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Influence of Density and Compressive Strength on Intrinsic Air Permeability and Porosity of Hybrid Fibre-Reinforced Lightweight Foamed Concrete

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ABSTRACT

Given the growing demand for sustainable and environmentally friendly building materials, lightweight foamed concrete (LFC) is a suitable choice for semi-structural applications. However, the low strength and high water absorption of LFC make it an unsuitable material for large structures. The building industry does not consider LFC cost-effective unless it undergoes strengthening with other materials, as its mechanical strength and durability are insufficient for building use. This paper aims to augment the mechanical and durability characteristics of hybrid fibre-reinforced lightweight foamed concrete (HFRLFC) by using nylon and polypropylene (PP) fibres under a sealed curing condition. A strict experimental method was used to compare HFRLFC to control mixtures (which didn't have any fibres), single-fibre mixtures (0.4% nylon), and hybrid-fibre combinations (0.13% PP and 0.27% nylon) at a constant 1:1 mixing ratio. The findings demonstrated a notable initial improvement in mechanical strength and durability, as well as heightened resistance to lower permeability via less cracking and improved compaction. Mixed HFRLFC with 0.27% nylon and 0.13% PP had better mechanical and long-lasting properties than control mixes and LFC with only nylon fibre. HFRLWC exhibits the synergistic reinforcement mechanisms of hybrid fibres, improving their structural integrity and durability over time. These findings emphasize the potential of HFRLFC as a sustainable and effective material for semi-structural applications.

1. Introduction

In recent years, the construction industry in Malaysia has shown substantial awareness in the usage of lightweight foamed concrete (LFC) as a building material owing to its many promising properties such as lighter weight, easier to manufacture, durable and cost efficient. LFC is a composite material comprising a Portland cement paste or cement filler matrix characterised by a uniform pore structure generated by the incorporation of air in the form of minute bubbles [1,2].

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One of the principles of sustainability that may be effectively implemented into the lowering of power utility costs is the Green Building. This is accomplished by enhancing the efficiency with which resources such as energy, water, and materials are used as the primary emphasis [3]. The use of LFC has risen due to recent legislation and technological and research developments. Recent improvements seek to decrease concrete density while preserving substantial strength [4]. LFC is a newly used energy-efficient material in construction that is lightweight, rapidly manufactured, sustainable, cost-effective, and adjustable in density [5]. According to Thienel *et al.,* [6], the latest stage in this development features a substance referred to as infra-lightweight concrete (ILC). The primary objective of ILC is to meet the necessary structural requirements and thermal insulation standards. The ILC offers potential for the construction of monolithic walls that adhere to current energy consumption regulations for buildings without requiring additional insulation materials.

Shahpari *et al.,* [7] categorize LFC into structural and non-structural types based on its strength. LFC is a type of concrete that has the potential to decrease the self-weight of structures and reduce expenses for enterprises in terms of material and manpower costs. Its limited mechanical strength and significant deficiency in elasticity render it structurally weak [8]. Moreover, due to its inferior heat conductivity compared to traditional concrete, LFC may serve as insulation [9]. This material has primarily been utilised as a filler in civil engineering projects. Nonetheless, its excellent thermal and acoustic properties suggest significant potential as a construction material [1]. The use of LFC in construction has been more prevalent owing to its superior thermal insulating characteristics, reduced structural weight, higher fire resistance, and economic efficiency. It may save manpower and financial resources. The ancillary advantages of using LFC include savings in transportation, labour, time, and energy costs, as well as the development of more efficient and economical foundation systems [10].

LFC provides several advantages, but its compressive strength, generally less than 60 MPa, limits its application. Because it absorbs a lot of water and particles float at high water-to-binder ratios, it is difficult to work with [11]. LFC is more brittle than normal-weight concrete (NWC) but has the same mix proportions and compressive strength [12]. More compressive strength means more fragility [13]. Compression makes it strong, but tension makes it weak and brittle. LFC's strength and water absorption limitations prevent it from meeting super high-rise structure requirements for strength and durability [14]. In addition, resolving these limitations was crucial to the development of LFC. These methods are not fully utilised in practical engineering due to their poor mechanical and durability properties.

Malaysia has recently introduced the concept of green building, which requires the use of innovative materials and technology in construction [9,15]. Therefore, the materials and technology remain scarce, posing challenges for developers, builders, and subcontractors in acquiring all necessary resources for the construction of green buildings. The new materials and technologies must be assessed and compared against a comparable product to get the most accurate results. Unknown obstacles exist about the green construction idea, its materials, and technology, hence creating impediments [16]. Reinforcing LFCs with single or hybrid fibres may help overcome these drawbacks. Using two or more types of fibres, each of which may carry out a different task, is a strength of this method. According to the findings of prior research, the use of hybrid fibres to combine two synthetic fibres into LFC may have limits, encounter problems, and be less commercialised due to the fact that only a few studies have been completed. Study on hybrid fibre-reinforced LFC (HFRLFC) is limited due to unknown ideal fibre ratios, limited understanding of long-term performance under a sealed curing processes and environmental exposures, and unexplored economic feasibility and scalability due to cost, processing, and material compatibility issues. This lack of awareness inhibits the creation of a more effective and sustainable LFC for numerous applications, including building.

Chen & Liu, [5] stated that the density of LFC varies between 1400 and 2000 kg/m³. Nensok *et al.,* [16] through the previous researchers Elshahawi and Hückler, stated that LFC has a variable density range of 400-1900 kg/m³. LFC with a density ranging from 800 to 1900 kg/m³ is classified as structural, while ultra-light foamed concrete (ULFC) has a density between 400 and 800 kg/m³. The previous definition refers to non-structural LFC, which results in lightweight materials exhibiting a lower thermal conductivity than the latter. Conversely, the density of NWC ranges from 2300 to 2400 kg/m³ [18]. Nevertheless, the widely accepted definition of LFC is concrete with a density below 2,000 kg/m³ [12, 18]. According to the EN 206-1 standard, LFC has a density between 800 and 2000 kg/m³.

This paper proposes the feasibility of integrating hybrid fibres with micro-synthetic fibres in the mixing process to enhance the mechanical and durability of LFC, thereby creating LFC suitable for semi-structural applications. Hybrid fibres were used to improve various properties of LFC, including different filler or binder ratios and LFC densities [19-20]. A thorough examination of the physical and mechanical characteristics of nylon and polypropylene (PP) fibres were undertaken. The study examined the effects of varying quantities of nylon and PP fibres on the mechanical and durability characteristics of LFC using a sealed curing condition, with tests conducted over a 90-day period.

1.1 Lightweight Foamed Concrete (LFC)

LFC reduces concrete density by combining cement paste and at least 20% air [19]. Making LFC involves adding a foaming agent to cement paste, creating microscopic air spaces within the building. It is very light [20]. The material is favourable because to its lightweight, great workability, ease of preparation and application, durability, cost-effectiveness, eco-friendliness, and energy efficiency.

LFC is a type of lightweight concrete (LWC) that is frequently employed in the construction sector. It may be considered relatively homogeneous in comparison to conventional concrete due to the absence of a coarse aggregate phase. The binder type, pre-foaming methods, and curing processes influence the microstructure and composition of foamed concrete, hence determining its properties [20]. Its limited mechanical strength and significant deficiency in elasticity render it structurally weak [8].

1.2 Uses of Fibre in LFC

The mechanical properties and durability of building materials may be enhanced by the use of readily available fibre materials. According to Khan *et al.,* [14], adding fibres to LFC may increase its mechanical characteristics, durability, ductility, performance, and energy absorption. However, this addition does not significantly affect the material's workability. In reality, the mechanical and durability properties of LFC are significantly enhanced by the inclusion of fibres [21]. On the other hand, this limitation can be addressed by incorporating a variety of fibres into concrete, particularly lightweight formulations, to enhance its energy absorption capacity following matrix failure [22]. According to previous researcher [23], fibres may be classified into two types, as seen in Table 1.

Table 1
The two categorization of fibres

No	Categorization of fibres
1	Fibres whose moduli are lower than the cement matrix, such as cellulose, nylon, polypropylene, etc.
2	Fibres with higher moduli than cement, such as asbestos, glass, steel, etc.

1.3 Utilisation of Nylon Fibre in LFC

The durability, thermal resistance, and high tensile strength of nylon fibre, which exceeds 550 MPa, are comparable to those of PP and polyvinyl fibres. Nylon fibre, a polyamide that is distinguished by the presence of recurring amide groups, possesses exceptional qualities, including resilience, chemical stability, temperature resistance, and strength. As a result, it is an exceptionally appropriate material for the reinforcement of fibres in composite development [11,13]. Furthermore, the insulating properties of nylon fibre are enhanced by its lightweight nature [7].

1.4 Utilisation of PP Fibre in LFC

The advantages of Forta-Ferro or PP fibre, which is classified as a macro-synthetic fibre, have piqued the interest of researchers in comparison to steel fibres. These advantages include its lightweight nature, resistance to corrosion and acid, exceptional toughness, and improved capacity to resist shrinkage and cracking [24]. According to Nensok *et al.,* [16], the incorporation of this fibre into LFC reduces contractions and improves its resistance to impact and fatigue, as well as its rigidity and elasticity. The composite material's endurance, structural properties, and management of secondary and thermal fractures are all improved as a result of the fibre's construction of a coherent network.

1.5 Effects of Hybrid Fibres on the Mechanical Strength on LFC

There is a great variety of fibre types, each with its own set of advantages and disadvantages and a vast array of sources from which LFC may be derived. It is clear that no one type of fibre can provide complete reinforcement in terms of strength, ductility, and longevity. According to Thienel *et al.,* [6], the successful integration of different kinds and sizes of fibres into LFC has improved several material qualities. Because of this, HFRLFC uses microfibres to bridge micro-cracks, which increases initial cracking strength and decreases shrinkage. Further refining of the fibres may result in a reduction in the cost of enhancing the properties of LFC with fibres or even more substantial improvements without an increase in the cost of reinforcement. Polyethylene (PE), polyvinyl alcohol (PVA), polyamide (PA), polypropylene (PP), aramid, acrylics (PAN), polyester (PES), polyamides (PA), and carbon are fibre varieties that have been incorporated into LFC mixtures [25].

The compressive strength of LFC was significantly increased by the incorporation of hybrid fibres. The porosity is not sufficiently reduced by an excess of fibres (more than 1%), which may result in the formation of microcracks that undermine the cement [26]. Additionally, the density is not significantly increased. In fact, it appears that the compressive strength of LFC is optimised by the inclusion of fibres.

1.6 LFC for Semi-Structural Applications

Low-density structural LFC is good for buildings, long-span bridges, tunnel linings, roof floors, screed concrete floors, bridge openings, and pre-stressed concrete units [10]. It also has a good strength-to-weight ratio and doesn't catch fire easily. Construction, bridges, aircraft, offshore platforms, and other industries widely employ LFC due to its lightweight, thermal insulation, and seismic performance [3]. LFC reduces dead loads, thereby decreasing strain on the formwork and facilitating placement and construction. Consequently, the structure will include reduced beams, columns, and foundations due to the decreased dead load. This clearly decreases labour, time, and material expenses, as well as the total construction cost.

2. Methodology

2.1 Experimental Program Design

This study uses British Standards for experimental testing unless otherwise stated. Varying foamed LFC formulations have varying densities. Bulk density and compressive strength are mechanical properties while porosity and intrinsic air permeability are determine durability properties. These HFRLFC for semi-structural applications were produced from hybrid fibres with the optimum quantity of micro-synthetic fibres and characteristics. Figure 1 shows the flowchart of the methodology. This research divided the experimental program into three key phases:

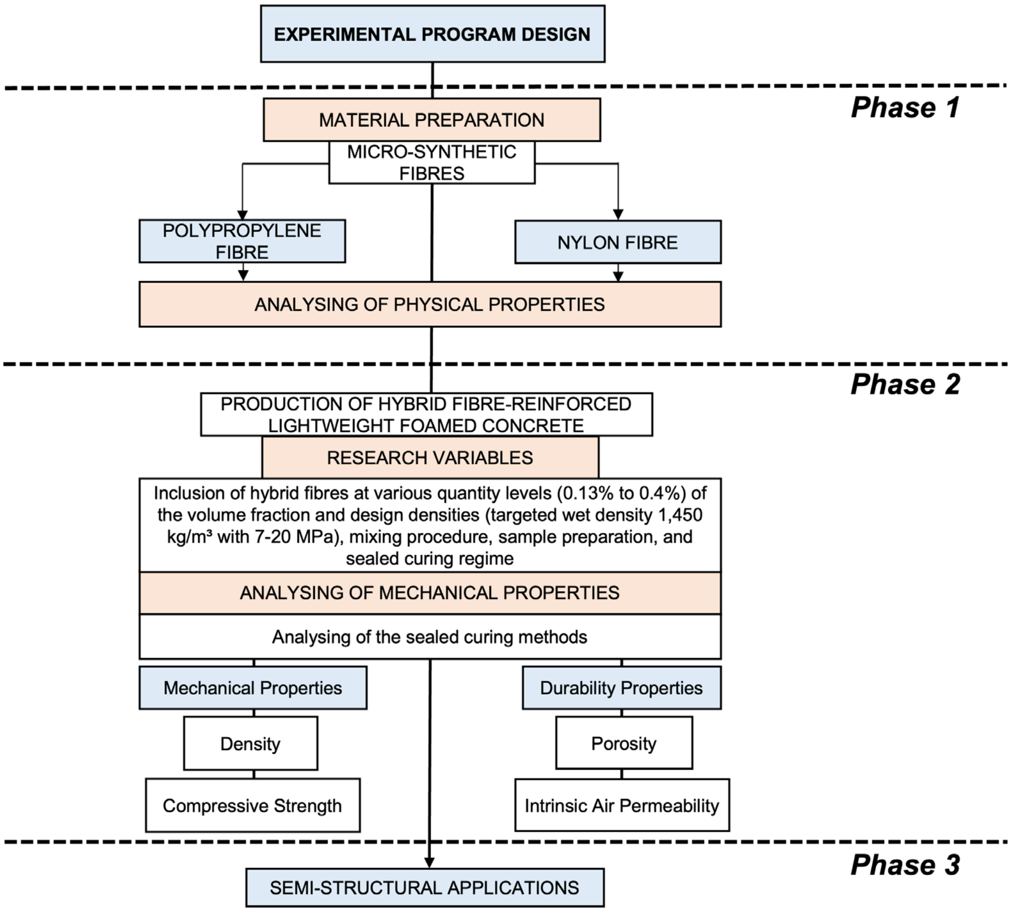


Fig. 1. Flowchart of the methodology

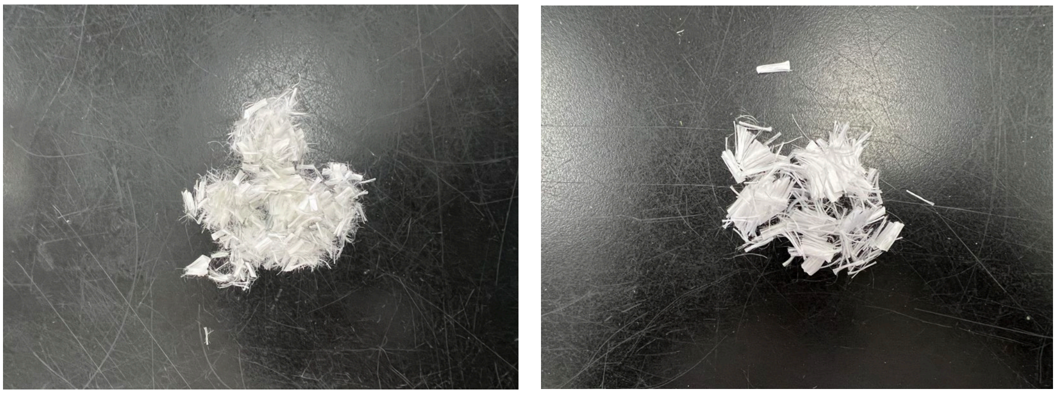
2.2 Materials

The principal binder in this experiment was Ordinary Portland Cement (OPC), also referred to as ASTM type 1, which is compliant with BS 12: 1991. The fine aggregate utilised was composed of natural river sand and uncrushed quartzite. Local domestic sources were utilised to obtain water for the experiments. The unique characteristics and specifications of PP and nylon filaments are presented in Table 2, which also provides a summary of all the items that were used. The micro-synthetic fibres as illustrated in Figure 2.

The use of a locally produced protein-based surfactant, PM-2, as the foaming agent in the study. The foaming agent is combined with water at a 1:30 ratio. The amalgamated solution is then aerated to produce a uniform foam with a density between 65 and 68 kg/m³. The generator produced a uniform foam with an exact density, as seen in Figure 3. Foam generators are mechanical devices that provide consistent bubble size and distribution.

Table 2
Develop appropriate mix-concrete design and mixing procedure

No	Constituent of materials	Description
1	Cement	Ordinary Portland Cement (OPC) which complies with BS 12: 1991
2	Fine natural aggregate	River sand. Max. size 2 mm. Carried out in accordance with BS EN12620:2002 AI:2008 to obtain its grading, specific gravity and water absorption
3	Water	Plain water
4	Foaming agent	Diluted in water at a ratio of 1:30. Density of 65 - 68 kg/m³
5	Fibre	Mega Mesh II – Multi-Filament (PP) and Scancem's Nylon Fibres Length 12 mm PP and 6 mm nylon



(a) (b)

Fig. 2. Micro-synthetic fibres (a) Nylon fibre (b) PP fibre

PP and nylon fibre diameters vary by application and product. Most micro-synthetic fibres have sizes between 10 and 50 micrometres (µm). It may review the manufacturer's specs for the PP and nylon fibre product it plans to employ, which should include fibre size, length, and other qualities. Material qualities and performance may affect fibre size. Smaller fibres may have benefits over bigger ones, thus choosing the right diameter is crucial.

Fig. 3. Consistent foam

2.3 Mixture Proportions and Specimen Preparation

This paper focused on the development and analysis of HFRLFC specimens with a targeted wet density of 1450 kg/m³. This paper aimed to investigate the impact of nylon and PP fibres on the mechanical and durability performance of HFRLFC under a sealed curing condition. Additionally, the experimental design included three distinct volume fractions, resulting in three unique experimental groups. A control group, devoid of any fibres, served as a benchmark for performance assessment. The mix design is shown in Table 3. The standard dimensions for specimens used in mechanical properties testing were 100 × 100 × 100 mm for bulk density and compressive strength tests. Standard dimension specimens for assessing durability qualities, measuring 45 mm in diameter and 40 mm in length. These dimensions were selected to facilitate a simple and effective measurement throughout the testing process. The sample preparation, shown in Figure 4, conforms to the technique established by the British Standards.

Table 3
Details of mixing proportion

Series	Design Density (kg/m³)	FB Ratio	Cement (kg/m³)	Sand (kg/m³)	Water (kg/m³)	Foam (kg/m³)	Volume Fraction of Fibre (%)	
							Nylon fibre	PP fibre
Co-M			583.62	583.62	262.63	58.36	-	-
SF-M1	1450	1	583.62	583.62	262.63	58.36	0.4	-
HF-M2			583.62	583.62	262.63	58.36	0.27	0.13

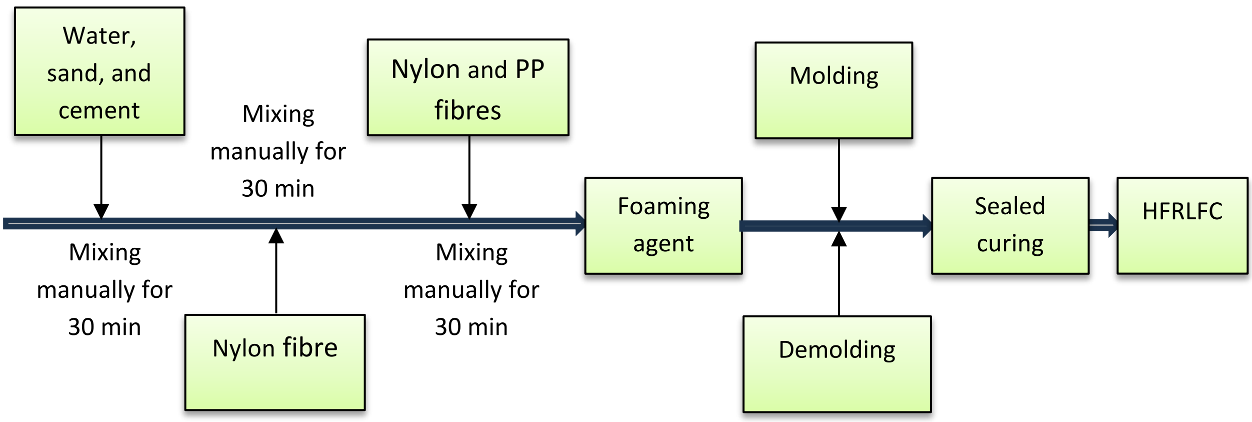
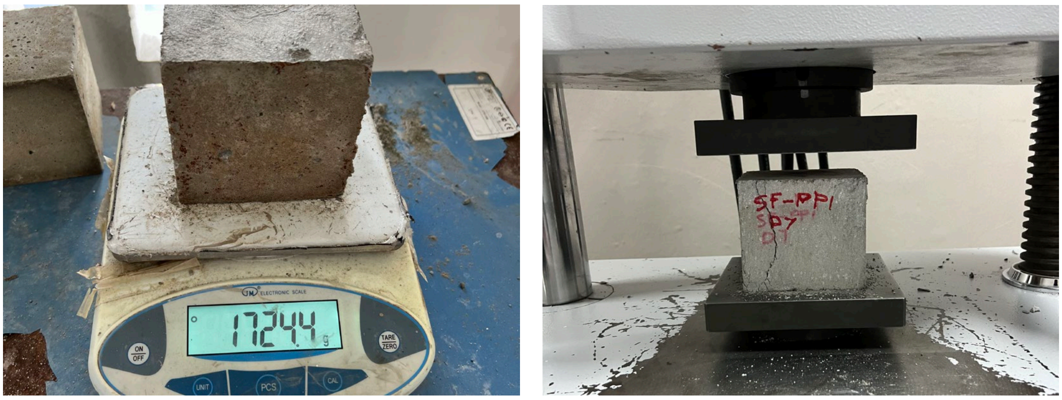


Fig. 4. Sample preparation

2.3.1 Bulk density and compressive strength test

The volume of hardened concrete specimens was calculated using water displacement and a buoyance balance, following BS 1881-114 (1983), and concrete density was estimated using an equation as shown in Figure 5. The experiment involved 100 mm LFC cubes under uniaxial compression using a GT-7001-LCU universal testing machine with a 50 kN capacity. Results were calculated by averaging three types of specimens at 7, 28, 56, and 90 days of sealed curing.



(a) (b)

Fig. 5. Mechanical properties testing for (a) Bulk density and (b) Compressive strength

2.3.2 Porosity

Water absorption is the easiest way to measure specimen porosity. Complete pore saturation is possible in a vacuum. The RILEM (1984) vacuum saturation technique was employed to measure concrete porosity. Coring LFC prism pieces and cutting them into slices at various depths yielded these specimens as shown in Figure 6. The test specimens were cylindrical LFC with a 45 mm diameter and 40 mm length. Concrete samples aged 7, 28, 56, and 90 days were tested for porosity.

(a) (b)

Fig. 6. (a) Vacuum saturation apparatus and (b) Cutting into various depth slices

2.3.3 Intrinsic air permeability

Coring each LFC mixture's prisms created two 45 mm diameter, 40 mm length of cylindrical LFC specimens for each series. Air permeability was tested on LFC blends at 7, 28, 56, and 90 days. All sample specimens were oven-dried at 105 °C for 24 ± 1 hours before testing. This method removed moisture from samples until a consistent mass was reached (Figure 7).

Fig. 7. Leeds cell permeameter

3. Results

3.1 Mechanical Properties

Table 4 demonstrated that Co-M has the lowest bulk density values throughout the curing stages, demonstrating a progressive decline over time attributable to hydration and the formation of voids. Microstructural instability is more likely to happen when there aren't any fibre reinforcements. SF-M1 begins at 1700 kg/m³ on day 7 and stabilises at 1718 kg/m³ by day 90, exhibiting a higher bulk density than Co-M. The use of 0.4% nylon fibre enhances matrix densification and reduces void formation. HF-M2 exhibits consistent and elevated bulk density values, commencing at 1695 kg/m³ on day 7 and reaching 1725 kg/m³ by day 56. By day 90, the density attains 1714 kg/m³.

Table 4
Bulk density of HFRLFC

Series type	Density (kg/m³)			
	7	28	56	90
Co-M	1647	1639	1626	1627
SF-M1	1700	1691	1708	1718
HF-M2	1695	1699	1725	1714

As Figure 8, the results demonstrate that fibre reinforcement significantly influences the bulk density of LFC, with hybrid fibres exhibiting superior performance. The use of 0.27% nylon and 0.13% PP in the HF-M2 mixture demonstrates improved density and stability, making it suitable for semi-structural applications that need durability and compactness.

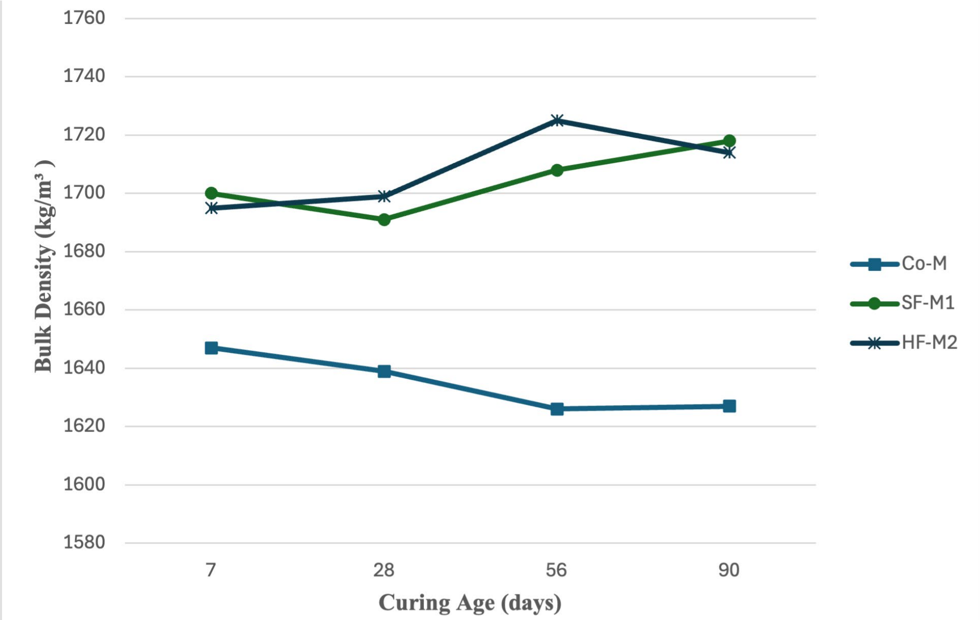


Fig. 8. Bulk density of HFRLFC

Table 5 demonstrated that Co-M is the lowest compressive strength at all curing ages, beginning at 11.80 MPa on day 7. The compressive strength consistently rises with curing duration, reaching 14.83 MPa by the day 90. The lack of fibre reinforcement leads to diminished mechanical qualities since the matrix is devoid of supplementary tensile support. On day 7, SF-M1 initiates at 12.30 MPa, demonstrating a marginal enhancement compared to Co-M, attributable to the incorporation of nylon fibre. Compressive strength markedly rises, reaching 18.20 MPa by day 90, the highest of all series. The use of 0.4% nylon fibre improves matrix compaction, connects microcracks, and offers enhanced load resistance.

Table 5
Compressive strength of HFRLFC

Series type	Compressive strength (MPa)			
	7	28	56	90
Co-M	11.80	12.57	13.10	15.20
SF-M1	12.30	15.20	16.00	18.20
HF-M2	12.90	15.50	15.47	17.47

HF-M2 has a peak strength of 12.90 MPa on day 7, indicating robust early performance attributed to the fibre mix. The strength reaches a maximum of 15.50 MPa on day 28, then stabilising at 17.47 MPa by day 90, which is somewhat lower than SF-M1. The hybrid fibre composition enhances tensile and compressive characteristics, equilibrating the influences of nylon and PP fibres. However, its compressive strength does not surpass that of SF-M1 during the final stages of curing.

The compressive strength of LFC rises with extended curing time across all mix designs as shown in Figure 9. The results underscore that fibre reinforcement significantly improves the compressive strength of LFC, with nylon fibres delivering greater long-term performance, while hybrid fibres provide balanced mechanical enhancements.

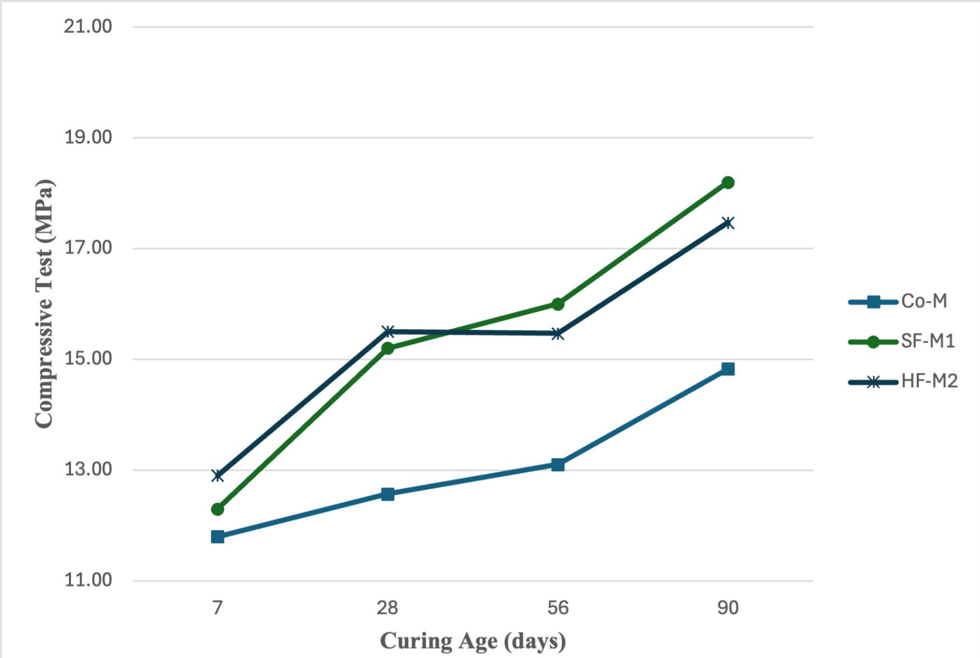


Fig. 9. Compressive strength of HFRLFC

3.2 Durability Properties

The presence of any fibre reinforcement considerably affects the void structure of LFC, as evidenced by the porosity test results in Table 6. Co-M consistently exhibits the highest porosity values, which suggests that the matrix is more susceptible to microstructural instability and less compact. The porosity of SF-M1 is diminished as a consequence of the 0.4% nylon fibre inclusion. This is due to the fact that the nylon fibre contributes to matrix densification and reduces cavity formation. This illustrates the synergistic effect of nylon and PP filaments on the reduction of void content and the enhancement of long-term durability.

Table 6
Porosity of HFRLFC

Series type	Porosity (%)			
	7	28	56	90
Co-M	34.71	32.91	36.23	34.37
SF-M1	30.89	28.84	26.47	26.73
HF-M2	26.31	27.08	25.93	24.62

The porosity of HF-M2, which is a critical attribute of this material, is the lowest in Figure 10. These findings underscore the importance of composite fibre reinforcement in enhancing the microstructural integrity of LFC. In comparison to single fibre reinforcement or reinforcement that is devoid of fibres, hybrid fibre reinforcement exhibits superior performance in terms of reducing porosity.

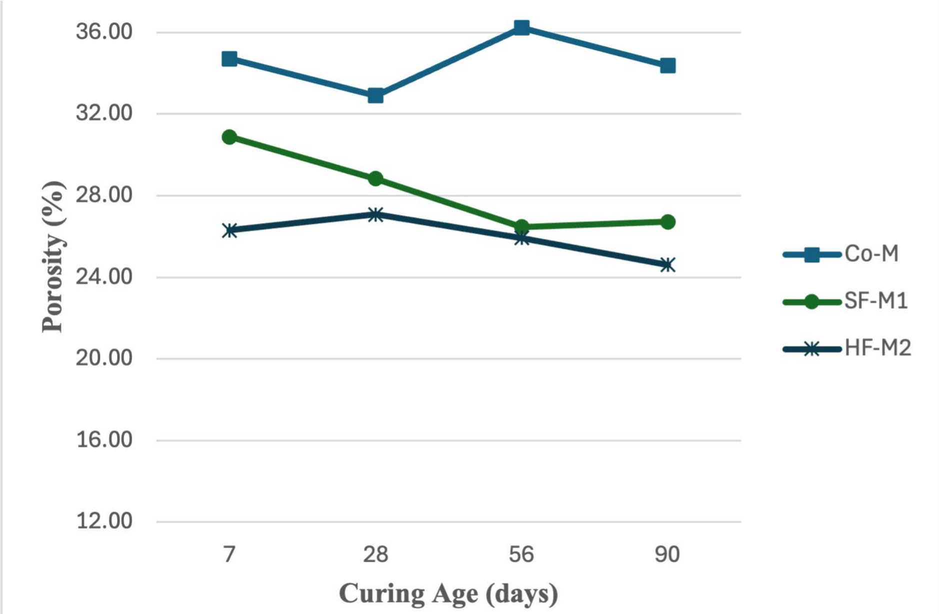


Fig. 10. Porosity of HFRLFC

The intrinsic air permeability test results in Table 7 provide insight into the significant role that fibre reinforcement plays in enhancing the durability of LFC. Co-M exhibits the highest permeability values, suggesting that it has a porous structure that is open to air infiltration. The substantial reductions in permeability observed in SF-M1 are the result of the densification effect of 0.4% nylon fibre, which effectively reduces the number of air routes.

Table 7
Intrinsic air permeability of HFRLFC

Series type	Intrinsic air permeability, K ($x10^{-15}$)			
	7	28	56	90
Co-M	6.12	5.02	4.62	4.57
SF-M1	5.88	4.39	3.12	2.88
HF-M2	4.00	3.18	2.29	2.77

Throughout the curing stages, HF-M2 obtains the lowest permeability values. This may be due to the synergistic impact of hybrid fibre reinforcement, which consists of 0.27% nylon and 0.13% PP. This reinforcement helps to improve matrix compaction and minimise void connectivity. This highlights the better performance of hybrid fibres in increasing the microstructural integrity and durability of LFC as shown in Figure 11. As a result, blends that include hybrid fibres are more resistant to air permeability than mixes that contain single fibres or mixes that do not contain fibres.

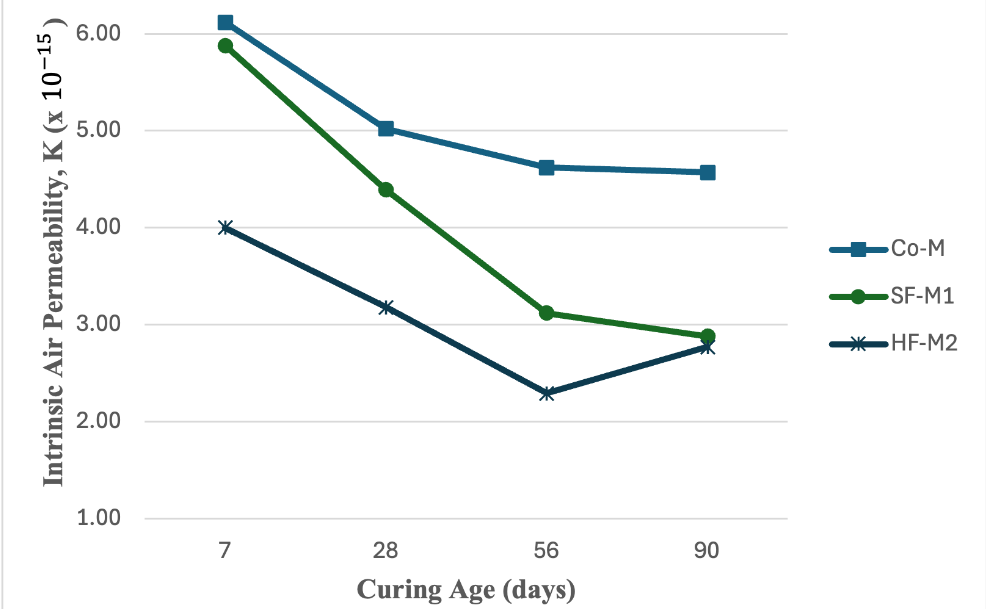


Fig. 11. Intrinsic air permeability of HFRLFC

4. Conclusions

The mechanical and durability qualities of LFC are greatly improved by adding fibres to it. The control mix shows benefits in density, strength, resistance to porosity and air permeability, and hybrid fibre reinforcement (HF-M2) shows the most significant gains. However, the single nylon fibre (SF-M1) also makes a positive contribution. HF-M2 has the best intrinsic air permeability, least porosity, greatest compressive strength, and greatest bulk density because of the nylon and PP fibres that work together in this material.

This study is limited by its fibre type and proportion emphasis. Although nylon and PP have shown promise, other fibre materials and ratios have yet to be tested. The trials were also done in sealed curing conditions, which may not represent HFRLFC's behaviour in air or water curing. This restricts the results' applicability to other building contexts. It also demonstrates that HFRLFC, despite its limitations, has significant implications for the construction industry. Nylon and PP fibres synergise to increase density, compressive strength, and resistance to porosity and air permeability, making them a lightweight, durable material. These qualities meet the increased need for lightweight, mechanically intact materials. Additionally, HFRLFC allows for greener construction. Its small weight decreases structural dead load, reducing material use, and shipping expenses. Improved durability means longer service life and fewer repairs and maintenance. These aspects make building more eco-friendly and affordable.

These findings suggest that future study must focus on several domains to mitigate the current limitations of HFRLFC and maximise its potential. Extended investigations are required to evaluate HFRLFC efficacy during freeze-thaw cycles, elevated humidity, and aggressive chemicals. Fibre combinations and ratios may be adjusted to enhance mechanical and durability properties. HFRLFC might enhance sustainability by using natural or recycled fibres instead of micro-synthetic fibres. Thermal conductivity and fire resistance must be assessed to determine the load-bearing and insulating capabilities of HFRLFC. Fire resistance is essential for the safety of high-rise and industrial structures. Extensive testing of beams, slabs, and walls will demonstrate the material's performance under actual loads. Through addressing its constraints and investigating its whole potential, HFRLFC might transform the building sector as a lightweight, durable, sustainable, and flexible material.

Adoption of it would help meet the future needs of the building industry by supporting safer, more effective, and environmentally friendly building techniques.

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