grading as per IS: 383-2016 [48]. The particle size distribution of the M-sand samples was analysed as per IS: 2386 (Part-2)-1963 [50], as shown in Figure 4.
Table 4 lists the properties of M-sand determined according to the IS: 2386 (Part-2)-1963 [50] and IS: 2386 (Part-3)-1963 [51] recommendations. The replacement levels of natural river sand with M-sand in the concrete mix were 100 % and 30 %.

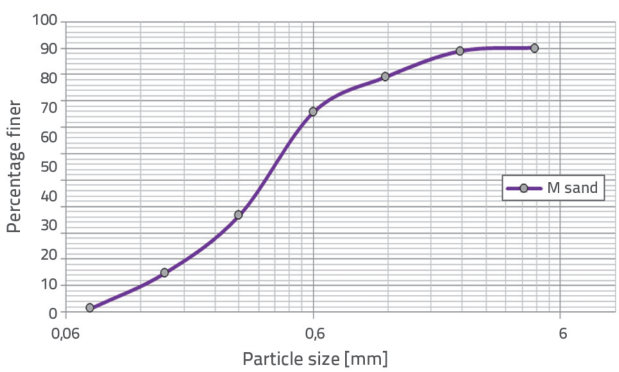

Figure 4. Particle-size distribution of M-sand

Table 4. Properties of the M-sand and WFS

No.	Properties	M-sand	WFS
1.	Specific gravity	2.65	2.7
2.	Fineness modulus	2.73	2.72
3.	Water absorption [%]	0.67	0.43
4.	Unit weight [kg/m³]	2590	2500

2.1.5. Coarse aggregate

Coarse aggregates used as fillers in concrete account for approximately 90 % of its total volume. In this study, coarse aggregates with a maximum particle size of 20 mm were used for concrete production. Specific gravity and water absorption tests were conducted as per IS 2386 (Part-3)-1963 [51], whereas the crushing, impact, and abrasion values of the coarse aggregate were tested in accordance with IS 2386 (Part-4)-1963 [53], and the values are listed in Table 5.

Table 5. Coarse aggregate properties

Properties	Value
Water absorption [%]	1.2
Specific gravity	2.69
Crushing value [%]	16.72
Impact value [%]	15.63
Abrasion value [%]	2.61
Fineness modulus	5.15

2.1.6. Water

Tap water free of organic compounds, oils, alkalis, acids, salt, and sugar was used in this study for concrete production. The pH of the water used for the concrete mix was 7.1, fulfilling the IS: 456-2000 [54] requirements for concrete production.

2.1.7. Banana fibre

The strength properties of concrete, especially the compressive strength and split tensile strength, were significantly enhanced by the incorporation of banana fibres. The banana fibres used in this study were obtained from a local village in Tamil Nadu and treated before use in concrete. Banana stem fibres were extracted using the water-wetting technique. The banana trunk, as shown in Figure 5, was cut to a length of approximately 500 mm, separated into smaller sizes by hand, as shown in Figure 6, and immersed in water for 14 days. Water penetrates the central stalk portion by rupturing the outermost layer, and then the fibres are separated, as shown in Figure 7.

Figure 5. Banana plant

Figure 6. Banana stem

Figure 7. Extracted banana fibres

Figure 8. Treated fibre

The extracted fibres were subjected to alkaline treatment to remove non-cellulosic components such as hemicellulose and lignin. An NaOH solution was prepared by diluting 3 wt. % NaOH in 250 ml of distilled water. The banana fibres were soaked in the prepared NaOH solution for 1 h at room temperature with intermittent stirring to remove cellulose, hemicellulose, pectin, and lignin. The fibres were then washed several times with distilled water to remove any alkali solution from their surfaces. The fibres were then neutralised with diluted 5 % (w/v) citric acid and repeatedly cleaned with water. The fibres were then allowed to dry for several hours in the open air and dried for further 24 h at 60 °C in an oven. The treated banana fibres are presented in Figure 8. The obtained banana fibre was cut into equal sizes (25 mm in length and 0.24 mm in diameter), as presented in Figure 9. The proportion of banana fibre utilised in the concrete mix was 0.5 % by cement mass. Many existing studies [55, 56] have reported that the 0.5 % addition of banana fibre causes significant performance improvement in concrete. The physical properties of the banana fibres were tested according to the ASTM D3822 [57] guidelines and are presented in Table 6.

Figure 9. Banana fibre

Table 6. Physical properties of banana fibres

Properties	Value
Length	25 mm
Diameter	0.24 mm
Aspect ratio	104
Young's modulus	3.5 MPa
Ultimate strength	56 MPa
% Elongation	10.35
Moisture content	11 %

2.2. Methodology

This study investigates the combined effect on the concrete's mechanical properties of replacing fine aggregate with WFS and M-sand, and cement with 10 % metakaolin, along with 0.5 % banana fibre addition. Using IS: 10262-2019 [58], the mix

Table 7. Mix proportioning

Designation	Cement [kg/m³]	Water [kg/m³]	Metakaolin [kg/m³]	M-sand [kg/m³]	WFS [kg/m³]	Coarse aggregate [kg/m³]	Banana fibre [kg/m³]
CC	413	185.85	-	682	-	1167	-
F100	413	185.85	-	-	682	1167	-
F70S30	413	185.85	-	204.6	477.4	1167	-
F70S30M	371.7	185.85	41.3	204.6	477.4	1167	-
F70S30MB	371.7	185.85	41.3	204.6	477.4	1167	2.065

proportion for M25-grade concrete was designed and around 15 trial mixes were prepared by varying the proportions of cement, M-sand, coarse aggregate, and water with the aim of achieving the 28-day target strength of 31.6 MPa. The control mix that achieved the target strength and workability was modified using the proposed replacement. Numerous tests were designed and conducted according to the Bureau of Indian Standard (BIS) and American Society for Testing and Materials (ASTM) recommendations. The concrete mixtures developed in this study are listed in Table 7.

Figure 11. Test specimens

3. Experimental investigations

3.1. Preparation of concrete specimens

For the CC mix, the cement, M-sand, and coarse aggregate were measured and batched in the necessary amounts as per the mix design. Subsequently, the materials were poured into a concrete mixer and mixed under dry conditions for 1 min. Water was then added to the mixture and mixed continuously. The total mixing time for complete mixing was 90 s. The primary goal of mixing was to consistently create a uniform mixture of cement, water, and fine and coarse aggregates in each batch. Freshly mixed concrete, as shown in Figure 10, was tested to measure its workability using a slump cone as per IS: 1199-1959 [59] standards.

Figure 10. Concrete mix

Workability tests were conducted using a slump cone equipment with a height of 300 mm, top diameter of 100 mm, and bottom diameter of 200 mm. Simultaneously, the freshly prepared concrete was filled in a cube mould of size 100 × 100 × 100 mm, a cylinder mould of 200 mm in height and 100 mm in diameter, and a prism mould of size 100 × 100 × 500 mm, as shown in Figure 11. The specimens were then cast as per IS: 516-2021 [60] with respect to various tests utilising steel moulds and compacted in two uniform layers using a table vibrator to provide external vibration as per ACI 544-1996 [61] and obtain the proper compaction of concrete. After 24 h of moisture curing, the test samples were removed from the mould and immersed in a curing tank for 7, 14, and 28 days from the casting day. The above procedure was followed for the CC, F100, F70S30, F70S30M, and F70S30MB concrete mixes based on their respective mix proportions, as listed in Table 7. In total, 45, 45, and 45 prism test specimens were cast for testing at 7, 14, and 28 days to determine the compressive, split tensile, and flexural strengths of the CC, F100, F70S30, F70S30M, and F70S30MB concrete mixes, respectively.

3.2. Mechanical properties and testing methods

The compressive strength, split tensile strength, and flexural strength of the CC, F100, F70S30, F70S30M, and F70S30MB concrete mixes were measured after 7, 14, and 28 days of curing with the cube, cylinder, and prism specimens tested according to IS: 516-2021 [60] standards using a compression testing machine (CTM) and a universal testing machine (UTM), as shown in Figures 12 to 14. Three specimens were tested to measure the average compressive strength, split tensile strength, and flexural strength of all mixtures at the three ages.

Figure 12. Compressive strength test setup

Figure 13. Split tensile strength test setup

Figure 14. Flexural strength test setup

4. Results and discussions

4.1. Workability of concrete

The workabilities of the CC, F100, F70S30, F70S30M, and F70S30MB concrete mixes in terms of the slump are presented in Table 8.

According to IS: 1199-2018 [59] and IS: 456-2000 [54], the slump values of the developed mixes fall under the categories of high and medium degrees of workability. The CC mix had a slump of 150 mm, which provided a high degree of workability and was easy to compact. The F100 mix resulted in a slump of 115 mm that fell under a high degree of workability, but was 23.33 % less than that of the CC mix because of the angular shape of the WFS particles. This outcome was consistent with the conclusion of Parashar et al. [62], who also concluded that the incorporation of WFS particles decreases the slump value of concrete because of the angularity of the particles. Similarly, Akmal et al. [63] reported that the utilisation of angular particles in concrete adversely affects flowability. The slump value of the F70S30 mix was 100 mm, which was approximately 33.33 % lower than that of the CC mix, but still had a high degree of workability. The F70S30M mix possessed a slump value of 110 mm, which was 26.67 % lower than that of the CC mix, indicating a high degree of workability despite the presence of metakaolin, which typically reduces fluidity. The F70S30MB mix possessed a slump of 75 mm, which was 50 % and 34.78 % lower than those of the CC and F100 mixes, respectively. The decrease in the slump value of F70S30 compared with that of F100 was due to the rougher texture and higher water absorption of M-sand. Among all the mixes, the lowest slump value was observed for F70S30MB, primarily owing to fibre-induced water absorption and its interlocking effects, further restricting workability. However, F70S30MB exhibited a medium degree of workability.

Table 8. Slump values of various mixes

Concrete Mix	Slump value [mm]	Degree of workability
CC	150	High
F100	115	High
F70S30	100	High
F70S30M	110	High
F70S30MB	75	Medium

4.2. Compressive strength of concrete

Figures 15.a to 15.c graphically present the variations in the compressive strengths of the CC, F100, F70S30, F70S30M, and F70S30MB concrete mixes at various curing days. The compressive strengths of the F100 mix were 16.3 %, 14.9 %, and 15.4 % lower than those of the CC mix at 7, 14, and 28 days, respectively. In other words, the complete replacement of M-sand with WFS in concrete decreased its compressive strength by 15 %. This reduction may be due to the rough texture of the WFS particles, which may prevent adequate compaction. A rough texture, particularly that of irregular or angular particles, hinders the creation of a densely packed concrete structure during compaction. The trapped air voids arising from improper compaction act as weak points, thereby reducing the compressive strength of the concrete. The compressive strengths of the F70S30 mix were 9.5 %, 7.8 %, and 8.3 % lower than those of the CC mix at 7, 14, and 28 days, respectively. However, the compressive strengths of the F70S30 mix were 8.1 %, 8.3 %, and 8.4 % higher

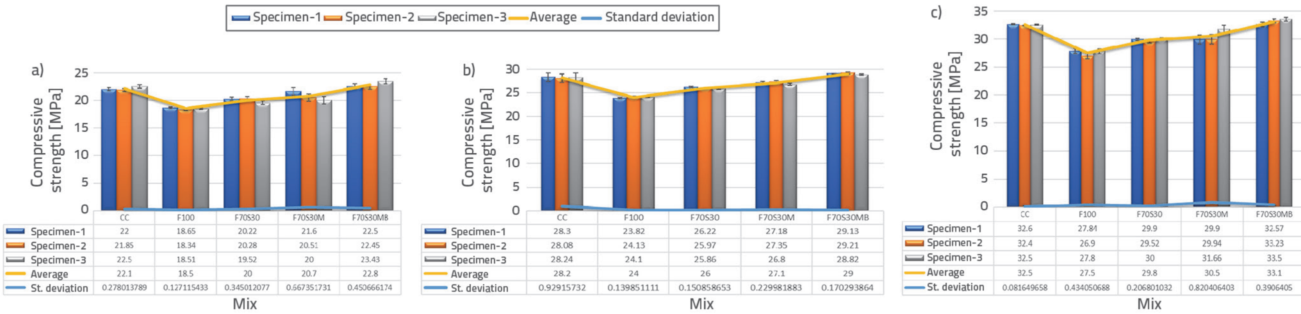

Figure 15. Variation in the compressive strength of various concrete mixes at: a) 7 days; b) 14 days ; c) 28 days

than those of the F100 mix at 7, 14, and 28 days, respectively. The F70S30 mix achieved almost 94 % of the compressive strength of CC after 28 days. The inclusion of 30 % M-sand along with WFS improved the strength by enhancing the particle packing and bonding within the mix, thus mitigating some of the weaknesses of using only WFS in the concrete. It was observed that the compressive strength of the F70S30M mix containing 70 % WFS, 30 % M-sand, and 10 % metakaolin for cement at 28 days was similar to the compressive strength of the CC mix at 28 days with a variation of only 6 %. However, the compressive strength of the F70S30M mix was higher than those of the F100 and F70S30 mixes because of the inclusion of metakaolin. The compressive strengths of the F70S30M mix were 11.9 %, 12.9 %, and 10.9 % higher than those of the F100 mix at days 7, 14, and 28, respectively. This indicates that the inclusion of metakaolin can compensate for some of the strength losses associated with the utilisation of 100 % WFS. Metakaolin, a pozzolanic material, increases the compressive strength by promoting the formation of additional calcium silicate hydrate (C-S-H), which densifies the concrete matrix and thus contributes to the increased compressive strength. The F70S30MB mix containing 70 % WFS and 30 % M-sand along with 10 % metakaolin for cement and 0.5 % addition of banana fibre achieved a compressive strength of 22.8 MPa at 7 days, 29 MPa at 14 days, and 33.1 MPa at 28 days. It was found that the compressive strength of the F70S30MB mix was 1.8 % and 20.4 % higher than the compressive strengths of the CC and F100 mixes at 28 days, respectively, further surpassing the target compressive strength of C 20/25 (M25) grade concrete. Kavitha et al. [29] concluded that the utilisation of more than 40 % WFS as fine aggregate in concrete decreased the compressive strength. In contrast, this study showed that the inclusion of 70 % WFS and 30 % M-sand for fine aggregate, along with 10 % replacement of cement with metakaolin and 0.5 % addition of banana fibre, led to a slight improvement in compressive strength and achieved a strength equivalent to that of the CC mix. This suggests that WFS at high replacement levels can be used without compromising the strength if metakaolin and banana fibres are used. Therefore, this approach enhances concrete sustainability and contributes to the utilisation of waste in construction. Reshma et al. [30] reported that beyond a 40 % replacement level of fine aggregate with WFS in concrete, the compressive strength of fly ash concrete was reduced; however, it was 8.32 % higher than that of the control mix at 90 days. In contrast, this study demonstrated that a mix of 70 % WFS and 30 % M-sand as replacement for fine aggregate along with 10 % replacement of cement with metakaolin and 0.5 % addition of banana fibre improved the early strength, which was 1.8 % higher than that of the control mix at 28 days. This implies that combining WFS with M-sand, metakaolin, and banana fibre improves strength in a shorter curing period, promoting faster, sustainable concrete solutions without compromising performance. The combined addition of metakaolin and banana fibres has a synergetic effect on the strength properties of concrete. The pozzolanic reaction increases the cement matrix, whereas the banana fibres can bridge the microcracks formed during loading [64, 65], thus improving the toughness of the materials. Zai et al. [66] reported that the utilisation of 50 % WFS as replacement for fine aggregate with a 1 % addition of glass resulted in a 9.51 % reduction in the compressive strength. However, a compressive strength approximately 1.8 % higher than that of the control mix was achieved with the utilisation of 0.5 % banana fibre along with 70 % WFS and 30 % M-sand as replacement for fine aggregate, and 10 % metakaolin instead of cement at 28 days. This study highlights the potential of banana fibre as a sustainable alternative to traditional synthetic fibres such as glass fibre in concrete. In addition, the combined use of alternative fine aggregates, such as WFS and M-sand, along with supplementary materials, such as metakaolin, presents an effective strategy for sustainable concrete production. This approach not only enhances the concrete performance but also reduces the environmental impact by minimising the reliance on virgin materials. It has been concluded that the inclusion of WFS and M-sand into concrete without the incorporation of SCMs, such as metakaolin and banana fibres, results in a decrease in strength. Similar findings were reported by Safiuddin et al. [67] and Raman et al. [68], who reported that the inclusion of quarry dust as a replacement for fine aggregate in concrete without the incorporation of SCMs such as fly ash results in a reduction in strength.

4.3. Split tensile strength of concrete

Figures 16.a to 16.c graphically present the split tensile strengths of the CC, F100, F70S30, F70S30M, and F70S30MB concrete mixes at various curing days. The split tensile strengths of the F100 mix containing 100 % WFS were 12.5 %, 11.3 %, and 11.5 % lower than those of the CC mix at days 7, 14, and 28, respectively. It was observed that the 100 % replacement of M-sand with WFS reduced the split tensile strength, with the F100 mix showing 12.5 %, 11.3 %, and 11.5 % lower values than the CC mix. The uneven and rough surfaces of the WFS particles with visible pores, as shown in the SEM image (Figure 2), caused by thermal fracturing during the casting process, might improve their mechanical interlocking with the cement paste in concrete. However, the roughness of the aggregate may enhance certain bonding properties that are absent from the packing efficiency and cohesion of M-sand [69]. This scenario was observed in this study, where there was a reduction in the split tensile strength with the use of WFS in concrete as a fine aggregate. The splitting tensile strengths of the F70S30 mix were 9.5 %, 7.8 %, and 8.3 % higher than those of the CC mix at 7, 14, and 28 days, respectively. The inclusion of the finer and smoother M-sand particles mitigated these effects by filling the gaps between WFS particles. Consequently, the cohesion and density of the mix improved, thereby increasing the splitting tensile strength of the concrete. Similarly, the split tensile strengths of the F70S30 mix were 18 %, 14.74 %, and 12.24 % higher than those of the F100 mix at 7, 14, and 28 days, respectively. The F70S30M mix accomplished a split tensile strength of 1.72 MPa at 7 days, 1.90 MPa at 14 days, and 2.53 MPa at 28 days, respectively. The split tensile strengths of the F70S30M mix were 29.32 %, 21.7 %, and 19.33 % higher than those of the F100 mix at 7, 14, and 28 days, respectively. The high strength of the F70S30M mix was due to the combined effect of metakaolin and M-sand. The finer particles of M-sand improved the packing and density by filling the gaps left by the angular WFS particles, whereas metakaolin improved the cement matrix through its pozzolanic reaction, producing more C-S-H gel, which increased the split tensile strength. The F70S30MB mix accomplished a split tensile strength of 1.96 MPa at 7 days, 2.81 MPa at 14 days, and 3.3 MPa at 28 days. The split tensile strength of the F70S30MB mix was 25.9 % and 55.6 % higher than those of the CC and F100 mixes at 28 days, respectively. This higher split tensile strength was caused by the combined effect of metakaolin, M-sand, and banana fibres. The finer M-sand particles filled the voids between the WFS particles, thereby improving the density and cohesion of the concrete mix. Through its pozzolanic reaction with calcium hydroxide, metakaolin formed an additional C-S-H gel, which strengthened the cement matrix and improved bonding. The inclusion of banana fibre further increased the tensile strength when compared to that of the concrete mix without fibre by bridging the microcracks formed during loading. This findings of this study align with those of earlier studies [30, 36, 42, 70, 71]. Liu et al. [36] reported a 33.5 % increase in the split tensile strength using 34 % WFS, 20 % fly ash, and 2.3 % steel fibres, whereas this study achieved a 55.6 % increase with 70 % WFS, 30 % M-sand, 10 % metakaolin, and 0.5 % banana fibre. Salim et al. [70] evaluated the impacts of pulverised used foundry sand (PUFS) as mineral admixture at a rate of 5 %, 10 %, 15 %, and 20 %. The addition of 5 %, 10 %, 15 %, and 20 % PUFS to the concrete mix increased the split tensile strength by 4.68 %, 9.72 %, 11.46 %, and 7.99 %, respectively. In contrast, this study showed that the inclusion of 70 % WFS and 30 % M-sand for fine aggregate along with 10 % replacement of cement with metakaolin and 0.5 % addition of banana fibre resulted in a 55.6 % increase in the split tensile strength. This substantial improvement in the split tensile strength highlights the effectiveness of combining a high content of WFS and M-sand as fine aggregates rather than using WFS as a mineral admixture in concrete. Sandhu and Siddique [71] reported that incorporating WFS at replacement levels in the range of 5 % to 30 % reduced the split tensile strength of fly ash-added concrete by 3.63 % to 11.03 % compared with that of the control mix at 28 days. Compared with Reshma et al. [30], who reported an 8.91 % increase with 40 % WFS, this study demonstrated a maximum of 55.6 % improvement in the split tensile strength with the utilisation of 70 % WFS and 30 % M-sand as fine aggregates, 10 % metakaolin, and 0.5 % banana fibre at 28 days. The results demonstrate that a higher WFS content combined with M-sand, metakaolin, and banana fibre can substantially enhance the split tensile strength of concrete, surpassing that of the modified concrete mixes proposed in earlier studies and advancing sustainable construction practices. Mouli et al. [42] used 15 % metakaolin as a replacement for cement, and the addition of 3 % banana fibre increased the split tensile strength by 43.39 % at 28 days. This study demonstrated a maximum 55.6 % increase in split tensile strength with the utilisation of 70 % WFS and 30 % M-sand as fine aggregates, 10 % metakaolin, and 0.5 % banana fibre at 28 days. The results suggest that even a lower

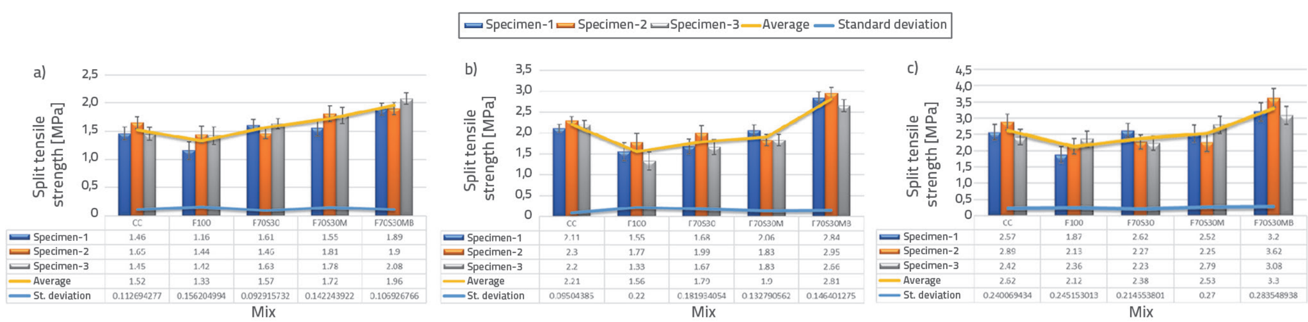

Figure 16. Variation in the split tensile strength of various concrete mixes at: a) 7 days; b) 14 days ; c) 28 days

percentage of banana fibres (0.5 %) can contribute significantly to the tensile strength. Furthermore, the results demonstrate that the utilisation of WFS and M-sand as fine aggregates, along with metakaolin and banana fibres as admixtures, promotes sustainable construction practices.

4.4. Flexural strength of concrete

Figures 17.a to 17.c graphically present the flexural strengths of the CC, F100, F70S30, F70S30M, and F70S30MB concrete mixes after various curing days. The flexural strengths of the F70S30 mix were 10 %, 5.7 %, and 5 % lower than those of the CC mix at 28 days, respectively. In contrast, Kumar et al. [72] found that the flexural strength of a concrete mix containing 50 % WFS and 50 % M-sand as fine aggregate was 12.86 % higher than that of a CC mix containing 100 % M-sand as fine aggregate at 90 days. This implies that a high content of WFS may improve the flexural strength of concrete, particularly at longer curing ages. However, this study demonstrated that the flexural strengths of the F70S30 mix were 8 %, 10 %, and 8.57 % higher than those of the F100 mix. This higher flexural strength of the F70S30 mix over the F100 mix was due to the better packing caused by the synergetic effect of M-sand and WFS in the concrete mix. The flexural strength of the F70S30M mix was found to be 6.7 %, 2.9 %, and 2.5 % lower than that of the CC mix. However, the flexural strengths of the F70S30M mix were 8 %, 10 %, and 8.6 % higher than those of the F100 mix at 6, 14 and 28 days, respectively. Similarly, the flexural strength of the F70S30M mix was found to be slightly higher (3.7 %, 3.03 %, and 2.63 %) than that of the F70S30 mix at 7, 14, and 28 days. This slight improvement in the flexural strength of the F70S30M mix over that of the F70S30 mix was due to the pozzolanic reaction of metakaolin, which improved the concrete matrix by the formation of more C-S-H gel, leading to better bonding and cohesion. This implies that metakaolin partially compensates for the reduced flexural strength caused by WFS.

The flexural strengths of the F70S30MB mix containing 70 % WFS and 30 % M-sand as fine aggregates, 0.5 % banana fibre, and 10 % metakaolin as a replacement for cement were 3.3 %, 2.9 %, and 5 % higher than those of the CC mix at 7, 14, and 28 days, respectively. The addition of banana fibres improves the flexural properties by bridging microcracks, enhancing energy absorption, and increasing resistance to crack propagation. Similarly, the flexural strengths of the F70S30MB mix were 24 %, 20 %, and 20 % higher than those of the F100 mix at 7, 14, and 28 days, respectively. Reshma et al. [30] observed that a 30 % replacement of fine aggregate with WFS can increase the flexural strength by 7.57 % at 90 days, whereas this study achieved a 5 % increase in the flexural strength with 70 % WFS, 30 % M-sand, 10 % metakaolin, and 0.5 % banana fibre at 28 days. Although a slight improvement in the flexural strength was observed in this study, the optimised mix with the combination of a higher content of WFS with M-sand as fine aggregate, metakaolin, and banana fibre provides a viable and sustainable mix that achieves early flexural strength gains, supporting its potential for eco-friendly construction with satisfactory structural performance. Selvarani and Prabhavathy [37] observed that a 10 % replacement level with WFS and 1 % polypropylene fibres increased the flexural strength by 4.1 % at 28 days. In comparison, this study used 70 % WFS, 30 % M-sand, 10 % metakaolin, and 0.5 % banana fibre in concrete to enhance the flexural strength by 5 % after 28 days. Accordingly, the flexural strength may be increased even more efficiently by combining a high WFS content, natural fibres (banana fibres), and supplementary materials such as metakaolin than by combining a lower WFS content with reinforcement such as synthetic fibres. Aggarwal and Siddique [73] reported that the replacement of fine aggregate with equal amounts of WSF and fly ash reduced the flexural strength by 7.66 %–18.92 % at 28 days. By contrast, this study demonstrated that the inclusion of 70 % WFS and 30 % M-sand as replacement for fine aggregate, along with the addition of 10 % metakaolin and 0.5 % banana fibre in the concrete, improved the flexural strength by 5 % at 28 days. By comparing the results of this study with those of Aggarwal and Siddique [73], it was found that using a high WFS content in the concrete along with the inclusion of metakaolin and banana fibres improved its flexural strength and surpassed the results obtained by Aggarwal and Siddique [73], who used WFS and fly ash as fine aggregates in concrete.

4.5. Embodied energy and carbon of concrete

This study focused on the development of sustainable concrete. Hence, measurement of the embodied energy

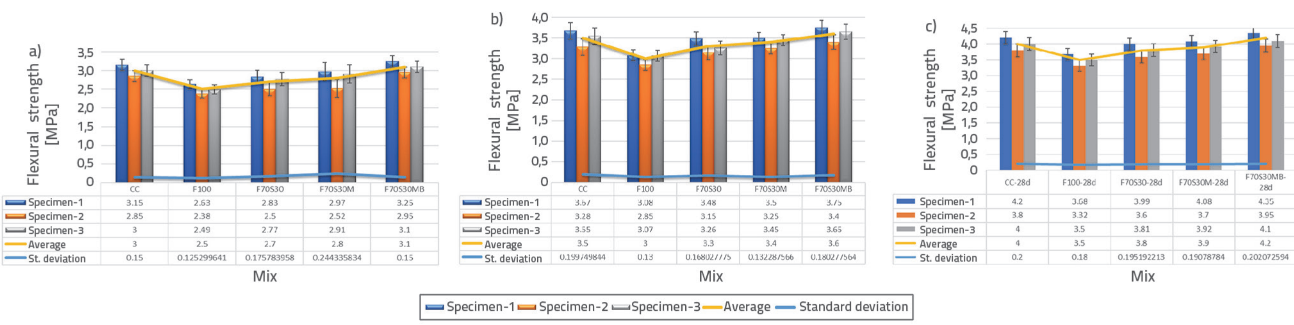

Figure 17. Variation in the flexural strength of various concrete mixes at: a) 7 days; b) 14 days ; c) 28 days

Table 9. Embodied energy and carbon of CC and F70S30MB concrete mixes

Component	**Embodied energy** [MJ/m^3]		**Embodied carbon** [kg CO_2-eq/m^3]	
	CC Mix	**F70S30MB Mix**	**CC Mix**	**F70S30MB Mix**
Cement	2416.05	2174.44	384.09	345.68
Water	0	0	0	0
Metakaolin	0	53.69	0	10.32
M-sand	55.24	16.57	2.73	0.82
Coarse aggregate	98.86	96.86	5.83	5.83
WFS	0	38.67	0	1.91
Banana fibre	0	0	0	0
Total	2570.15	2380.23	392.65	364.56

and carbon in the modified concrete mixes was essential. Based on the mechanical properties of the CC, F100, F70S30, F70S30M, and F70S30MB concrete mixes, it was observed that the F70S30MB concrete mix was optimal as it demonstrated the best balance between mechanical performance and environmental viability, with enhanced strength properties incorporating waste foundry sand as fine aggregate. Hence, the embodied energy and carbon of the F70S30MB concrete mix was observed and compared with those of the CC mix. Embodied energy is the total energy consumed for the extraction, production, transportation, and processing of all the materials used in the concrete mix. Embodied carbon is defined as CO_2 associated with this process. The evaluation of these factors makes it easier to determine the environmental effects of each concrete mix produced. The embodied energy and carbon of the F70S30MB concrete mix were determined according to the Inventory of Carbon and Energy (ICE) database and compared with the embodied energy and carbon of the CC mix. The embodied energy and carbon of the CC and F70S30MB concrete mixes are listed in Table 9.

The embodied energy and embodied carbon of the F70S30MB concrete mix were 7.39 % and 7.16 % lower, respectively, than those of the CC mix. The utilisation of the F70S30MB concrete mix in construction projects represents a significant step towards more sustainable concrete production. The decrease in embodied energy and carbon is an outcome of innovative material compositions that encourage the use of SCMs and recycled aggregates. These reductions not only contribute to a reduction in environmental impact, but also align with broader sustainability goals within the construction industry, paving the way for eco-friendly construction practices. The modified F70S30MB concrete mix supports and aligns with the United Nations Sustainable Development Goals (SDGs) 9, 11, 12, and 13. By embracing sustainable materials and decreasing the environmental impact of construction, this approach contributes to a more resilient, resource-efficient, and eco-friendly infrastructure.

5. Conclusions

This study examined the mechanical properties of sustainable concrete containing WFS and M-sand as fine aggregates, with partial replacement of cement with metakaolin and a constant 0.5 % addition of banana fibre. The conclusions drawn from this study are as follows:

- The slump values of the F70S30MB mix decreased because of the angular shape of the WFS and the incorporation of banana fibres. However, the mix retains a medium degree of workability, which is suitable for structural applications.
- The inclusion of 70 % WFS, 30 % M-sand, 10 % metakaolin, and 0.5 % banana fibre in concrete led to a sustainable mix with mechanical properties comparable with or better than those of conventional concrete.
- This study demonstrated that an F70S30MB mix containing 70 % WFS and 30 % M-sand as replacement for fine aggregate along with 10 % replacement of cement with metakaolin and 0.5 % addition of banana fibre improved the early strength. This mix achieved 1.8 %, 5 %, and 55.6 % higher compressive, tensile, and flexural strengths, respectively, than the control mix at 28 days.
- The embodied energy and embodied carbon of the F70S30M concrete mix were 7.39 % and 7.16 % lower, respectively, than those of the CC mix. This indicates that the utilisation of WFS, M-sand, metakaolin, and banana fibres in the concrete mix reduces the environmental impact and promotes sustainable construction practices.
- The findings demonstrated that modifying concrete with industrial waste and natural fibres may result in improved mechanical properties and a lower environmental impact, thus supporting the development of sustainable construction materials.

The developed concrete (F70S30MB), featuring improved flexural strength and lower environmental impact, is suitable for applications in pavements, industrial floors, precast components, and lightweight structures that require high flexural strength while promoting sustainable construction.

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