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Mechanical performance and long-term durability of hybrid fiber-reinforced high-performance concrete

ABSTRACT

This paper analyses the fresh properties, mechanical, durability, and microstructure properties of sustainable high-performance concrete containing fly ash, coir pith ash (CPA), coir fiber, polypropylene (PP) fiber, and M-sand. Ten mixes of concrete were studied by conducting workability, strength parameters, saturated water absorption, sulphuric acid resistance, Rapid Chloride Penetration Test (RCPT), and Scanning Electron Microscope(SEM). The findings indicate that the addition of fibers led to gradual decrease in workability whereas the use of supplementary cementing materials contributed to improving fresh properties. The mixture CFCP2 gave the best mechanical property among all others, with a compressive strength of 75.67 MPa, tensile strength of 5.02 MPa, and flexural strength of 7.84 MPa at 28 days; that was about 12.8% better than ordinary concrete. In addition, at 90 days the lowest water absorption and sulphuric acid weight loss was achieved in CFP2 as 1.89% and 5.02% respectively, but CFCP2 had the lowest value of RCPT as 974 C. Therefore, SEM analysis indicated that there was denser matrix, refined porosity, and good fiber-matrix interaction. Consequently, it can be concluded that hybrid coir-PPfibers along with fly ash and CPA enrich the strength and durability of sustainable high-performance concrete.

***Keywords**: High-performance concrete; Fly ash; Coir pith ash; Coir fiber; Polypropylene fiber; M-sand; Durability*

1. INTRODUCTION

HFRHPC has emerged as a popular area of study due to the capability of HFRHPC in addressing the problems related to brittleness, crack formation, and low performance after cracking in high-performance concrete. Use of more than one type of fibers possessing mechanical and geometrical properties helps in reinforcing the concrete at different levels during the process of crack formation. Various natural fibers like coir, sisal, kenaf, and date-palm fibers have been combined with various synthetic fibers like PP along with steel, basalt, glass, and PVAfibers to enhance the mechanical and durability properties of the concrete [1,2].

Most studies have revealed that there were increases in compressive strength due to the use of hybrid fibers. The coir-PP combination, which involved 0.2% fiber volume fraction in a 50:50 ratio, had the best combination of strength, durability, and ductility [1]. Compressive strength of 64.5 and 66 MPa were attained in coir- and PP-fiber reinforced high-performance concretes, respectively [2]. Steel-PPfiber hybrid reinforcement was proven to yield good mechanical performance in high-strength concrete, where the optimal ratio was 0.85% steel fiber and 0.15% PPfiber [3]. In concrete with M-sand and recycled coarse aggregates, inclusion of 0.75% steel fiber and 0.1% PPfiber resulted in a 27.91% increase in compressive strength when compared with control concrete [4]. A similar increase in compressive strength by 14.1% was achieved with basalt fiber and PPfiber in a ratio of 0.15% and 0.033%, respectively [5]. It is evident from above literature that hybridization enhances compressive strength; however, such an effect greatly depends on fiber-

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matrix compatibility.

Hybrid reinforcement offers greater advantages with regard to tensile and flexural properties due to the direct involvement of fibers in crack bridging after matrix cracking. The PP-sisal hybrid fiber concrete has shown increments in splitting tensile strength by approximately 47.54% after 7 days and 37.19% after 28 days when compared to conventional concrete [6]. Similarly, date-palm-PP hybrid fiber concrete has shown improvements by about 14.6% in splitting tensile strength and 9.5% in flexural strength using appropriate total fiber contents [7]. Furthermore, the basalt-PP hybrid high performance concrete showed increase of approximately 48.6% in splitting tensile strength as compared to corresponding control mixture [5, 8]. The hybrid coir-steel fiber concrete has also shown better tensile and flexural properties with relatively lower coir fiber contents offering a good compromise between strength and permeability [9]. The recycled concrete has exhibited better splitting tensile and flexural strengths using basalt-PP and basalt-glass hybrid fiber combinations [10]. The above-mentioned conclusions show that the key advantage of hybrid fibers is their ability to control fracture behavior on different scales. Large cracks can be managed through stiff fibers, while small cracks are managed through flexible fibers.

While mechanical properties are always improving, the durability performance of hybrid fiber concrete is far more complicated, being dependent on the matrix and fiber content. Hybrid fiber reinforced concrete with fly ash displayed better durability performance under exposure to hydrochloric acid, sulfuric acid, and magnesium sulfate attacks, proving that the combination of SCMs and fiber reinforcement may work well [11]. PP and PP-coir fiber mixtures also demonstrated low weight loss and compressive strength loss under alkaline environment [12]. Coir fibers were also found to have a preferable resistance to chloride penetration than polypropylene and some hybrid fiber mixtures [13]. Nevertheless, there are cases where the use of fibers is not an improvement for all durability parameters. Some high-strength fiber reinforced concrete systems have higher chloride permeability and lower electrical resistivity after adding fibers [14].

The water absorption, porosity, and sorptivity parameters also show varied performance based on fiber type and fiber content. Concrete made of date palm-PPfiber showed a greater water absorption and porosity content, which was attributed to the hydrophilic nature of the natural fiber and extra formation of voids at the interface [15]. On the other hand, coir fiber-PP systems have shown reduced values of water absorption and porosity under optimal fiber amounts [16]. Hybrid fibergeopolymer concrete incorporating M-sand also showed 21.65% reduced sorptivity compared to the conventional concrete mixture [17]. Studies on microstructure analysis of hybrid basalt-steel-PPfiber systems have also revealed the increased compactness of the matrix and low porosity [18]. Such different observations imply that optimal fiber amount is important: appropriate fiber amounts will help limit cracking, while too many fibers will create more voids and reduce matrix compactness.

Integration of SCMs is one of the key approaches through which sustainability and the performance of high-performance concrete can be enriched. Fly ash has received considerable attention in recent years as a substitute for cement based on its pozzolanic nature and capacity to change the porosity of the cementitious matrix. The use of fly ash as a partial cement replacement has been found to increase the compressive, splitting tensile, and flexural strength of HPC by 8.1%, 5.9%, and 7.8%, respectively [15]. The use of fly ash in combination with hybrid fibers has also provided some good results from the perspective of mechanical properties and durability of concrete [19]. The use of hybrid basalt, steel, and PPfibers in high-volume fly ash concrete was better than low order hybrid systems [20].

Improved behavior of hybrid fibers is due to synergic effect of various fibers. For example, high modulus fibers like steel or basalt are mainly used for tensile strength, energy absorption, and load transfer, while PP or natural fibers play a role of dispersed reinforcement and regulation of micro-crack formation [21, 22]. SEM researches have proven that properly designed hybrid fibers can help increase matrix compactness, fiber bonding, and matrix-fiber interaction [23]. Therefore, use of different types of fibers with varying properties and sizes can ensure multiscale crack control.

However, very high amounts of fibers will negatively influence concrete properties. Increased amounts of PPfibers lead to fiber aggregation, poor distribution, high amount of entrained air, and non-uniformity of matrix [24]. Therefore, the optimal fiber ratio is not the fiber ratio producing the highest value of the strength property. On the contrary, it should be the fiber ratio balancing crack bridging, workability, compactness of matrix, and durability. This becomes especially important in the case when natural fibers are used since they have different properties compared to synthetic fibers. [25]

Workability is one of the major constraints that are linked with the hybrid FRC. Due to the inclusion of fibers in the mixture, the internal friction is increased and the movement of fresh concrete

becomes difficult due to which slump and Vebe time become less and more respectively. An average decrease of around 58.33% in the slump value and an increase of 84.62% in Vebe time has been observed with the increase in the amount of PPfibers [26]. Natural fibers can also create workability problems due to their hydrophilic nature. [27].

Studies into the thermal and freeze-thaw performance of hybrid FRC are not abundant yet. In coir-PP hybrid systems, there were observed quite low rates of strength reduction under moderate heating, along with a satisfactory fiber-matrix bonding [28]. Also, hybrid basalt-PP and basalt-glass fiber recycled concrete proved themselves to be resistant to 300 freeze-thaw cycles, with minimal mass loss and dimension change [29]. Furthermore, steel-PP hybrid reinforcement provides enhanced resistance to explosive spalling of ultra-high-performance concrete under elevated temperatures [30]. However, there is still much research to conduct about long-term performance of sustainable hybrid fiber systems, especially for mixes with agro-waste-based SCMs.

Previous literature reveals the efficiency of hybrid fibers, SCMs, and alternative aggregates in enriching the properties of high-performance concrete. Nevertheless, no adequate research has been done to analyze the effects of coir and polypropylene (PP) fibers together with fly ash, coir pith ash, and M-sand in the sustainable concrete mixes. Especially, the effects of coir pith ash in the mechanical and durability characteristics of hybrid fiber-reinforced concrete have not been adequately understood, whereas the optimal ratio of coir-PPfibers has not yet been determined [1,3,5,7,8,10,15,16]. Hence, the need for this study is to develop a sustainable concrete mixture where there will be less use of cement and natural sands while using the agricultural and industrial wastes. Fly ash and coir pith ash can be used to replace partially cement, M-sand can replace natural river sand, and coir and PPfibers can act as complementary crack bridging fibers. Development and evaluation of sustainable hybrid fiber-reinforced high performance concrete mixes using the above-listed materials in relation to their workability, compressive, splitting tensile and flexural strength, water absorption and resistance to RCPT will be the main objective of this study.

2. MATERIALS

Cement, M-sand, coarse aggregate, fly ash of class F, coir pith ash (CPA), coir fiber, and polypropylene (PP) fiber were used in this experimental mix. Cement was used as the binder, while fly ash and coir pith ash (CPA) were added as partial cement substitutes due to their ability to bring down the environmental burden resulting from cement production. M-sand was selected for the purpose of reducing the dependence on river sand. The coarse aggregate gave the skeletal structure to the concrete matrix. Properties of cement and aggregates are given in Tables 1.

Table 1. Physical properties of cement and aggregates

Property	Cement	M-Sand	Coarse Aggregate
Specific gravity	3.15	2.67	2.81
Bulk density (g/cc)	—	1.74	1.67
Water absorption (%)	—	0.4	0.25
Fineness modulus	—	2.79	7

Class F fly ash and CPA were selected as complementary mineral additions because of their silica-, alumina-, and iron-rich compositions. The chemical composition and relevant physical characteristics of both materials are presented in Table 2. Fly ash contained 56.80% SiO_2, 27.10% Al_2O_3, and 6.35% Fe_2O_3, while CPA exhibited a comparatively high SiO_2 content of 71.65%. These characteristics indicate their potential contribution to matrix densification and secondary reaction within the cementitious system.

Table 2. Physical and chemical characteristics of supplementary cementitious materials

Property	Fly Ash	Coir Pith Ash
Specific gravity	2.45	2.26
Bulk density (kg/m³)	—	630
Particle size	Fine	<75 µm
Specific surface area (m²/kg)	—	428
SiO_2 (%)	56.8	71.65
Al_2O_3 (%)	27.1	1.22
Fe_2O_3 (%)	6.35	2.72
CaO (%)	4.12	3.57
MgO (%)	1.25	1.12
SO_3 (%)	0.48	—
Na_2O (%)	0.32	—
K_2O (%)	1.08	—
LOI (%)	2.5	7.14

Both coir and PPfibers have been used as hybrid reinforcements because of the benefits of both natural and synthetic fibers. The coir fiber is a renewable source of reinforcement while the PPfiber has fine crack bridging properties and low

water absorption. Table 3 displays the mechanical characteristics of both kinds of fibers. The variations in the diameters, aspect ratios, water absorption properties, and stiffness of the fibers will affect their dispersion and crack control.

Table 3. Properties of coir and polypropylene fibers

Property	Coir Fiber	PPFiber
Density (g/cc)	1.1	0.9
Young's modulus (GPa)	4	5.5
Water uptake (%)	42	1
Diameter (μm)	100	30
Length (mm)	10	10
Aspect ratio (L/D)	100	333

3. METHODOLOGY

This test was conducted in order to study the properties of hybrid FRCHPC concrete containing fly ash, coir pith ash, M-sand, coir fiber and PPfiber. The properties that were studied include workability, strength, durability, and SEM analysis. The specimens were made based on the selected proportions and then subjected to the required tests after proper curing periods.

3.1. Workability Properties

The workability of fresh concrete was determined through slump and compaction factor tests. In the slump test, the fresh concrete mix was cast and compacted into the standard slump cone and then lifted upwards to measure the reduction in height of the fresh concrete mix. For the compaction factor test, it was applied in order to find out how compact the mixes are, especially since the introduction of fibers has a great effect on the flow of fresh concrete mixes. This was determined by comparing the weight of partly compacted and completely compacted mixes.

3.2. Mechanical Properties

Mechanical properties were evaluated based on strength parameters. Specimens for each mix were prepared according to the standard and tested after the necessary period of curing. In the compression test, cube-shaped specimens were subjected to axial loading until failure, and then the compressive strength was calculated from the maximum load. The tensile strength test was performed by applying the diametrical compression force on cylinder-shaped specimens until cracking occurs. The flexural strength test was conducted on the beam-shaped specimens by applying the transverse load.

3.3. Durability Properties

Durability was determined using saturated water absorption test, acid resistance test, and RCPT. Saturated water absorption was determined by drying the cured specimens to a constant mass, saturating the samples with water and weighing the mass. The difference in mass before and after saturation was used to calculate water absorption. Acid resistance was determined by exposing the specimens to the selected acidic liquid for specified time periods and measuring the changes in weight, appearance, and remaining strength. RCPT was done by applying electrical potential to conditioned concrete disc and recording the amount of current flow.

3.4. SEM Analysis

The SEM technique was employed for investigating the inner structure of certain concrete test pieces. Suitable samples were made and observed under appropriate magnifications for investigating the density of matrix, microcracking, pores, and bonding between fibers and matrix. The findings from SEM investigations were related to the outcomes of mechanical strength and durability to understand the effect of fly ash, coir pith ash, coir fiber, and PPfiber on the formation of the concrete matrix.

3.5. Mix Design and Mix Proportions

M60 grade HPC has been designed as per the guidelines of IS 10262:2019, with the consideration of target mean compressive strength 68.25 MPa, maximum nominal aggregate size 20mm, severe exposure condition, and a target slump of about 120 mm. Ordinary Portland cement, fly ash, coir pith ash, manufactured sand, and crushed aggregate have been considered as main ingredients. Polycarboxylate-ether based superplasticizer has been taken into account to provide desired workability with water to cementitious materials ratio of 0.36. From the design calculations of the mix, the quantity of cementitious material has been fixed as 431 kg/m^3. In case of the control mix, named CC, 20% of cementitious material has been replaced by fly ash. While in case of other mixtures, 10% fly ash and 10% coir pith ash have been used as the replacement of cementitious material, giving a total of 344.8 kg/m^3 cement, 43.1 kg/m^3 fly ash, and 43.1 kg/m^3 coir pith ash.

In order to test the individual and combined properties of both natural and synthetic fibers, the coir fiber and PPfiber were used in varying proportions. In case of the CFC series, there were different amounts of coir fibers, while, in case of CFP series, there were varying amounts of PPfibers. The CFCP series was created by combining the above-mentioned fibers in order to test the effect of their hybrid reinforcement. The amount of fibers was calculated based on the chosen volumes of fibers and converted into weight

with respect to the densities of the fibers. Apart from changes in the proportions of the fibers and the binder, all other major ingredients of the mixture remained constant to allow for a comparative analysis.

Table 4. Mix Proportions of Concrete Mixtures

Sl. No.	Mix ID	Cement	Flyash	Coir Pith Ash	Coir Fibre	Polypropylene fibres	Fine Aggregate	Coarse Aggregate
		(kg/m³)						
1	CC	344.8	86.2	-	-	-	710	1080
2	CF	344.8	43.1	43.1	-	-	710	1080
3	CFC1	344.8	43.1	43.1	0.25	-	710	1080
4	CFC2	344.8	43.1	43.1	0.51	-	710	1080
5	CFC3	344.8	43.1	43.1	0.76	-	710	1080
6	CFP1	344.8	43.1	43.1	-	0.31	710	1080
7	CFP2	344.8	43.1	43.1	-	0.62	710	1080
8	CFP3	344.8	43.1	43.1	-	0.93	710	1080
9	CFCP1	344.8	43.1	43.1	0.25	0.62	710	1080
10	CFCP2	344.8	43.1	43.1	0.51	0.31	710	1080

4. RESULTS AND DISCUSSION

4.1. Workability Test

The obtained slump and compaction factor values varied between 78-86 mm and 0.74-0.82, respectively, implying significant effects of the binder modification and addition of fibres on the performance of the mixes in their fresh state. The CF mix had the maximum workability with a slump value of 86 mm and compaction factor value of 0.82 in comparison with 82 mm and 0.78 of CC mix. It can be concluded that using both fly ash and coir pith ash results in a relatively movable cementitious paste.

With the inclusion of the fibres, however, the workability exhibited a steady decline. For the CFC series, addition of coir fibres saw slump decrease from 83 to 80 mm, with the compaction factor also decreasing from 0.79 to 0.76. This was mostly because of the fact that coir fibres, with their ability to absorb water and their rough surface texture, made it necessary for more water to be included in the wet mix. The CFP series also witnessed a similar trend, with slump decreasing from 81 to 78 mm, while the compaction factor decreased from 0.77 to 0.74. Here, the change was largely due to the increased fiber-particle interactions, rather than water absorption.

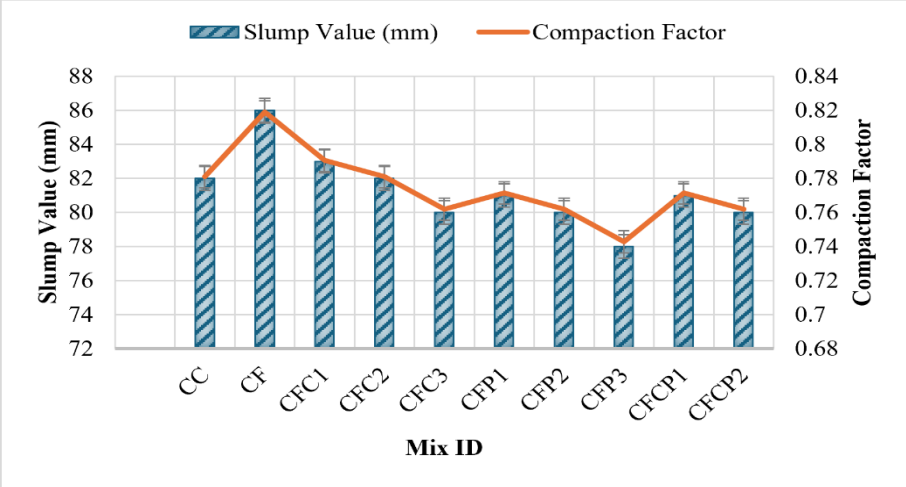


Figure 1. Workability Test Results

Workability of the blended CFCP composites was moderate (slump value 80-81 mm and compaction factor 0.76-0.77), which suggested that there was no sudden deterioration of flow characteristics due to the combined use of the two fibres. In general, it can be concluded that the use of SCM as a modifier of the composite matrix leads to an improvement in its mobility, while the inclusion of fibres contributes to increasing the resistance to flow step-by-step. Figure 1 illustrates

workability tests performed.

4.2. Strength Parameters

From the mechanical test results, it is clear that there is always an improvement in the performance of concrete upon adding the coir pith ash and the hybrid fiber reinforcement, with a slight decrement at high amounts of fibers. In the control concrete (CC), the 28-day strengths parameters are 67.08 MPa, 4.45 MPa, and 6.95 MPa, respectively. By adding fly ash and coir pith ash in CF, the strengths improved to 70.43, 4.67 and 7.30 MPa. This improvement may be attributed to the fillers and pozzolans of the admixtures added.

Further improvement was achieved after fibre addition. CFC grades showed an increase in strength until CFC2, whereby 0.51 kg/m3 of coir fibre resulted in 75.05 MPa compressive, 4.98 MPa split tensile and 7.77 MPa flexural strengths after 28 days of curing. A slight reduction in CFC3 grade indicates that the further addition of fibres above the optimal amount will not lead to any additional strength gain. This is due to the fact that excess fibres may inhibit homogenous dispersion of the fibres resulting in concentrated areas or even formation of voids, which cancel out the effect of crack bridging.

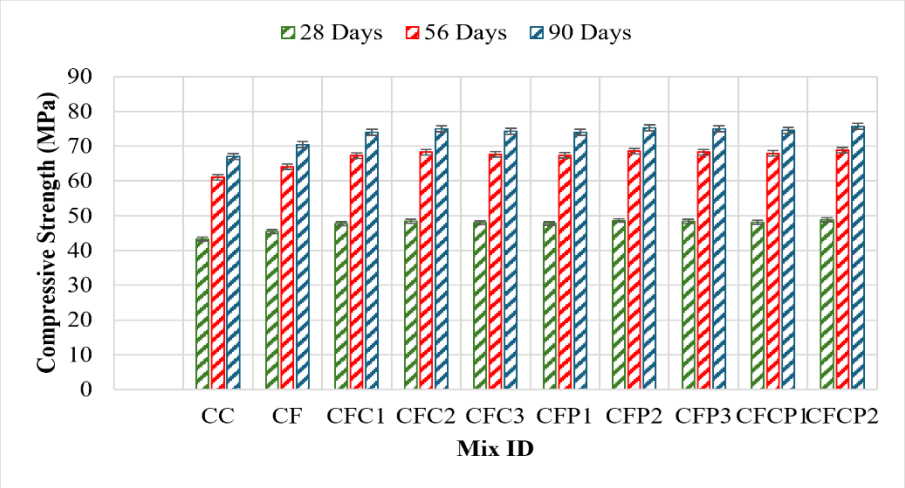


Figure 2. Compressive Strength Results

PP-fibre series has also shown a similar trend, wherein CFP2 is the most efficient mixture of individual fibres. Its strengths after 28 days are 75.32 MPa, 5.00 MPa and 7.80 MPa respectively. The main reason for the improvement is the capability of the PP fibres to act as bridging agents for crack control especially under tensile and flexural stresses. The slight drop in CFP3 signifies that the optimal fibre content has already been achieved in CFP2.

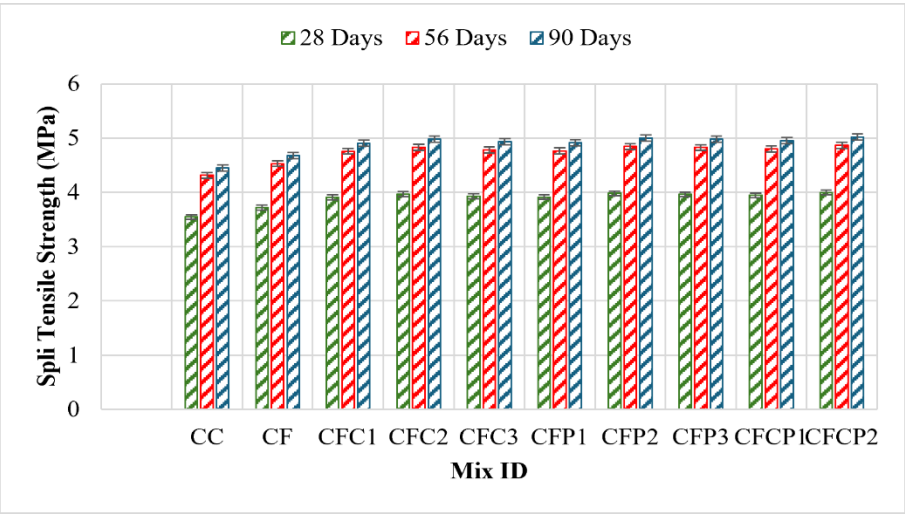


Figure 3. Split Tensile Strength Results

Intriguingly, the hybrid mixtures gave the best overall performance. CFCP2 mixture had the

maximum values of all the mixtures in terms of compressive strength of 75.67 MPa, tensile strength of 5.02 MPa, and flexural strength of 7.84 MPa. Complementary crack arresting properties exist when coir fibers work together with PPfibers, wherein the former serves as mechanical reinforcement and crack arresting, whereas the latter helps in restricting fine cracks.

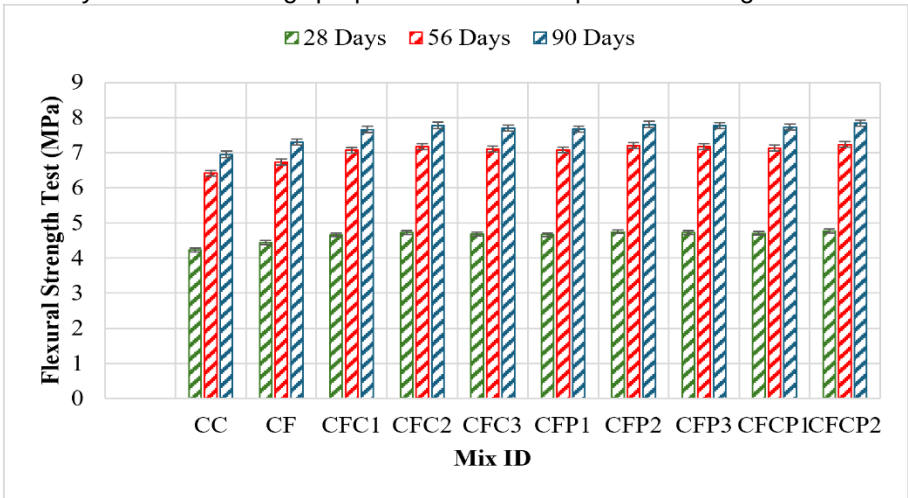


Figure 4. Flexural Strength Results

The strength gained from day 7 to day 28 was observed in all mixes due to ongoing hydration and pozzolanic reactions. The relatively minor variation observed in the optimum fibre mixes and the mixes with higher amounts of fibres is a further indication of how fibre optimization is more crucial than increasing fibre amount. On the whole, CFCP2 proved to be the optimal mix providing the best mechanical performance since an adequate mix of natural and artificial fibres increases the strength without excessive use of fibres.

4.3. Durability Parameters

From the findings on the durability test, it can be seen that the use of SCM's and FRC has generally increased the resistance to water permeability, sulphuric acid and chloride ion penetration. From the decrease in water permeability from 2.32% in CC to 2.24% in CF, after 28 days, one can conclude that the use of part of the cementitious binder with fly ash and coir pith ash has resulted in densification of the microstructure.

Further curing resulted in lower water permeability, the values falling to 2.01% in CC and 1.98% in CF, after 90 days. The decrease in the value is due to the pozzolanic reaction and refining of pores in the cementitious microstructure. These findings are shown in Figures 5, 6 and 7.

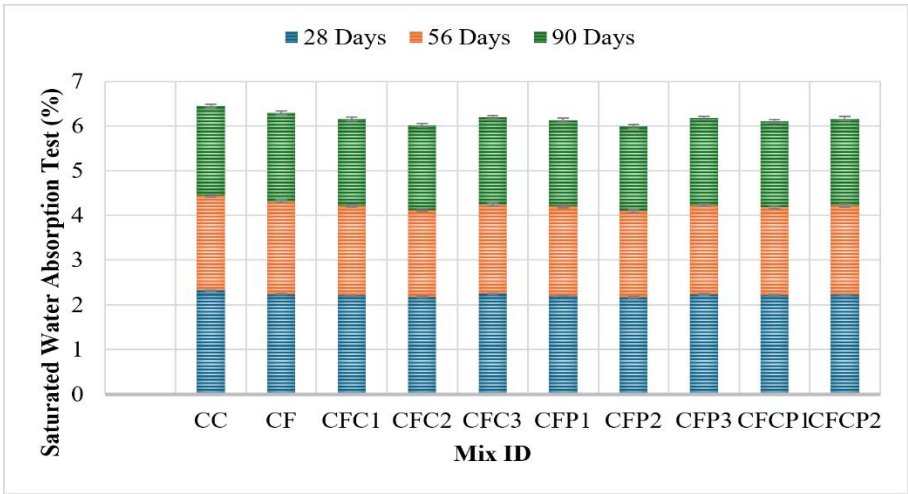


Figure 5. Saturated Water Absorption Results

The other improvement that was easily noticeable was through the use of fibers. CFC2 showed the lowest water absorption of the coir-fiber blends, having reduced from 1.94% after 56

days. On the other hand, CFP2 shows the lowest value of water absorption in the PP series with 1.93%. This can be explained by the presence of fiber bridging which limits the development of cracks and thus reduces the means of water entry. On the contrary, the increase shown by CFC3 and CFP3 indicates over addition of fiber.

The results of sulphuric acid resistance follow a similar pattern as well. The percentage weight loss of CC was reduced from 6.53% to 5.20%, for the periods of 28 days and 90 days, respectively, while for CF, these values were 6.42% and 5.12%, respectively. The CFP2 mix, out of all the modified mixes, had the least percentage weight loss of 5.02% at 90 days. This may be due to pore refinement due to the addition of the supplementary cementitious material and the capability of the fibres in restricting crack formation.

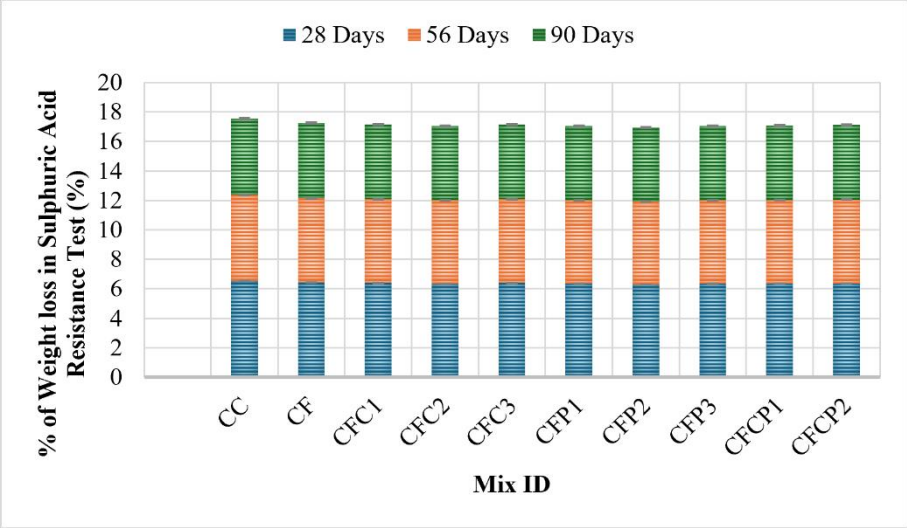


Figure 6. Percentage of Weight Loss in Sulphuric Acid Resistance Test

The RCPT tests further confirm the increase in resistance to penetration by chloride ions. For CC, the coulombs registered at 28 days were 1532, but it was reduced to 1163 coulombs at 90 days. The CF mixture registered a lower value of 1028 coulombs at 90 days, whereas CFP3 and CFCP2 had the lowest values of 976 and 974 coulombs, respectively. The gradual decrease with an increase in the age of curing is a result of continuous hydration and modification of the pore structure. Lower RCPT values of fibre mixes suggest a reduction in chloride penetration paths.

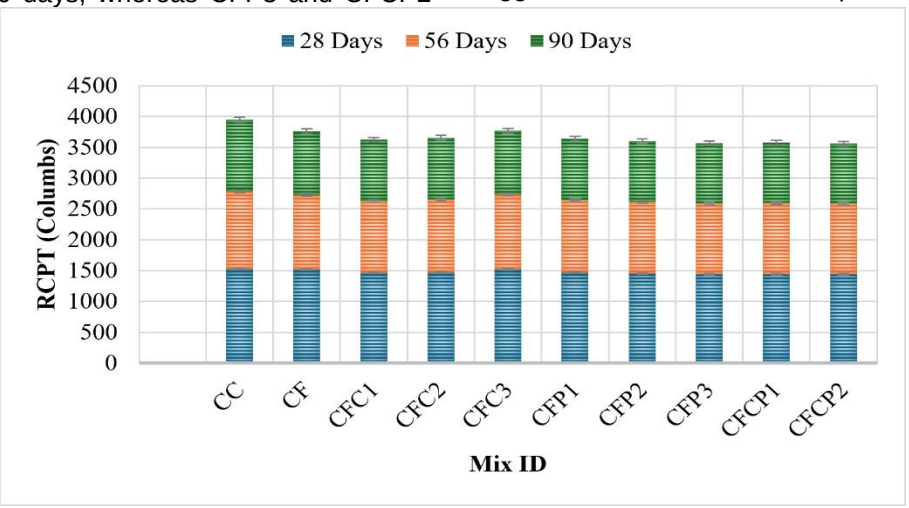


Figure 7. RCPT Results

In summary, it can be stated that the results of durability tests show that the application of a combination of fly ash, coir pith ash, coir fibre, and polypropylene fibre would enhance the resistance of concrete against water and aggressive chemicals. Moreover, it should be noted that the optimal amount of fibre is not always the maximum amount because too much fibre could harm dispersion and porosity of concrete. Among all tested concrete types, CFCP2 showed the lowest

value of RCPT (974 coulombs after 90 days).

4.4. Microstructural Analysis – SEM Analysis

SEM investigation was performed to observe the evolution of the microstructure of the concrete mixtures, in order to make a correlation between the internal microstructure of the mixture and the experimentally determined mechanical properties. Emphasis was made on the formation of hydrates, distribution of supplementary cementitious materials, interface between the fibre and matrix, porosity, and ITZ. The findings of the SEM investigation are microstructurally confirmed by the trends observed in strength parameters.

SEM morphological examination of the conventional concrete (CC) shows that there is a relatively heterogeneous cement paste with pores and discontinuities. This is because there is an area in the matrix that has loose hydrates and weak interfacial bonds. Such a condition can provide a medium for the formation of internal cracks when the material is subjected to loads. This finding corroborates the relatively low values of strength properties of CC. At 28 days, the strength parameters of the material was 67.08, 4.45, and 6.95 MPa, respectively.

The use of fly ash and coir pith ash in the CF mixture gave rise to relatively denser cementitious matrix. The small size of the supplemental cementitious materials assists in enhancing the particle packing efficiency; on the other hand, the reactive silica and alumina in them get involved in the secondary reactions with calcium hydroxide. These extra hydration products of C-S-H type can gradually fill the capillary spaces and enhance the binder phase continuity. This microstructural modification is in agreement with the increase in 28-day compressive strength from 67.08 MPa in CC to 70.43 MPa in CF. Likewise, the tensile and flexural strengths increased from 4.45 to 4.67 MPa and from 6.95 to 7.30 MPa, respectively. Thus, the SEM microstructure confirms the enhancement of the three strength properties because of SCMs.

The effect of adding coir fibre is clearly visible from the CFC series. The fibre surface seems to be enveloped by the cementitious hydration products, implying mechanical interaction and bonding between the fibre and matrix. The addition of fibres makes the material capable of crack bridging, which does not occur in the case of the control material. Once the crack occurs, the embedded fibre helps in transmitting part of the load from one side of the crack to another and limits the crack propagation. Compressive strength after 28 days of curing was 73.96 MPa in CFC1, and tensile and flexural strengths were 4.91 and 7.66 MPa, respectively. Further improvement in strength was achieved in CFC2, in which the compressive strength was 75.05 MPa, tensile strength was 4.98 MPa, and flexural strength was 7.77 MPa.

The minor drop in performance of CFC3 relative to CFC2 is equally important from a microstructure point of view. While more coir fibers offer better chances of cracking bridging, too much fiber can result in non-uniform distribution of fibers with possible formation of voids in some areas. This will negate some of the reinforcing effect. Hence, CFC3 showed relatively low 28-day strength parameters of 74.32, 4.93, and 7.70 MPa, respectively. The phenomenon suggests that the addition of fibers has an optimal level.

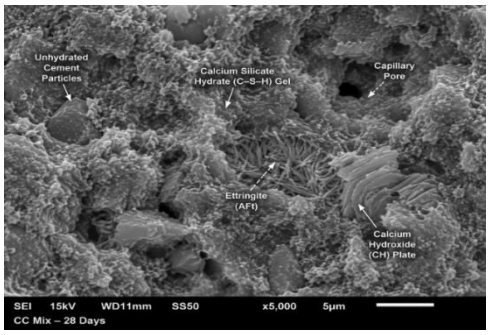
Similarly, a parallel observation was made in relation to the mixtures of polypropylene fibres. In the case of CFP1, the 28-day strength parameters were found to be 74.03, 4.91, and 7.67 MPa, respectively. Increasing the dosage of the PP fibres in CFP2 raised these values to 75.32, 5.00, and 7.80 MPa. Due to the very small diameter and higher aspect ratio of fine PP fibres, they can effectively intercept the growing micro-cracks. Hence, the significance of the role played by fine PP fibres in improving the mechanical properties will lie in the field of tensile and flexural strength of concrete specimens. The lowering in the strength of CFP3 to 75.01, 4.98, and 7.77 MPa is indicative of this fact.

The most significant microstructure response is found in the case of the mixed coir-PPfiber samples. The CFCP1 and CFCP2 microstructures consist of a relatively well-integrated cementitious matrix that consists of hydration products, ash particles, coir fiber, and reinforcing fiber. The combination of both coir and PPfibers creates a multilevel mechanism for controlling cracking. The relatively bigger coir fibers create the capability to bridge larger cracks, while the smaller PPfibers can control the creation of smaller cracks.

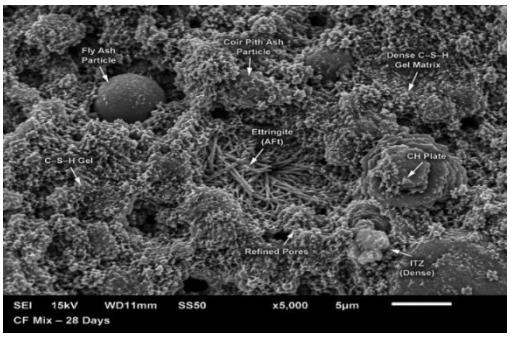
Of all the mixtures, CFCP2 showed the best performance in terms of mechanical properties. The compressive strength after 28 days was 75.67 MPa for CFCP2, while it was 67.08 MPa for CC, indicating an improvement of approximately 12.8%. The tensile strength rose from 4.45 MPa for CC to 5.02 MPa for CFCP2, and the flexural strength rose from 6.95 to 7.84 MPa. This is a relative increase of about 12.8% and 12.8%, respectively. Compared with the SCM-added CF mixture, there was an improvement of approximately 7.4%, 7.5%, and 7.4% in strength parameters.

The age-dependent strengthening of CFCP2 also supports the proposed microstructural understanding. The compressive strength of this FRC was 48.82 MPa at 7 days, 68.86 MPa at 14

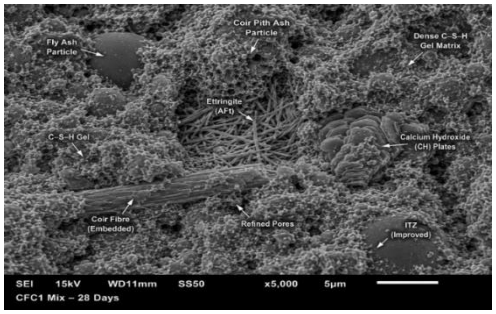
days, and 75.67 MPa at 28 days. Meanwhile, the tensile strength of the fiber reinforced concrete was 4.00 to 4.87 and 5.02 MPa while the flexural strength of the concrete was 4.77 to 7.23 and 7.84 MPa. This gradual enrich in strength may be attributed to the ongoing process of hydration and pozzolanic action.



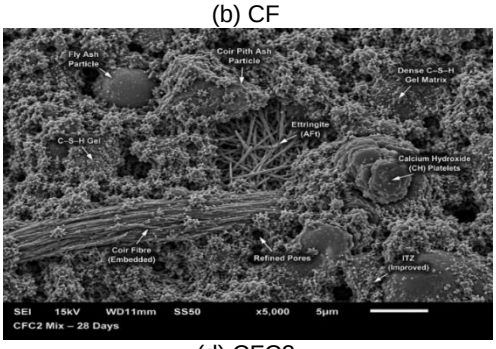
(a) CC mix



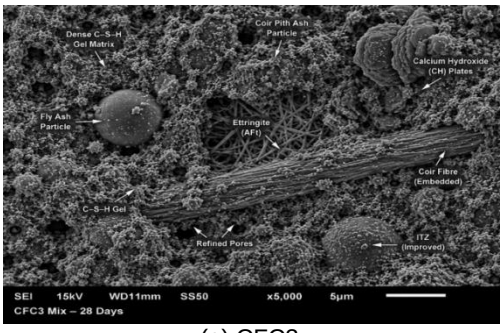
(b) CF



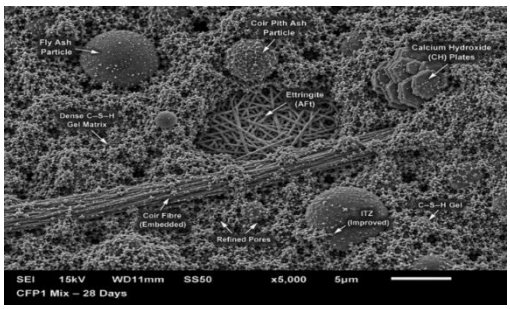
(c) CFC1



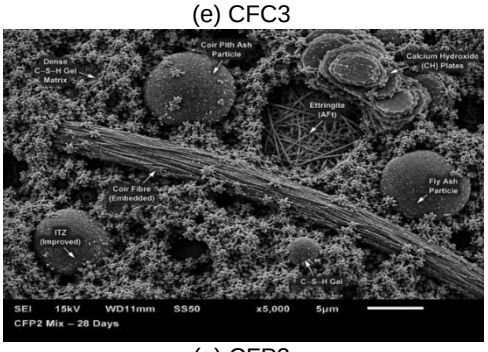
(d) CFC2



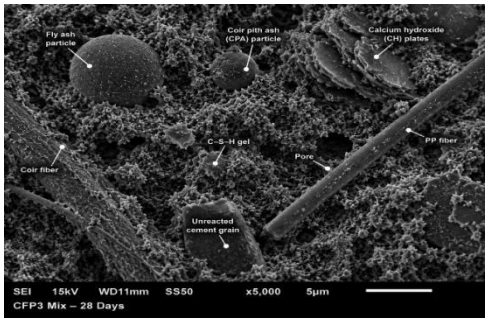
(e) CFC3



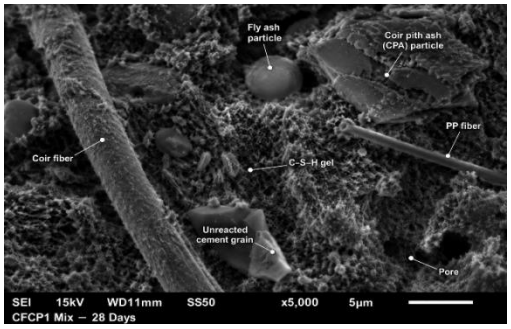
(f) CFP1



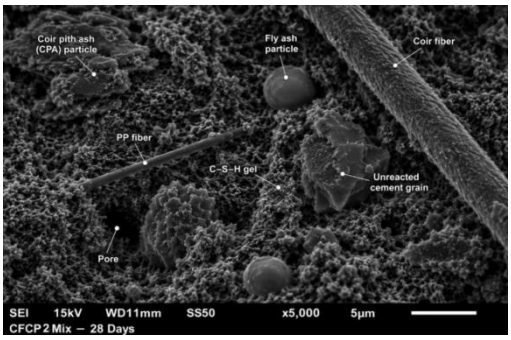
(g) CFP2



(h) CFP3



(i) CFCP1



(j) CFCP2

Figure 8. SEM images of various mixes

The SEM findings thus form valuable support for confirming the strength parameters obtained experimentally. The increased strength levels in the case of fibres added mixtures are due to the presence of denser matrix, enhanced development of hydration products, better fibre bonding, and effective crack bridging. On the other hand, the relatively small reduction in strengths at higher single-fibre content is in line with the probability of defects related to dispersion and porosity. The high level of performance recorded in CFCP2 suggests that a balanced approach is required.

In general, SEM results confirm the presence of a well-defined microstructure-property relationship. The continuous evolution of the cementitious matrix and the achievement of effective fiber-matrix interaction is well in line with the improvement in strength parameters. The CFCP2 blend is the most favorable one in this respect and, hence, demonstrated maximum strength parameters. In this way, SEM characterization not only provides an idea about the morphology of the prepared concrete but also confirms the experimental improvement in the strength parameters from the microstructure point of view, thus, verifying the effectiveness of the fly ash, coir pith ash, coir fiber, and PPfiber blend in high-performance concrete. Figure 8 represents the SEM images of different blends.

5. CONCLUSION

The current study examines the mechanical, durable and microstructure features of HPC containing fly ash, coir pith ash (CPA), coir fiber, polypropylene (PP) fiber, and M-sand. It can be observed that a combination of supplementary cementing materials with hybrid fiber reinforcement can greatly improve concrete performance while also ensuring better use of industrial and agricultural wastes.

The workability test revealed that CC has a slump value of 82 mm and a compaction factor of 0.78, while the maximum values of 86 mm and 0.82 were obtained by the CF mixture without fibres. Workability decreased with the addition of fibre, with the minimum values of 78 mm and 0.74 obtained in CFP3 mixture. This decrease in workability could be primarily due to increase in surface area and water retention in fibres.

The mechanical properties were found to be enhanced with curing time, and the CFCP2 gave the optimum result. The compressive strength was enriched from 67.08 MPa in case of CC to 75.67 MPa in case of CFCP2 at 28 days, which is a 12.8% enhancement. The same goes for the splitting tensile strength that was enriched from 4.45 to 5.02 MPa and for the flexural strength that was increased from 6.95 to 7.84 MPa. This enhancement was due to matrix densification through pozzolanic reaction and the crack-bridging effect of hybrid fibres.

In the durability test, there was improvement in the performance of the modified mixes. At 90 days, the water absorption values had reduced from 2.01% of CC to 1.94% of CFCP2, while the lowest was seen in CFP2 with 1.89%. Resistance to sulphuric acid had increased, whereby the weight losses at 28, 56, and 90 days were 6.37%, 5.69%, and 5.08% in CFCP2 as compared to 6.53%, 5.81%, and 5.20% in CC. The lowest weight loss at 90 days was seen in CFP2 with 5.02%.

This was proven by SEM studies, which showed that the cementitious matrix was relatively dense and had C-S-H gel, supplementary materials, fibers, and few pores. The good fiber-matrix interaction and few pores facilitated the good strength and durability of the concrete.

CFCP2 exhibited the best balanced property, where it exhibited the highest strength for 28 days strength parameters, while having the lowest RCPT at 90 days. CFP2 performed well compared to CFCP2 regarding water absorption and acid resistance; however, the overall best property was exhibited by CFCP2. The results clearly indicate the potentiality of fly ash, CPA, coir fiber, and PPfiber for sustainable high-performance concrete.

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IZVOD

MEHANIČKE PERFORMANSE I DUGOROČNA IZDRŽLJIVOST HIBRIDNOG VISOKOPERFORMANSNOG BETONA ARMIRANOG VLAKNIMA

Ovaj rad analizira svojstva u svežem stanju, mehanička, izdržljiva i mikrostrukturna svojstva održivog visokoperformansnog betona koji sadrži leteći pepeo, pepeo od kokosovih vlakana (CPA), kokosova vlakna, polipropilenska (PP) vlakna i M-pesak. Deset mešavina betona je proučavano sprovođenjem obradivosti, parametara čvrstoće, apsorpcije zasićene vode, otpornosti na sumpornu kiselinu, brzog testa penetracije hlorida (RCPT) i skenirajućeg elektronskog mikroskopa (SEM). Rezultati pokazuju da je dodavanje vlakana dovelo do postepenog smanjenja obradivosti, dok je upotreba dodatnih cementnih materijala doprinela poboljšanju svojstava u svežem stanju. Mešavina CFCP2 je dala najbolja mehanička svojstva među svim ostalima, sa čvrstoćom na pritisak od 75,67 MPa, zateznom čvrstoćom od 5,02 MPa i čvrstoćom na savijanje od 7,84 MPa nakon 28 dana; to je bilo oko 12,8% bolje od običnog betona. Pored toga, nakon 90 dana, najniža apsorpcija vode i gubitak težine sumporne kiseline postignuti su kod CFP2, 1,89% i 5,02% respektivno, ali je CFCP2 imao najnižu vrednost RCPT od 974 °C. Stoga je SEM analiza pokazala da postoji gušća matrica, rafinisana poroznost i dobra interakcija vlakana i matrice. Shodno tome, može se zaključiti da hibridna vlakna od kokosa i PP, zajedno sa letećim pepelom i CPA, obogaćuju čvrstoću i izdržljivost održivog visokoperformansnog betona.

***Ključne reči**: Visokoperformansni beton; leteći pepeo; pepeo od kokosovih vlakana; kokosova vlakna; polipropilenska vlakna; M-pesak; izdržljivost*

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