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Effect of hybrid fibres on mechanical behaviour of magnesium oxychloride cement-based composites

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ABSTRACT

Magnesium oxychloride cement (MOC) as a green cement has superior mechanical properties such as high strength and quick gain of early strength, however the inherent brittleness has limited its applications where ductility is crucial. To enhance the strength and ductility, a novel hybrid fibre-reinforced MOC-based composite (FRMOC) is developed for the first time using polyethylene (PE) fibres and basalt fibres (BF) to reinforce the MOC. A systematic investigation of the effect of fibre dosage on the flowability, rheological properties, compressive strength, and tensile properties of the developed FRMOC is conducted in this study. The results revealed that the addition of fibre reduces flowability while increasing the yield stress and plastic viscosity. The 1-day compressive strength of the FRMOC reached 68.2–85.4% of the corresponding value at 28 days, demonstrating its high early strength characteristic. The mix with 1.25% PE and 0.75% BF exhibited the maximum compressive strength at all curing ages. All the mixes consistently demonstrated excellent tensile strength and tensile strain capability (ductility), with the tensile strength and tensile strain capacity of 10.95 MPa and 4.41% achieved for the mix of 2% PE fibre, and 8.49 MPa and 2.43% for the mix of 1.25% PE and 0.75% BF respectively. Moreover, a decline in strength characteristics and strain capacity was observed as BF percentages increased. Scanning electron microscope (SEM) analysis was further employed to investigate the morphological changes in the FRMOC matrix at the microscale to discover the fibre reinforcing mechanism.

1. Introduction

Cementitious materials are fundamental construction materials utilized in various civil engineering infrastructures, and continuous rise in population, urbanization, industrialization, and economic expansion have boosted their use considerably [1]. Ordinary Portland cement (OPC) is the essential ingredient of construction materials, and its manufacturing involves a high energy-intensive process, contributing greatly to carbon dioxide (CO_2) emissions accounting for 5–10% of the world's greenhouse gas (GHG) emissions [2]. It is estimated that 0.85 ton of CO_2 is generated for every ton of OPC produced [3]. Therefore, researchers are constantly investigating ways to reduce GHG emissions from the cement industry, either by partially substituting OPC with supplementary cementitious materials (SCMs), such as fly ash, silica fume, slag [4,5], or by developing a new type of cement, such as magnesium oxychloride cement (MOC) [6].

MOC, also referred to as Sorel cement, was discovered just after the development of OPC by S.T. Sorel in 1867 [7]. It is an air-dried and nonhydraulic cement produced by the reaction of magnesium oxide (MgO) powder (by-product from magnesium mines) with magnesium chloride ($MgCl_2$) solution. The significantly lower calcination temperature (typically 700–900°C for MgO versus 1400°C for OPC) makes the manufacturing of MOC less energy-intensive. MOC has been regarded as a green cement due to the less energy consumption in manufacturing and use of industry by-product as main ingredient [3,8]. In addition, MgO could capture CO_2 from surroundings and produce carbonates and hydroxy carbonates, making the composite even more environment friendly [9]. MOC has attracted increasing researchers and industry attention for its advantages over OPC, including low density, low thermal conductivity [10], fast setting [6,11], high early strength [11], low

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alkalinity, good fire and abrasion resistance [12], and high mechanical strength [13,14].

MOC has been widely used in many commercial applications such as industrial flooring, wall panels [15], thermal insulation panels [16], and floor tiles [17,18]. It also bonds well to an extensive variety of fillers, including wood particles and fibres, and sets swiftly with a significant early strength gain [3]. Moreover, it's capability to handle solid waste improves recycling and further lowers product costs [19]. In recent years, MOC-based products have undergone significant development especially with the improvement of water resistance [20], which previously restricted its application to mainly indoors. Guo et al. [21] developed a water-resistant MOC by utilizing locally available industrial by-products including fly ash and silica fume. They reported that after 28 days and 56 days of water immersion, MOC mixes comprising 15% silica fume-15% fly ash retained 100% and 95% compressive strength, respectively. Likewise, Guo et al. [22] discovered an optimal mixture for water-resistant MOC in both cold and warm water, with molar ratios of $MgO/MgCl_2$-9 and $H_2O/MgCl_2$-13, 30% Fly ash (FA), 0.5% sodium monofluorophosphate (MFP), and 0.5% phosphoric acid (PA). The optimised compressive strength was 110.1 MPa, with the strength retention under room temperature and warm water immersion being 1.08 and 0.91, respectively.

In spite of these advantages, MOC is notably brittle and non-ductile. Currently, in the MOC industry, it is common practice to incorporate multiple layers of fibre mesh or grid to improve the flexural strength of MOC [3]. However, the inclusion of multiple layers of fibre meshes reduces working efficiency and hence, fibre addition may be a viable method for increasing the ductility of MOC based composites. Considering the excellent bonding potential of MOC with fibres [23,24] and its lower alkalinity, the resultant matrix is expected to have high potential to form an improved bond with regularly used fibres e.g., polyethylene (PE) fibre, polyvinyl alcohol (PVA) fibre, basalt fibre (BF), reducing aging-related challenges [6]. Thus, fibre-reinforced MOC (FRMOC) composites are expected to achieve high strength and ductility by tailoring the design using fibres, which will finally make them a prime candidate for manufacturing fire-resistant cladding and facades, offering enhanced performance.

Various fibres, including low modulus fibre such as PE fibres and PVA fibres, and high modulus fibre such as steel fibres, have been employed in the production of OPC based fibre reinforced cementitious composites such as engineered cementitious composites (ECC). The mechanical properties of ECC can be tailored via the type and dosage of the fibres. ECCs with mono fibre could achieve high strength by using high modulus fibre or high ductility by using low modules fibre, and hybrid fibre reinforced ECCs were reported to achieve both high strength and ductility via hybrid application of both low and high modulus fibres [25,26]. PE fibre reinforced ECC has been found to be able to achieve the highest ductility with tensile strain capability up to 6–8% with 2% PE fibre. [27]. As far as FRMOC is concerned, very limited research has been reported so far. Wei et al. [28] studied the behaviour of FRMOC reinforced with 2% PE fibre and reported that FRMOC exhibited a tensile strain capacity of 5–7%. Wang et al. [24] reported that PE fibre-reinforced MOC demonstrated excellent tensile behaviour, strain hardening capacity, and multi-cracking behaviour, revealing that the tensile strength and tensile strain capability of FRMOC were 7 MPa and 8%, respectively. Similarly, Yu et al. [3] demonstrated that PE fibre-reinforced MOC exhibited outstanding mechanical properties (i.e., compressive, tensile, and flexural strengths of 127.4 MPa, 11 MPa, and 29.8 MPa, respectively, after 28 days of curing) and strain hardening capability of up to 8%. Therefore, it is clear that the addition of PE-fibre may significantly improve the tensile strength and ductility of MOC composites due to its high tensile strength and hydrophobic nature [29].

It has further been reported that the incorporation of BF or steel fibre as a replacement of the primary polymer fibres may not only help in reducing the embodied energy requirement of the composite, but also help in maintaining the composites' integrity under extreme loading conditions, such as fire, which represents a primary application area for this material [29,30]. Although PE-reinforced cementitious composites (FRCCs) have high tensile strain capacity, the tensile strength is usually low, whereas BF or steel fibre reinforced FRCCs have a higher ultimate strength, and a minimal strain capacity, [31–34]. Therefore, with the hybrid application of both PE and BF or steel fibres, an enhanced overall mechanical performance with both high strength and strain capability (ductility) is expected [35]. However, steel fibre is not suitable for MOC matrix due to the corrosion issue resulting from chloride ions. On the other hand, BF, obtained from natural rock, has potential to be used in high-performance applications due to its high melting point (>1400°C), inert, and sustainable nature. However, the research in this area is very limited and to the best of the authors' knowledge, no previous research on hybrid fibre reinforced FRMOC has been carried out.

Therefore, this study aims to develop green FRMOC with both high strength and ductility (tensile strain capacity). For this purpose, hybrid PE fibres and BF are employed in the matrix developed by Guo et al. [22] and the effect of fibre dosage on the physical properties (flowability, setting time, and rheological properties, including plastic viscosity and yield stress), compressive strength and tensile performance of FRMOC are investigated. The compressive strength has been specifically analysed at different curing periods ranging from 1 to 28 days to understand the strength gain with time. The mechanism of strength development with age and role of fibres are further justified using scanning electron microscope (SEM) analysis. The presence of chloride ions in the MOC matrix renders it unsuitable for steel reinforcement, and the developed FRMOC with enhanced ductility and strength by using hybrid fibre could be a potential solution, expanding the scope of MOC applications.

2. Experimental programs

2.1. Materials and mixes

The MOC mix design developed by Guo et al. [22] was adopted as the base matrix in this research. Their optimal mix design contained 30% FA-0.5%MFP-0.5%PA-$MgO/MgCl_2$(M):9-$H_2O/MgCl_2$(H):13 (molar ratio). This design presented the best water-resistance with compressive strength retention coefficients being 1.08 and 0.91 when exposed to water at ambient temperature (22–26°C) and 60°C, respectively for 28 days.

Among the constituents of the matrix, MgO powder (95% purity) and FA were used as the binders. MgO and FA powder were purchased from local Australian companies QMag Queensland and Cement Australia, respectively. The MgO powder exhibited a chemical reactivity of 73%, assessed according to the method outlined in WB/T 1019–2002 [36]. Magnesium chloride hexahydrate ($MgCl_2.6H_2O$) flakes were purchased from Weifang Haizhiyuan Chemistry and Industry, China. The $MgCl_2.6H_2O$ flakes had 99% purity and were characterized by their colourless and odorless nature, with a density of 1570 kg/m^3. Fig. 1 shows a pictorial view of MgO, $MgCl_2$ crystals, and FA. Table 1 further illustrates the elemental constituents of MgO, $MgCl_2$ crystals, and FA determined using energy dispersive X-ray (EDX) analysis, whereas Fig. 2 displays the EDX spectrums of these materials.

Fig. 3 shows the morphology of FA and MgO indicating that FA has a smooth and round surface texture while MgO has an angular surface texture. MFP and PA were also added to the mix as a modifier. The MFP (95%) was purchased from Sigma Aldrich (Merck, Germany), whereas PA (85%) used in this study was obtained from Bosca, Australia. Locally available river sand was sieved with a 300-micron sieve as the primary aggregate and the sand to binder ratio was kept constant as 0.23 [3]. High range water reducing admixture (HRWR) ADVA LS780 was utilized to maintain the flowability of the mix and ensure proper fibre distribution. The BF and PE fibre used in this study are shown in Fig. 4 and their general characteristics are further presented in Table 2. Not only both the fibres have high elastic modulus (PE - 116 GPa, BF -

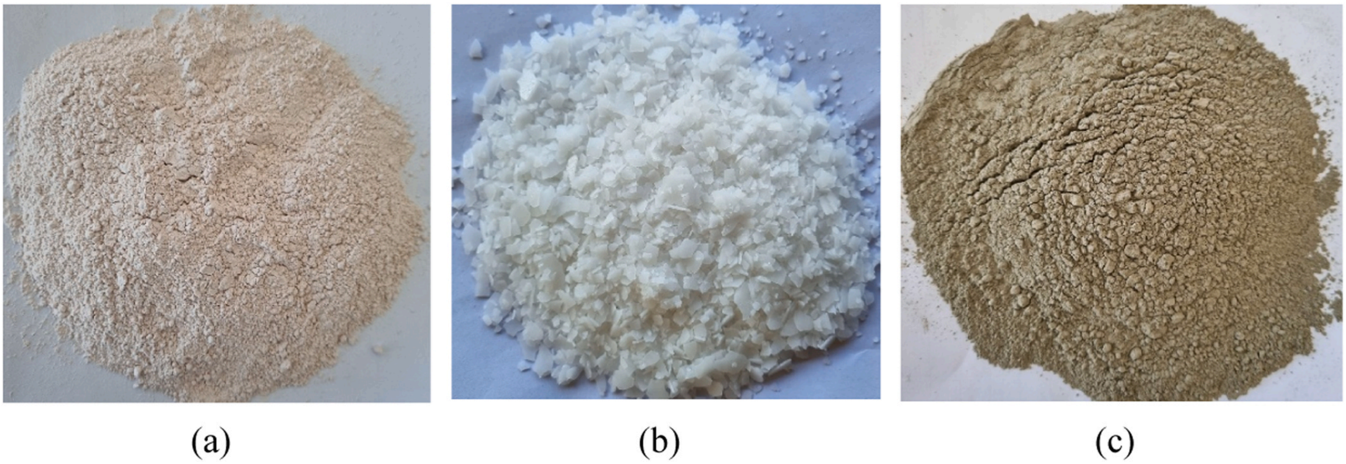


Fig. 1. (a) MgO, (b) $MgCl_2$ crystals, and (c) Fly ash.

Table 1
Elemental compositions of the raw materials.

Elements	O	Mg	Cl	Si	Al	Fe	Ca	K
Fly ash	54.03	0.39	_	37.17	5.44	1.55	0.97	0.45
MgO	28.5	71.5	_	_	_	_	_	_
$MgCl_2$ flakes	19.91	37.14	42.96	_	_	_	_	_

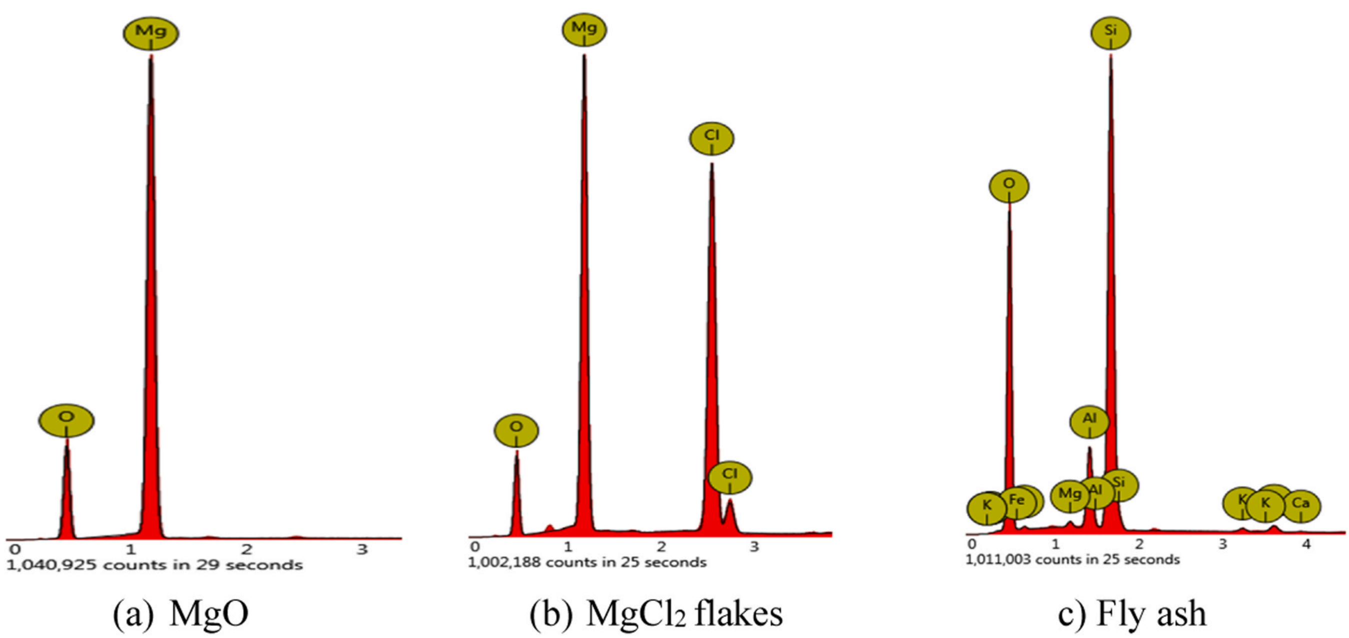
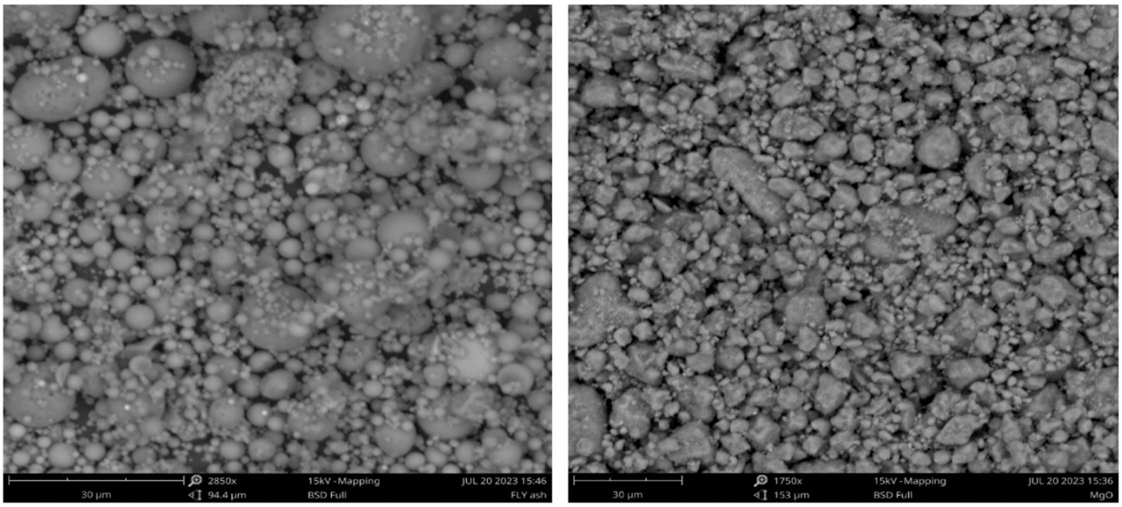


Fig. 2. EDX analysis of the raw materials.

91–110 GPa), but their tensile strength is also high (BF~3300–4840 MPa, PE-3000 MPa). Therefore, the hybrid combination of PE fibre and BF is anticipated to improve both strain capacity and strength of the composite.

Five mixes were adopted in the study with varying PE fibre and BF dosage, maintaining a constant total volume of 2%. The dosage was selected based on the existing research on FRMOC. Prior studies by Yu et al. [3] and Wei et al. [28] recommended 2% PE fibre as the optimal dosage for producing MOC composites with enhanced strain capacity (8% and 5–7%, respectively). Therefore, PE fibre dosage was kept a maximum of 2% and replaced with BF to reduce the embodied energy requirement and further improving the sustainability of the mix. Recently, Rawat et al. [37] found that increasing BF content up to 2% in MOC enhanced compressive (~70 MPa) and tensile (~9 MPa) strengths but led to lower tensile strain capacity (0.03%). Additionally, studies indicated that increasing BF content up to 1% resulted in internal cavities/voids between aggregate and cement paste due to BF agglomeration, weakening the composite and reducing strength characteristics [38,39]. Therefore, BF was incorporated as a replacement to PE fibre from 0.75% to 1.25% to develop a hybrid FRMOC with enhanced mechanical performance and sustainability. The mix proportion adopted in the present study are shown in Table 3. The mix IDs are denoted as MXPEYBF where M represents mix, X represents % volume of PE fibre and Y denotes % volume of BF. For instance, M2PE0BF denotes a mix



(a) (b)

Fig. 3. (a) Fly ash, and (b) MgO.

(a) (b)

Fig. 4. (a) PE fibre and (b) BF.

Table 2
General properties of the PE and BF fibres.

Fibre Type	Length (mm)	Diameter (µm)	Tensile strength (MPa)	Elastic modulus (GPa)	Density (g/cm^3)
PE fibre	12	24	3000	116	0.97
BF	12	13	3300–4840	91–110	2.65

with 2% PE fibre and 0% BF.

2.2. *Mixing procedures and sample preparation*

Fig. 5 shows a schematic illustration of the complete mixing procedure. This mixing technique was precisely devised to achieve proper fibre dispersion. Firstly, the concentrated $MgCl_2$ solution (prepared 24 hours before casting) was properly mixed with MFP, PA, and HRWR using a magnetic stirrer for 2 minutes. Moreover, the dry materials such as MgO, FA, and sand were separately mixed for up to 2 minutes. Thereafter, the dry mix and the solution were added together, and the

Table 3
Mix proportions used in the present study.

Mix ID	Molar ratio	FA	MFP	PA	PE fibre (%)	BF (%)	HRWR (litre/m^3)
M0PE0BF	M9H13	30%	0.5%	0.5%	0	0	15.5
M2PE0BF	M9H13	30%	0.5%	0.5%	2	0	15.5
M1.25PE0.75BF	M9H13	30%	0.5%	0.5%	1.25	0.75	15.5
M1PE1BF	M9H13	30%	0.5%	0.5%	1	1	15.5
M0.75PE1.25BF	M9H13	30%	0.5%	0.5%	0.75	1.25	15.5

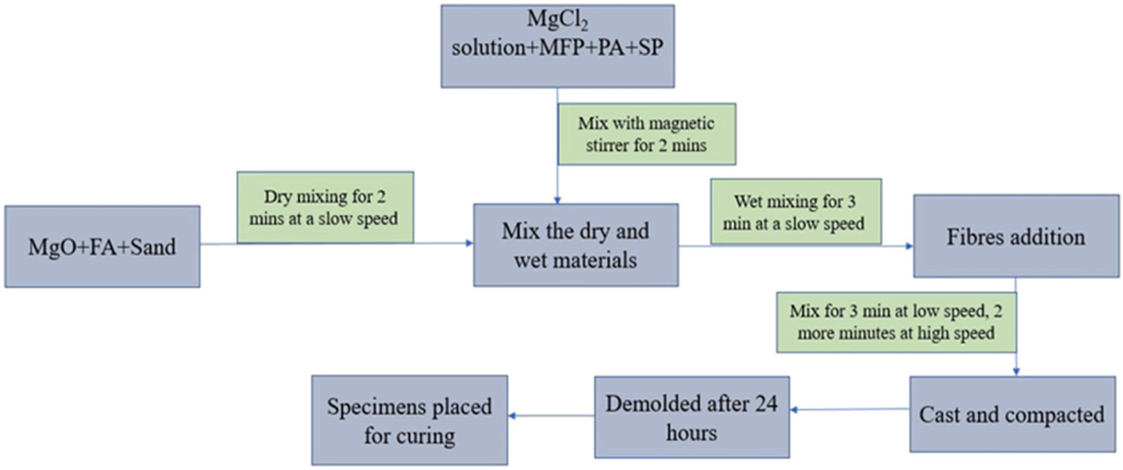


Fig. 5. Schematic representation of mixing procedure.

wet mixing (stirred liquid + dry mix) was done slowly for up to 3 minutes. Fibres were then added and mixed for 3 minutes at low speed, followed by 2 minutes at high speed. Finally, the resulting mix was used to fill the suitable moulds, and the flowability and rheological tests were carried out immediately after mixing.

Cubic specimens of 50 mm size were cast for compressive strength test, whereas dog bone specimens of size 340 mm (length) × 50 mm (width) × 13 mm (thickness) were used for tensile strength test. The moulds were wrapped in polythene sheet after casting and demoulded after 24 hours. The specimens were then kept for curing under controlled conditions (25±2°C and 65±5% relative humidity) till the testing date.

2.3. Testing procedures

2.3.1. Flowability and setting time

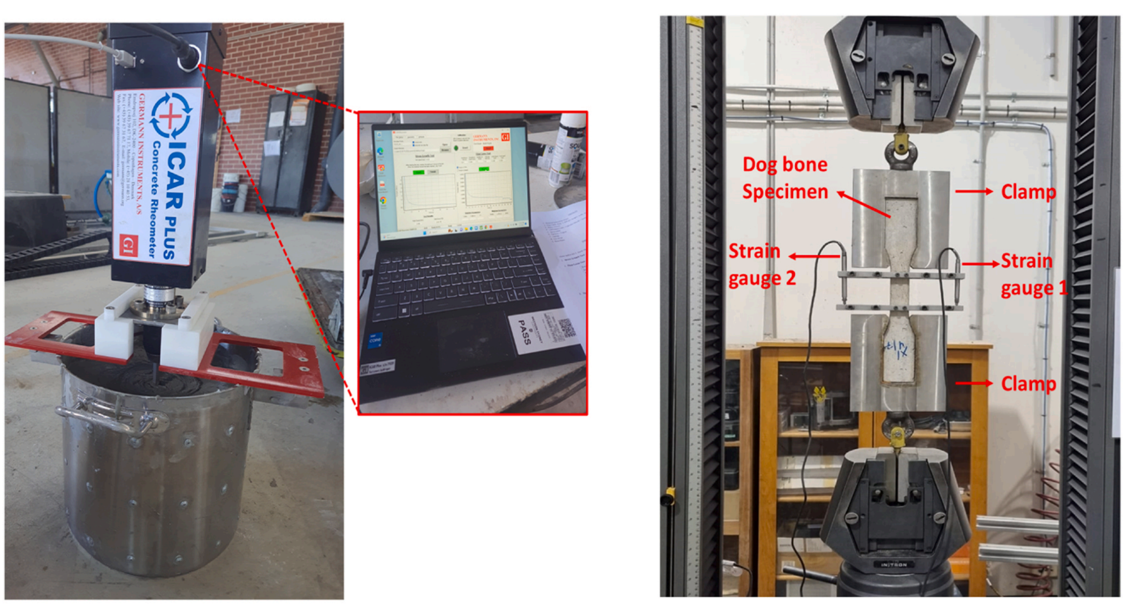
The flowability of fresh MOC mortars was assessed using flow table test as per ASTM C1437 [40]. Setting time (initial and final) was determined using the Vicat apparatus as per ASTM C191 [41]. Both tests were performed just after mixing. Three specimens were cast, and the average of each was used to get the average result. The hardened density of 28-day cured MOC based cementitious composites was assessed via an analytical balance by gauging their weight and size.

2.3.2. Rheological properties

Rheological properties such as the plastic viscosity and dynamic yield stress were measured using an ICAR Plus concrete rheometer (Germann Instruments). Fig. 6(a) illustrates the rheometer test setup. FRMOC mix was rotated using a multi-blade with a radius and height of 63.5 mm and 127 mm, respectively. The ICAR flow curve test was employed for calculating the Bingham parameters namely shear stress and plastic viscosity. The test parameters are further highlighted in Table 4. Torque values were measured at 7 different rates for each sample (0.500 rps, 0.425 rps, 0.350 rps, 0.275 rps, 0.200 rps, 0.125 rps, and 0.050 rps). After every 5 seconds, the torque value corresponding to each speed was determined. This data was then used to compute the Bingham parameters to study the rheological properties of FRMOC.

2.3.3. Compressive strength

The cube specimens were tested at different curing periods including



(a) (b)

Fig. 6. (a) ICAR Rheometer test setup (b) Uniaxial tensile test setup.

Table 4
Parameters for rheological experimental testing.

Breakdown speed (rps)	Breakdown time (s)	Initial speed (rps)	Final speed (rps)	Number of points	Time per point (s)
0.500	60.0	0.500	0.050	7	5.0

1-day (d), 3d, 7d, 14d, and 28d to assess the compressive strength development with curing age. The tests were conducted using INSTRON compressive testing machine with 3000 kN capacity at 20 MPa/min loading rate. Three samples were tested for each set, and the average was determined to be the compressive strength. In addition, standard deviation of the data was also calculated and reported alongside the strength to demonstrate the consistency of the results.

2.3.4. Tensile behaviour

The 28d cured dog bone specimens with a gauge length of 60 mm were tested to examine the stress-strain behaviour of the FRMOC under uniaxial tension. INSTRON tensile testing apparatus shown in Fig. 6(b) was used for the testing at a constant loading rate held at 0.1 mm/min. Tensile parameters including initial cracking strength, peak tensile stress, and strain capacity were then determined using the obtained data.

2.3.5. SEM analysis

SEM analysis was conducted to examine the morphology of the FRMOC mixes. Fragments extracted from the core of the cube specimens after compression testing were immersed in acetone for 48 hours to cease hydration. Subsequently, the samples were carbon coated and examined via a Phenom XL SEM, functioning at an accelerating voltage of 15 kV and a chamber pressure of 1 Pa.

3. Results and discussion

3.1. Flowability

Fig. 7 illustrates the flowability values of the FRMOC mixes. It can be clearly seen that the flowability significantly reduces by incorporating different hybrid fibre dosages. The maximum flowability value was 170 mm for M0PE0BF, which decreased to 129 mm for M0.75PE1.25BF demonstrating around 24.1% reduction in flowability value. The flowability was found to reduce on increasing BF content and mix M2PE0BF with only 2% PE fibre exhibited the lowest reduction in flowability of around 17.6%. The flowability of hybrid fibre mixes M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF further decreased by 5.3%, 4.7%, and 6.5%, respectively, as compared to M2PE0BF. The reduction in flowability due to fibre addition was attributed to the internal flow resistance caused by fibre-matrix network structure and the entanglement effect of the fibre [42]. This effect was further elevated by the addition of BF which may absorb water from the mix due to their hydrophilic nature [38,43].

3.2. Setting time

In general, the initial setting denotes the time at which the cementitious material begins to lose plasticity after being mixed with water, while the final setting denotes the point at which the material completely loses its plasticity and develops a specific strength. For practical application in the construction sector, such as formwork removal, construction planning and scheduling, setting time is one of the essential factors to consider. The results of the setting time of mixes of the FRMOC are illustrated in Fig. 8. The initial and final setting time of M0PE0BF is 397 min and 542 min, respectively. The results indicate that the setting time increased with addition of fibres. In comparison to M0PE0BF, the initial setting times of M2PE0BF, M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF increased by about 4.53%, 7.05%, 4.03%, and 6.8%, respectively, whereas the final setting times increased by 2.77%, 11.4%, 1.29%, and 12.9%, respectively. The prolonged initial and final setting periods for the M2PE0BF, M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF mixes compared to M0PE0BF were attributable to the inclusion of fibre in these mixtures. Fibres can impede the movement of cement particles, thereby retarding the hydration process and prolonging the setting time [44,45]. Additionally, the hydrophilic nature of basalt fibres may lead to water absorption from the paste, influencing its hydration kinetics and further delaying the setting process. The cumulative impact of these factors contributes to the observed increase in setting time upon fibre incorporation into the MOC matrix. This prolonged setting time may be utilized in placing, compacting, and finishing cement paste, particularly in large or complex structures where rapid

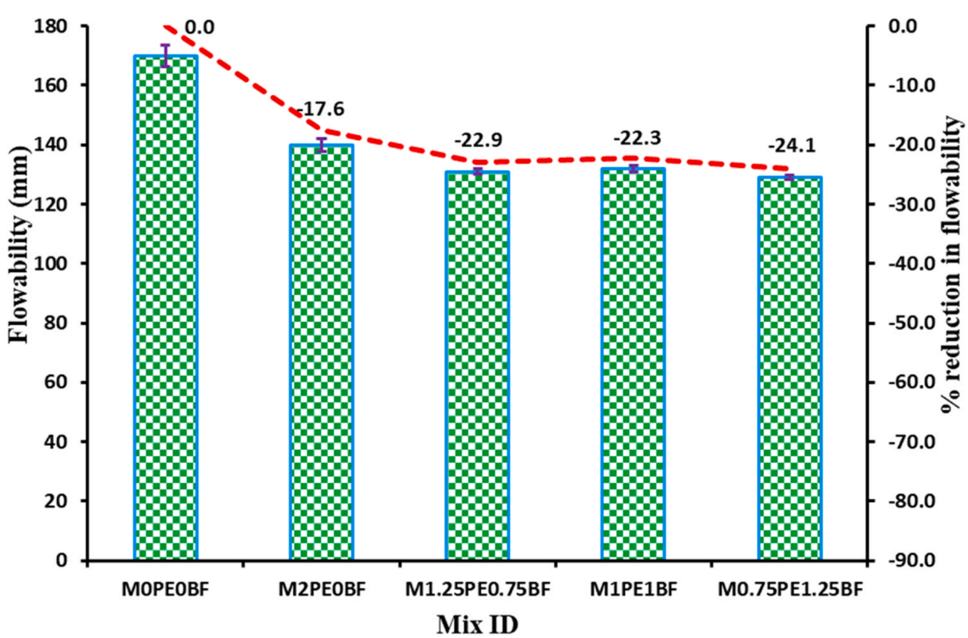


Fig. 7. Flowability of FRMOC.

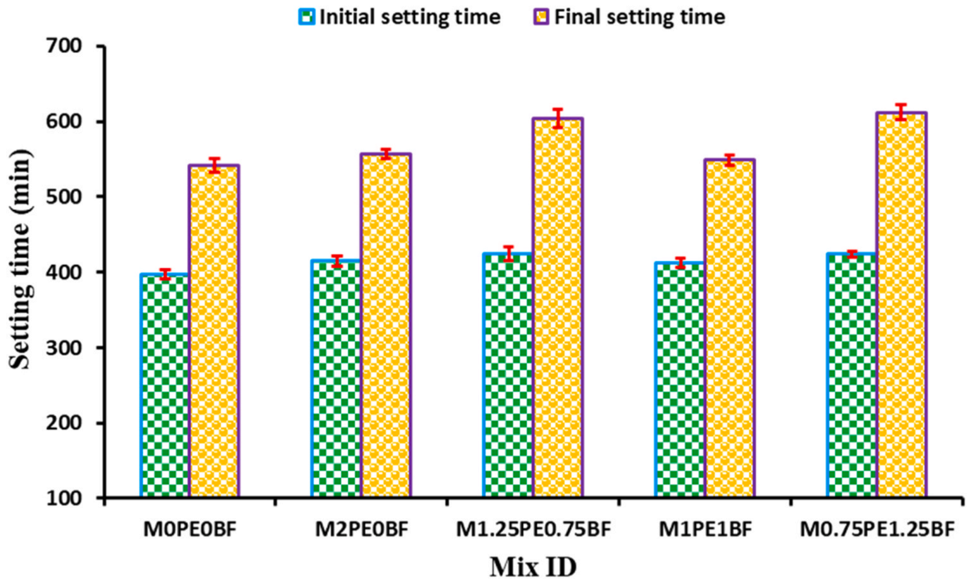


Fig. 8. Setting time of FRMOC.

setting could hinder construction progress.

3.3. Hardened density of FRMOC

The hardened density of FRMOC mixes cured for 28 days was measured, revealing that M0PE0BF exhibited the highest density compared to all other mixes. M0PE0BF showed a hardened density of 1984.6 kg/m^3. However, with the addition of fibres, the density reduced and mix M2PE0BF, M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF exhibited hardened densities of 1950.8, 1924.3, 1920.7, and 1953.7 kg/m^3, respectively. This may have been due to the presence of fibres that have less unit weight. The developed FRMOC had a significantly lower density as compared to that of some other types of OPC based fibre reinforced cementitious composites, for example, 2400–2500 kg/m^3 for the ultra-high-performance concrete [46] and 2300–2400 kg/m^3 for the ultra-high-performance strain hardening cementitious composites [47]. This suggests that FRMOC has high potential in lightweight infrastructure applications and can serve as a lightweight material with several advantages, including reduced manufacturing and handling efforts, reduced transportation and haulage costs [16].

3.4. Rheological parameters of FRMOC

In comparison to the traditional workability test which is primarily based on perception and empirical data, rheology is an area of study that characterizes the fluid and the deformation resistance of fluids against exterior shear stress with higher accuracy and impersonality [48]. Rheological parameters are important in almost all technical fields as viscosity is a crucial component of several pertinent equations for the conversion of observed data into basic physical values. The current study also thoroughly investigates the rheology of the FRMOC mixes.

The shear stress versus shear rate data obtained from the rheology

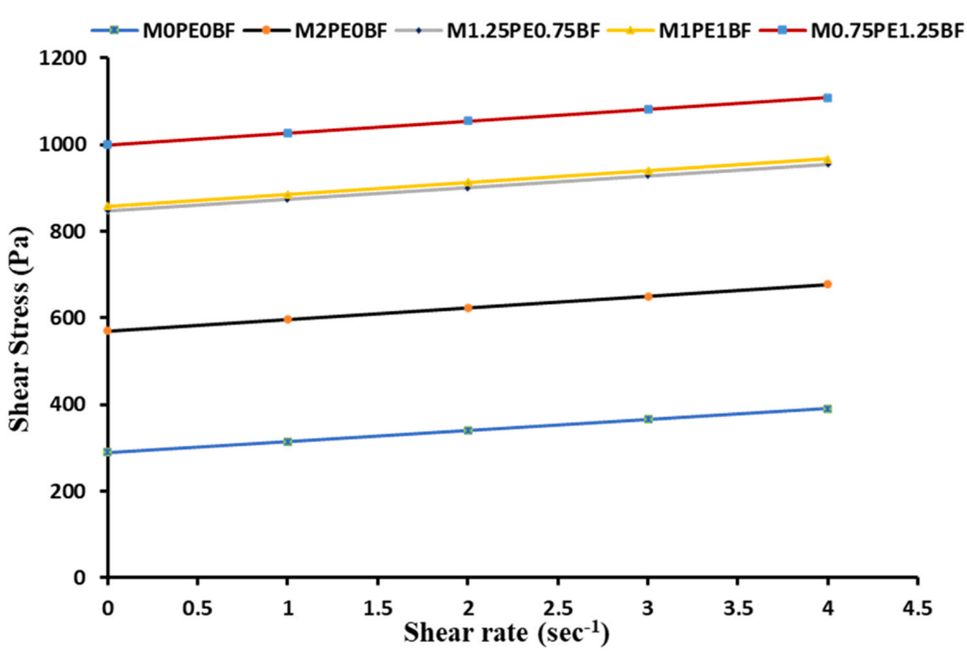


Fig. 9. Shear stress versus shear rate curves for FRMOC.

test is displayed in Fig. 9. The results show that the shear stress increased with the incorporation of fibre in the mixes. The shear stress of M0PE0BF (without fibre) was significantly lower in contrast to M2PE0BF-M0.75PE1.25BF mixes containing fibres. The mix M0.75PE1.25BF containing 1.25% BF and 0.75% PE fibre exhibited maximum shear stress followed by M1PE1BF, M1.25PE0.75BF, M2PE0BF, and M0PE0BF. The addition of fibres made the MOC paste stiffer due to the internal flow resistance caused by fibre-matrix interaction, thereby increasing shear stress. Though the increase in the shear rate facilitated a more uniform distribution of fibres within the MOC matrix [49], however, at the same time, the impact strength of the binder particles and fibres on the rotor blade increased which further contributed to increase in shear stress. As a result, the overall shear stress due to fibre addition remained consistently high at all shear rates.

The torque versus rotational velocity curves also exhibited a similar trend to the shear stress versus shear strain curves as shown in Fig. 10. The results demonstrate that the torque value increased with increasing rotational velocity for all mixtures. M0.75PE1.25BF demonstrated a substantial increase in torque values corresponding to different speeds, followed by M1PE1BF, M1.25PE0.75BF, M2PE0BF, and M0PE0BF, with M0PE0BF exhibiting the lowest torque values. At 0.5 rps, the torque values of M2PE0BF, M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF were approximately 21.4%, 58.1%, 97.1%, and 120% higher than M0PE0BF. The absence of fibre was ascribed to the lowest torque values of M0PE0BF, and the presence of fibres was linked to an increase in torque value for M2PE0BF, M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF, which resulted in higher flow resistance and stiffened mixture [50]. Moreover, the higher torque value of M0.75PE1.25BF compared to other mixes may be attributed to the presence of high amount of BF, which tends to agglomerate in cement paste, resulting in increased torque. Furthermore, the three-dimensional randomly distributed BF form a network in the matrix, considerably limiting mortar spread [38,39,51].

Fig. 11 (a and b) shows the yield stress and plastic viscosity results of each FRMOC mix obtained from the y-intercept and slope of the corresponding shear stress-shear strain curves (Fig. 9), respectively. The yield stress and plastic viscosity of the M0PE0BF (without fibre) were 289.4 Pa and 25.45 Pa.sec, respectively, and were lower than all other mixes. The mixture M0.75PE1.25BF exhibited the maximum yield stress of 1000 Pa, which was approximately 245.5% greater than M0PE0BF. It was followed by M1PE1BF, M1.25PE0.75BF, and M2PE0BF, which exhibited yield stresses that were 196.6%, 192.7%, and 96.9% higher than M0PE0BF, respectively. The yield stresses of hybrid fibre mixes M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF were approximately 32.74, 33.6%, and 43% higher than M2PE0BF (2% PE fibre), respectively. Similar trend was observed for plastic viscosity. Mix M0.75PE1.25BF had the highest value at 27.3 Pa.sec, followed by mixtures M1PE1BF, M1.25PE0.75BF, M2PE0BF, and M0PE0BF at 27.2, 26.9, 26.8, and 25.5 Pa.sec, respectively. The significant increase in yield stress and plastic viscosity values following the addition of fibre was due to the fibre's substantial flocs production and tangling impact, which led to enhanced flow resistance and a stiffer structure of the new MOC paste [52,53]. Song et al. [54] also observed that the yield stress and plastic viscosity escalated with higher BF dosages and attributed this finding to the clustering and inter-fibre interaction of BF. The rheological insights in the present study clearly align with the flowability results, indicating that the incorporation of fibre stiffened the MOC paste, resulting in enhanced plastic viscosity and yield stress, while concurrently reducing flowability. Though the flowability and viscosity values of developed FRMOC is considerably inferior to MOC without fibres, these can be improved with an effective use of HRWR during mixing. Moreover, use of proper vibration technique during placement can further ensure efficient implementation of the material.

3.5. Compressive strength

Fig. 12 depicts the compressive behaviour of FRMOC tested after 1d, 3d, 7d, 14d, and 28d curing. It was observed that the FRMOC composites demonstrated significant strength gains after 1d of curing. The mix M0PE0BF without fibres exhibited the lowest compressive strength compared to other mixtures. Furthermore, a significant increase in compressive strength was observed with the addition of hybrid fibres.

The findings further indicate that M1.25PE0.75BF with 1.25% PE fibre and 0.75% BF displayed maximum compressive strength at all curing periods followed by M2PE0BF, M1PE1BF, M0.75PE1.25BF, and M0PE0BF, which can be attributed to the overall homogeneous dispersion throughout the matrix, resulting in an enhanced fibre-matrix interaction. This has been explained later through SEM analysis. The

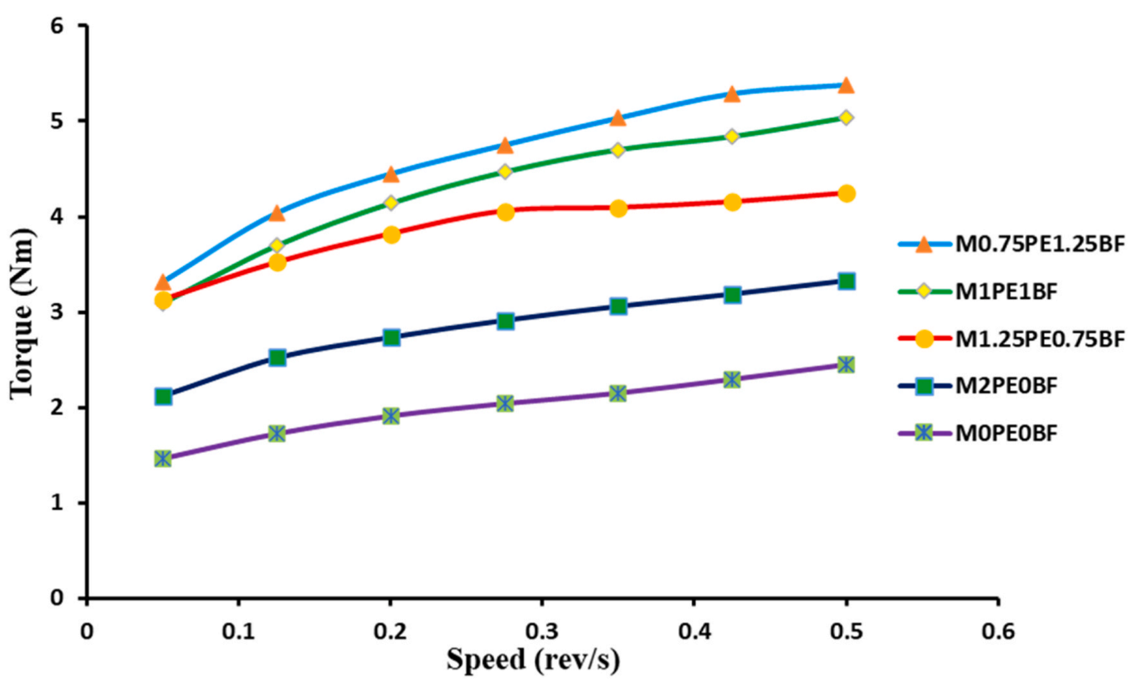


Fig. 10. Torque versus speed curves for FRMOC.

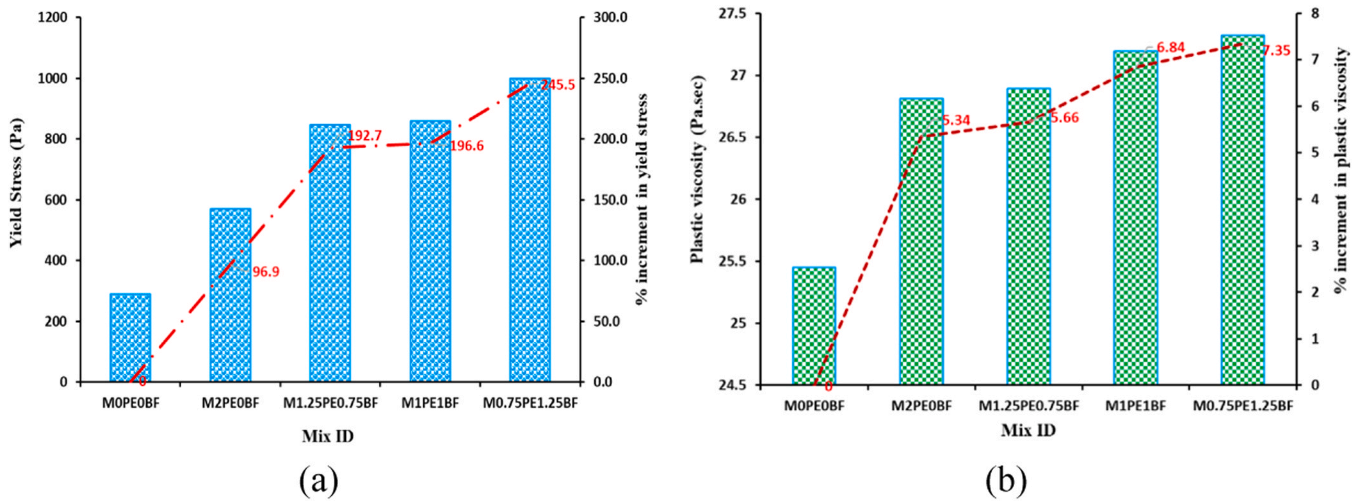


Fig. 11. Rheological parameters of FRMOC (a) Yield stress and (b) Plastic viscosity.

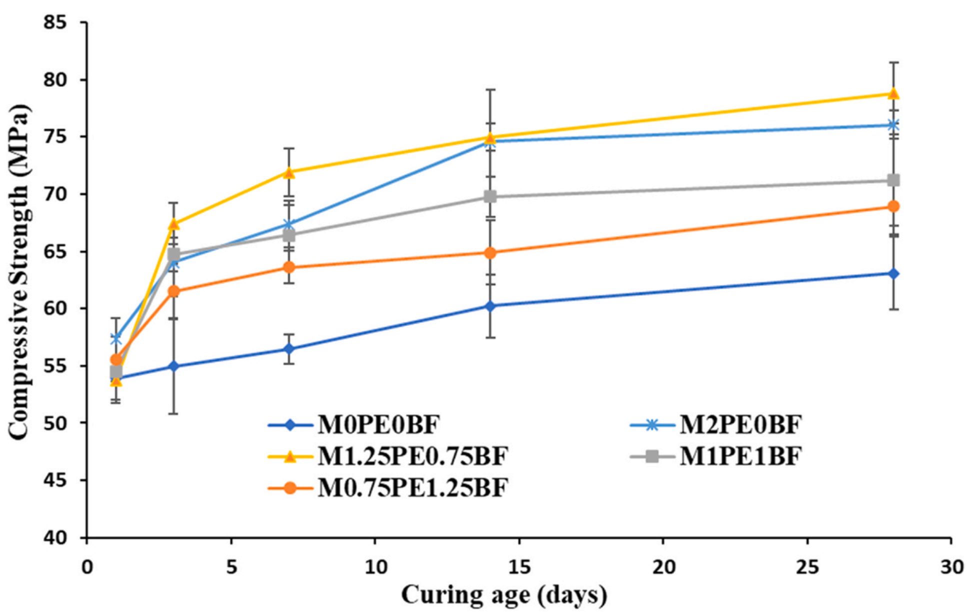


Fig. 12. Compressive strength of FRMOC composites.

1d compressive strength of M1.25PE0.75BF was 53.7 MPa representing approximately 68.2% of its corresponding 28d strength (78.8 MPa). This notable early strength gain in the M1.25PE0.75BF specimen was ascribed to the rapid formation of needle-shaped phase 5 (5Mg $(OH)_2 \cdot MgCl_2 \cdot 8H_2O$) gel. Furthermore, the formation of small quantity of other phases like magnesium hydroxide ($Mg(OH)_2$), and magnesium-chloride silicate hydrate gel (M-Cl-S-H-gel) may also have been responsible for strength development in MOC composites [3,6,55]. Comparable results regarding the high early compressive strength gain were also documented by Yu et al. [3] and Guo et al. [20], with reported values of approximately 71.4 MPa and 50–70 MPa, respectively, for 1d cured MOC composites. This rapid strength gain of the FRMOC provides a potential avenue for repair applications particularly in situations with quick turnaround time. Moreover, due to their lightweight properties, the developed materials also hold great potential for a range of applications including cladding, facades, and panels.

As the curing period increased, the strength also increased, though at a slower rate from 1d to 28d, owing to the gradual transformation of unreacted MgO particles to phase 5 during hydration. The presence of these phase 5 crystals, coupled with well-dispersed fibre reinforcement, contributed to the observed maximum compressive strength at 28d [3]. The mix M2PE0BF containing 2% PE fibre showed slightly lower compressive strength as compared to M1.25PE0.75BF depicting that PE fibres are also well-distributed and showed excellent bonding potential with the MOC matrix, as revealed in past studies as well [3,24]. However, other mixes such as M1PE1BF (1% PE fibre and 1% BF) and M0.75PE1.25BF (0.75% PE fibre and 1.25% BF) showed a minimal increment in compressive strength with respect to the curing period. This may have been due to the higher amount of BF, which causes the fibre to flock and generate stress concentration zones in the matrix [51, 56].

To explain the observed compressive behaviour, the morphology of FRMOC composites was examined at the micro level using SEM analysis. The microstructure of M0PE0BF without the hybrid fibre is shown in Fig. 13 (a), whereas that of M2PE0BF, M1.25PE0.75BF, and M0.75PE1.25BF mixes with the hybrid fibre are displayed in Fig. 13 (b), (c), and (d), respectively. Phase 5 crystals in the needle shape were the most distinctive feature observed in each sample. The resulting rods or needles seemed to be intermittently connected, which contributed to their strength [57,58]. In voids or pockets of each sample, the

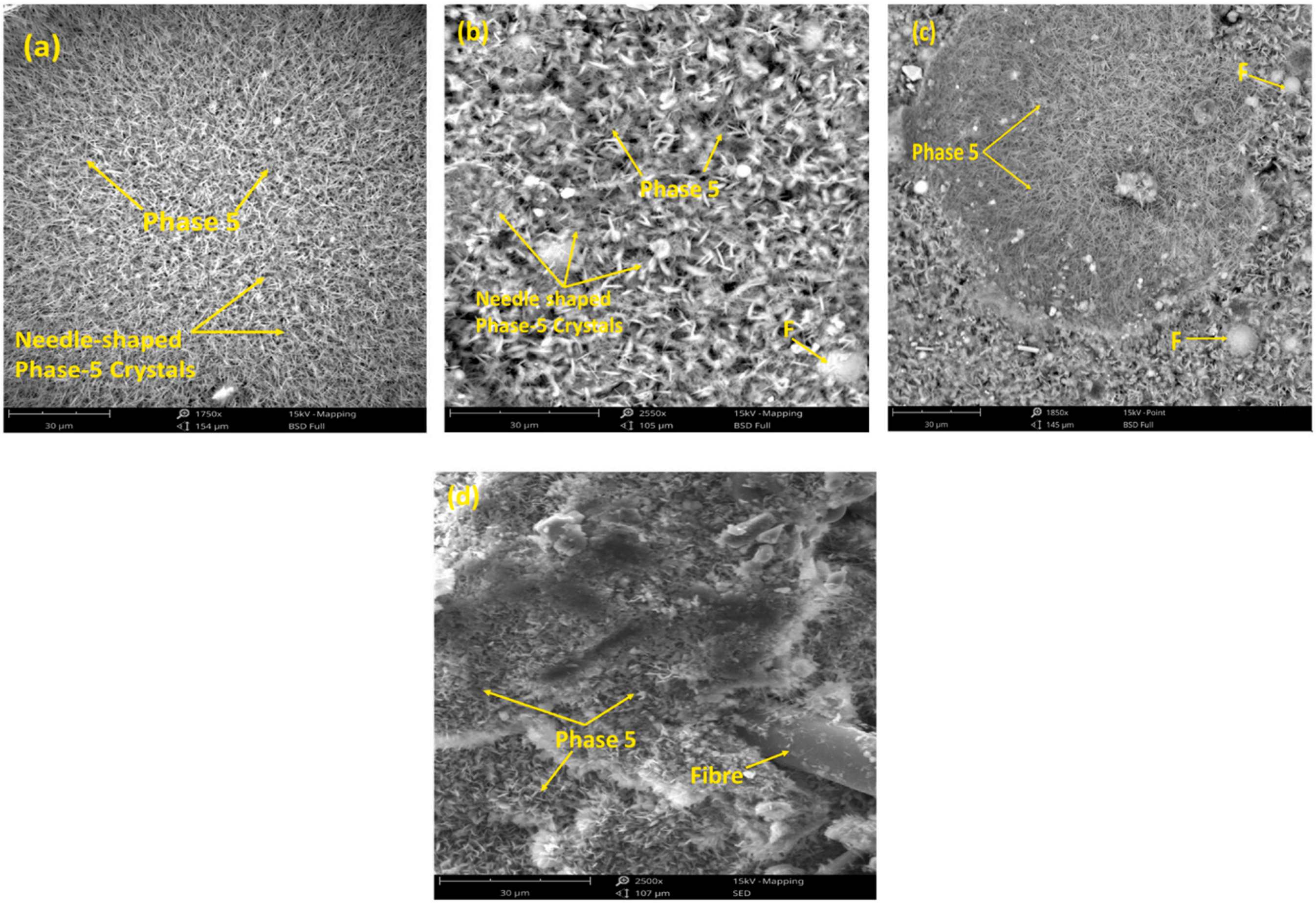


Fig. 13. SEM analysis of 1d cured FRMOC specimens: (a) M0PE0BF, (b) M2PE0BF, (c) M1.25PE0.75BF, and (d) M0.75PE1.25BF.

needle-shaped structures of phase 5 were easier to identify. The spherical-shaped particles, represented by the letter 'F' were also found in certain images, indicating the presence of unhydrated fly ash. Hence, the rapid formation of needle-shaped phase 5 crystals/flakes was responsible for the early development of strength in MOC composites as stated above [55,59], where 1d compressive strength was equivalent to more than 68% strength of 28d cured MOC composites.

Fig. 14 further illustrates SEM images of 28d cured FRMOC composites. The morphology of the M0PE0BF matrix without fibre is shown in Fig. 14(a), exhibiting the well-compacted matrix. However, some cracks/fractures were also visible on the surface, which may be the probable cause of its decreased strength. The cracks might exist due to unreacted MgO particles leading to a weak interfacial transition zone (ITZ) within the matrix [20,60]. M2PE0BF with only 2% PE fibre (Fig. 14 (b)) demonstrated uniform fibre dispersion with proper fibre bridging effect and bonding with the MOC matrix. Past works also demonstrated strong bonding of PE fibre with the MOC matrix, resulting in improved fibre-matrix interaction [3,47].

Furthermore, the mixes M1PE1BF and M0.75PE1.25BF (as illustrated in Fig. 14 (d) and (e), respectively) reveal the flocculation of fibres in their matrices. The presence of increased cracks and porous structures in the vicinity of agglomerated fibres disrupts the interfacial bonding characteristics and the overall synergy between MOC paste and fibres, resulting in a reduction in strength. Furthermore, fibres agglomeration influences fibre to fibre compactness [38,51]. As a result, the loss of strength in these mixtures could be overall attributed to poor fibre dispersions, which generate stress concentration zones and weak bonding with the matrix at the ITZ level.

In comparison to other hybrid fibre FRMOC mixes, mix M1.25PE0.75BF (Fig. 14 (c)) exhibits excellent fibre dispersion and a well-compacted and dense matrix. The interaction between the fibres and the matrix at ITZ also shows that the fibres and MOC matrix were properly bonded, producing excellent bridging and stable networks that may have resulted in a notable improvement in strength [24].

3.6. *Tensile behaviour of FRMOC*

3.6.1. *Stress-strain behaviour*

Fig. 15 displays the tensile stress-strain curves of the 28d cured FRMOC with varied fibre dosages. Mix M0PE0BF exhibited the lowest tensile stress and strain capacity as expected. Brittle failure was also observed just after attaining the maximum tensile stress, which can be attributed to the lack of fibre. However, other mixes containing fibres showed ductile failure. Among these mixtures, M2PE0BF with only 2% PE fibre showed the highest tensile stress and strain capacity, followed by M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF with hybrid fibre. The M2PE0BF curves showed excellent strain hardening behaviour after the elastic zone followed by peak tensile stress and strain softening stage. Similar observations regarding the enhanced strain hardening and multiple cracking behaviours of PE fibre-reinforced MOC were also documented by Wang et al. [24] and Wei et al. [28].

An increase in the replacement levels of PE fibre with BF resulted in a considerable decline in the tensile properties of FRMOC. As a result, the strain hardening demonstrated by M1.25PE0.75BF with 1.25% PE fibre and 0.75% BF was lower than that observed for mix M2PE0BF. This further reduced with an increase in BF content for mix M1PE1BF and M0.75PE1.25BF. Overall, among hybrid FRMOC specimens, M1.25PE0.75BF containing the least BF dosage showed excellent tensile

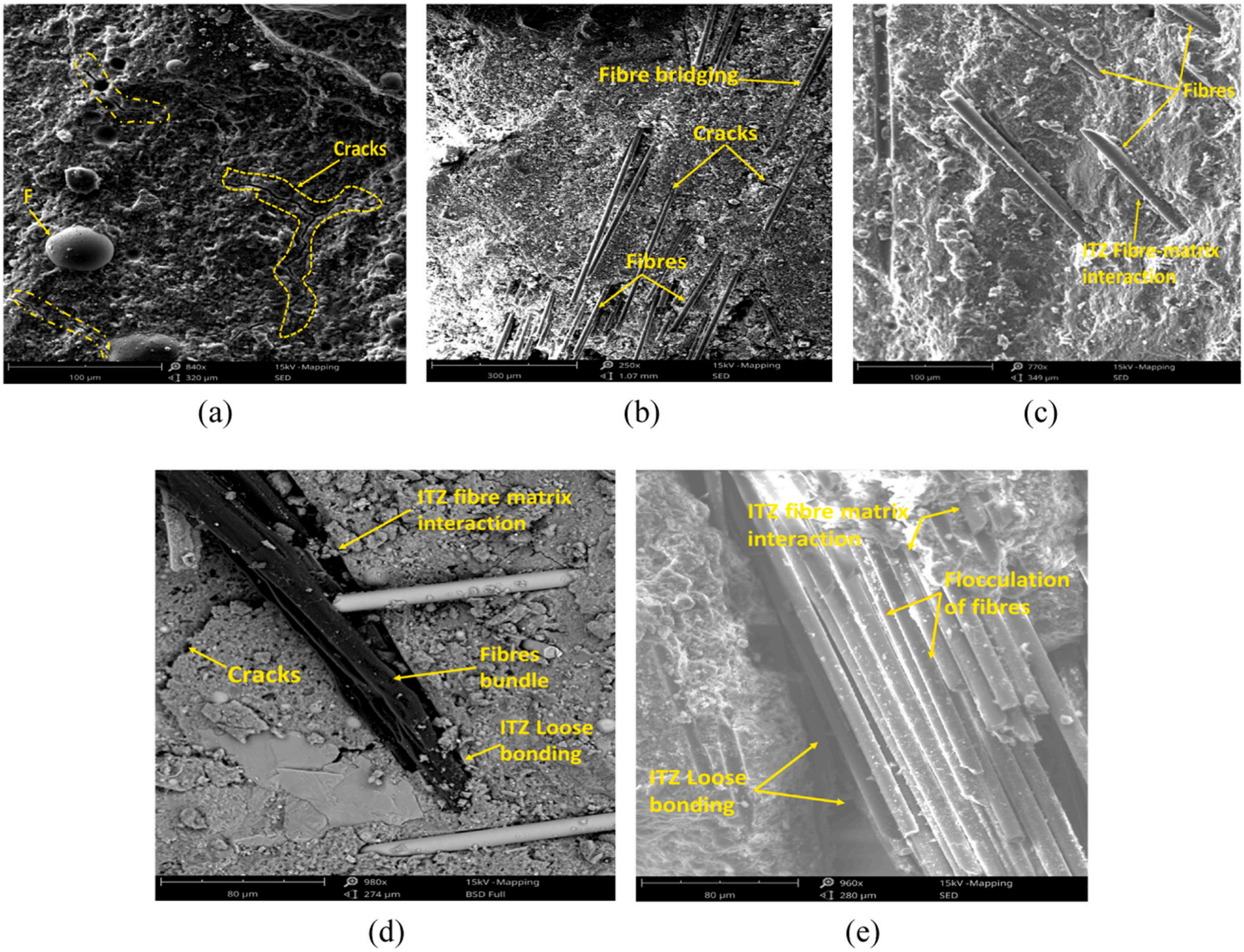


Fig. 14. SEM analysis of 28d cured FRMOC specimens: (a) M0PE0BF, (b) M2PE0BF, (c) M1.25PE0.75BF, (d) M1PE1BF, and (e) M0.75PE1.25BF.

performance.

3.6.2. First cracking and peak tensile stress

Fig. 16 displays the first cracking and peak tensile stress of FRMOC composites. The peak and first cracking strength of M0PE0BF were both 5.24 MPa. This is due to the lack of fibre in M0PE0BF, which results in brittle failure just after attaining peak load. The first cracking strength increased from 5.24 MPa (M0PE0BF) to 8.21, 6.71, 6.94, and 5.45 MPa for M2PE0BF, M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF, respectively. The maximum increase in first cracking strength observed for M2PE0BF was approximately 56.68%, whereas the minimal increase observed for M0.75PE1.25BF was 4.01% when compared to M0PE0BF.

Similarly, peak tensile stress also increased from 5.24 MPa (M0PE0BF) to 10.95, 8.49, 7.41, and 6.4 MPa for M2PE0BF, M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF, respectively. Among FRMOC composites, the mix M2PE0BF having only 2% PE fibre demonstrated the highest initial cracking and peak tensile stress, followed by M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF including hybrid fibre combinations. This further confirms that the addition of BF negatively affects the tensile performance. The highest strength as observed for mix M2PE0BF can be attributed to the good bonding ability of the MOC matrix with PE fibre resulting in an improved fibre matrix interaction.

It is important to note that despite the use of hybrid PE and BF, the peak tensile stress for mix M1.25PE0.75BF surpassed the previous findings, such as 7 MPa, 8.28 MPa, and 5 MPa reported by Wang et al. [24], Yu et al. [3], and Wei et al. [28], respectively, on PE fibre-reinforced MOC. This confirmed the effectiveness of the adopted hybrid fibre dosage and matrix to achieve an optimized performance in terms of both compressive and tensile strength.

3.6.3. Strain capacity

Fig. 17 depicts the tensile strain capacity of FRMOC. It can be observed that mix M2PE0BF showed a maximum strain capacity of 4.41%. The value decreased to 2.43%, 0.95%, and 0.29% for M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF, respectively. The declining trend in strain capacity was attributed to an increasing level of PE fibre replacement with BF, with M1.25PE0.75BF, M1PE1BF, and M0.75PE1.25BF comprising 1.25% PE fibre + 0.75% BF, 1% PE fibre + 1% BF, and 0.75% PE fibre + 1.25% BF, respectively. The increased strain capacity of M2PE0BF can be attributed to the strong bonding between the PE fibre and the MOC matrix, which results in improved fibre-matrix interaction [3,47]. Furthermore, uniformly distributed multiple cracks on the surface of dog bone specimens were observed, resulting in higher strain capacity, as shown in Fig. 18. Besides, the M1.25PE0.75BF hybrid FRMOC composite also exhibited a higher strain capacity that was approximately 155.8% and 227.6% higher than the M1PE1BF and M0.75PE1.25BF. This may be due to excellent fibre dispersion, which results in improved fibre-matrix interaction. The SEM investigation in Section 3.5 clearly indicated poor fibre dispersion and flocculation in M1PE1BF and M0.75PE1.25BF, resulting in stress concentration zones and weak fibre bonding/adhesion to the matrix which

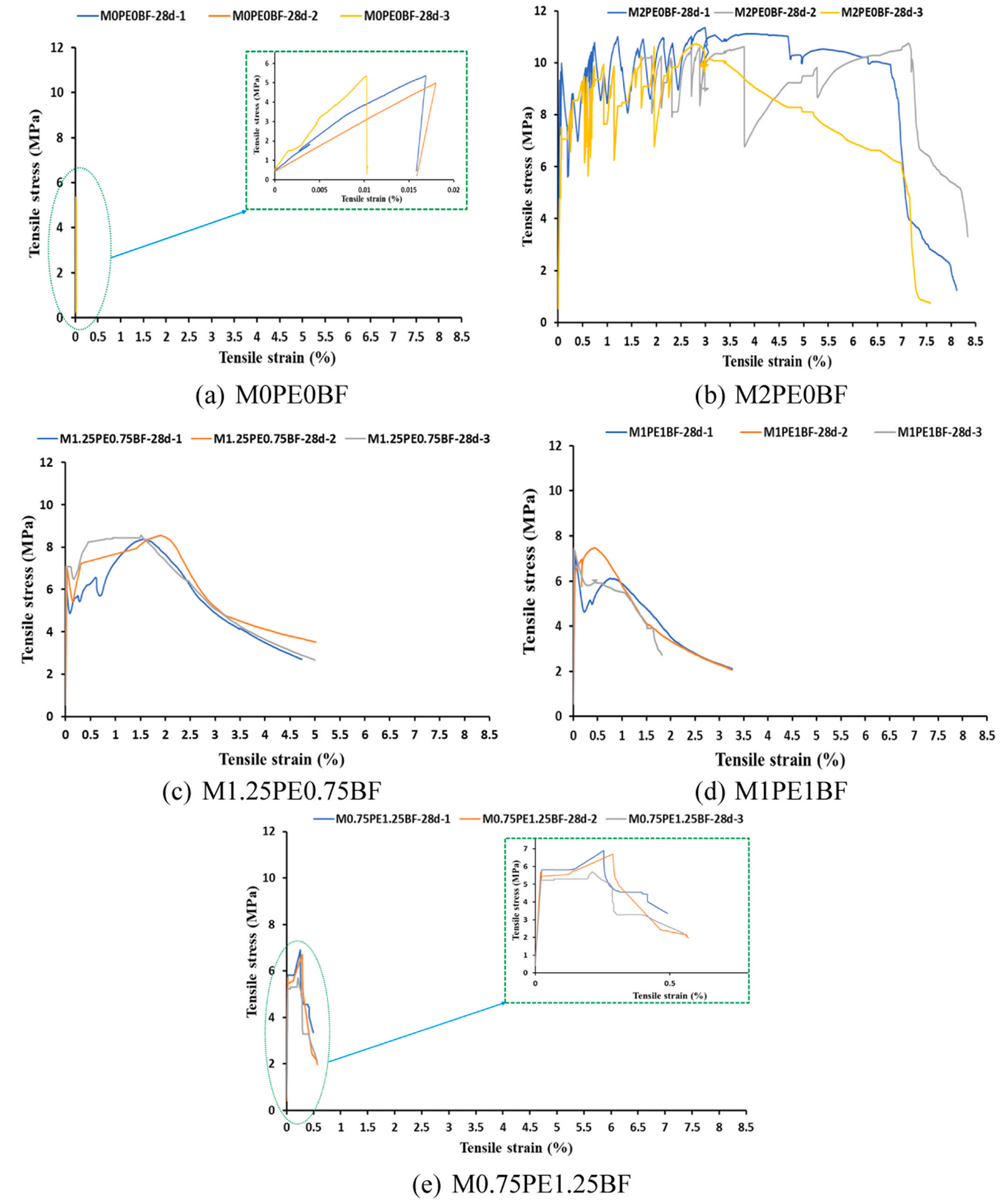


Fig. 15. Tensile stress-strain curves of FRMOC.

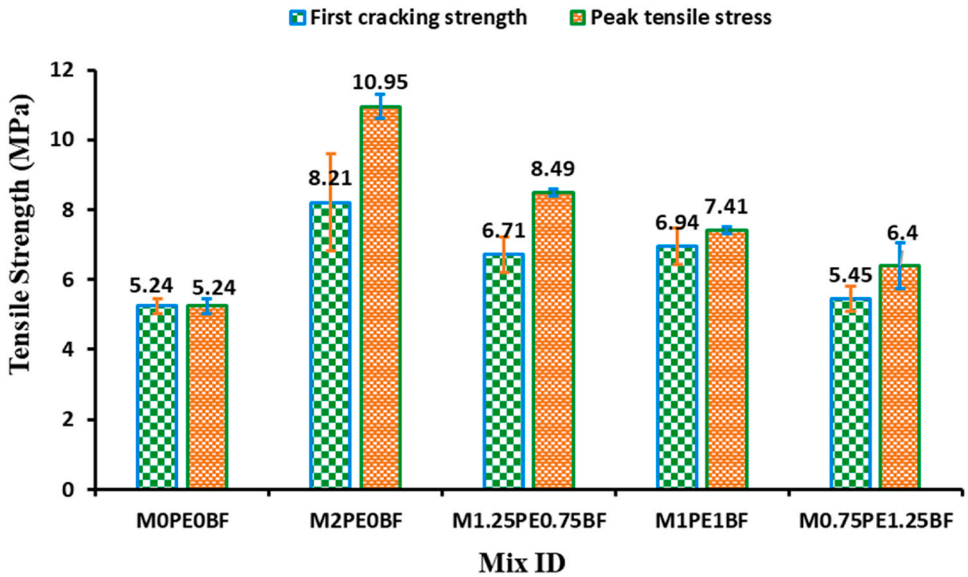


Fig. 16. First cracking and peak tensile stress of FRMOC.

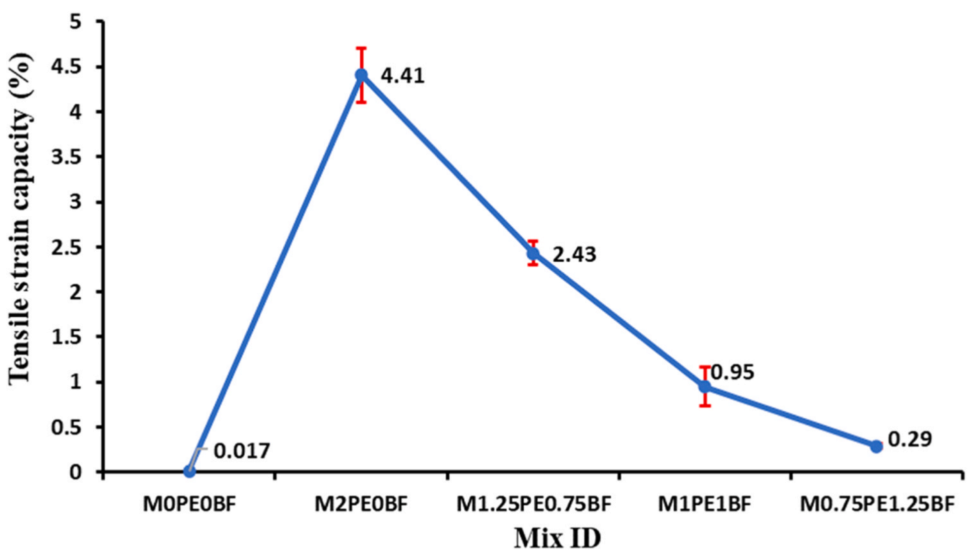


Fig. 17. Tensile strain capacity of FRMOC.

may have resulted in lower strain capacity. Furthermore, the tensile strain capacity of M1.25PE0.75BF lies in the 2–4% range, as reported in previous studies for PVA fibre-reinforced OPC-based ECCs and MgO-based ECCs [61–64]. Therefore, not only this mix demonstrates acceptable tensile ductility, but its unique composition, containing both low-melting PE fibre (~140℃) and high-melting BF (~1450℃), also suggests its suitability as a fire-resistant cladding material [65,66].

Overall, M1.25PE0.75BF (1.25% PE fibre and 0.75% BF) demonstrated excellent tensile performance with enhanced tensile strength (8.49 MPa) and strain capacity (2.43%), as compared to other hybrid FRMOC. Consequently, the reliability of FRMOC as a construction material is significantly boosted, positioning it as a viable material for application as cladding material, especially in high-rise buildings where resilience against lateral loadings like wind and seismic forces is paramount.

4. Conclusion

This study presents the development of a novel hybrid fibre reinforced MOC based composite with enhanced strength and ductility by incorporating both hybrid PE and basalt fibres. The influence of different hybrid fibre dosages on the behaviour of the FRMOC was systematically examined. Through a comprehensive experimental investigation, the following key findings have been derived from this study.

- The addition of fibres in MOC mixes resulted in a reduction in flowability, with a more pronounced decrease observed when hybrid fibres were included. Concurrently, the rheological parameters such as plastic viscosity and yield stress increased with the incorporation of hybrid fibres.
- Fibres also increased the setting time of MOC mixes. The initial and final setting times increased from M2PE0BF to M0.75PE1.25BF within the range of 4.53–6.8% and 2.77–12.9% respectively, when compared to M0PE0BF without fibres.
- The flowability reduced and the setting time increased with an increase in the dosage of BF. This may have been due to their

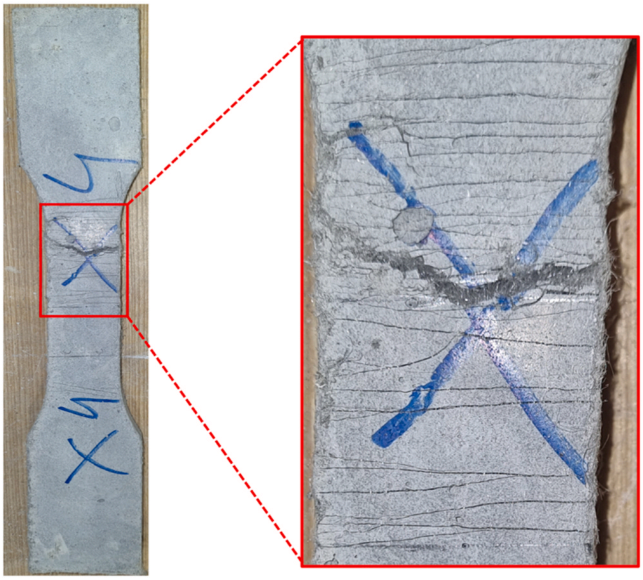


Fig. 18. Microcracks observed in FRMOC (M2PE0BF mix).

hydrophilic nature along with fibre entanglement effect which can influence the hydration kinetics.

- FRMOC mixes showed a substantially lower hardened density than fibre-reinforced OPC-based composites, making them lightweight cementitious composites. Fibre addition further reduced the density of MOC mixes, with 3.22% being the maximum reduction reported for M1PE1BF in contrast to M0PE0BF.
- The compressive strength of the FRMOC mixes was found to increase gradually with curing age. The 1d compressive strength of FRMOC composites reached 68.2–85.4% of the corresponding value at 28d, indicating a considerably higher early gain of high strength for the FRMOC. This attribute will encourage the practical implementation of the FRMOC composite where speedy maintenance is required. However, the strength gain over time was slower, reaching a maximum of 78.8 MPa for mix M1.25PE0.75BF.
- The tensile stresses and strain capacity of FRMOC decreased with increase in the percentage of PE fibre replaced with BF. The strain capacity of mix with 2% PE fibre (M2PE0BF) was 4.41%, which decreased to 0.29% for mix with 0.75% PE + 1.25% BF (M0.75PE1.25BF). The tensile strength also followed similar trend with mix M2PE0BF showing the highest strength (10.95 MPa) and M0.75PE1.25BF showing the least (6.4 MPa).
- Overall, M1.25PE0.75BF with 1.25% PE fibre and 0.75% BF was considered to be the optimal FRMOC mixture among the considered hybrid fibre combinations, exhibiting the maximum compressive strength (78.8 MPa), along with high tensile strength (8.49 MPa) and strain capacity (2.43%).
- SEM analysis ascribed the improved performance of M1.25PE0.75BF to superior fibre dispersion in the MOC matrix coupled with needle-shaped phase 5 crystals resulting in stronger fibre-matrix interaction. Additionally, agglomeration of fibres was observed in hybrid fibre mixes containing 1% and 1.25% BF, leading to stress concentration zones and weak bonding with the matrix, resulting in a decrease in strength.

Based on the findings of this research, it is recommended to explore the utilization of FRMOC for cladding and facade applications. Additionally, future research could investigate the effects of incorporating other high-modulus fibres such as carbon fibre, recycled carbon fibre, glass fibre, etc. into MOC to assess their impact on strength and ductility. Furthermore, the synergistic effects of additives like ground granulated blast furnace slag (GGBFS), metakaolin, silica fume, etc. in combination with hybrid fibres should be investigated to understand their influence on the MOC matrix. Conducting a life cycle assessment of the mixes would also be beneficial to evaluate the cost and sustainability implications of the selected factors in MOC mixes.

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CRediT authorship contribution statement

Sanket Rawat: Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Farhan Ahmad:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lihai Zhang:** Supervision, Resources, Methodology, Funding acquisition. **Richard (Chunhui) Yang:** Writing – review & editing, Supervision, Resources. **Yingying Guo:** Validation, Methodology, Formal analysis, Data curation. **Y.X. Zhang:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Daniel J. Fanna:** Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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