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Study on Polypropylene Twisted Bundle Fiber Reinforced Lightweight Foamed Concrete

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Abstract: Recent industrial developments have focused more and more on the applications of lightweight foamed concrete (LFC) in the construction industry, having advantages over normal-strength concrete. LFC, however, has several drawbacks including brittleness, high porosity, excessive drying shrinkage, rapid cracking, and low deformation resistance. Practical engineering typically chooses steel fiber or polymer fiber to increase the tensile and fracture resistance of LFC. The polypropylene twisted bundle fiber (PTBF) was added to the LFC with varying weight fractions of 0.0%, 0.5%, 1.0%, 1.5%, 2.0% and 2.5%. Three low densities of LFC were prepared, specifically 500 kg/m^3, 700 kg/m^3 and 900 kg/m^3. The mechanical and durability properties of PTBF-reinforced LFC were determined through compression, flexural, splitting tensile, flow table, porosity, and water absorption tests. The results show that the addition of PTBF in LFC significantly improves the strength properties (compressive, flexural, and splitting tensile strengths) and reduces the water absorption capacity and porosity. The optimal weight fraction of PTBF was between 1.5 and 2.0% for mechanical properties enhancement. The inclusion of PTBF increased the ductility of LFC, and the specimens remain intact from loading to failure. The PTBF reduces the original cracks of the LFC and inhibits the development of further cracks in the LFC.

Keywords: durability; strength; porosity; foamed concrete; polypropylene twisted fibers; water absorption

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1. Introduction

Vulnerability and eco-friendly building materials are currently prominent topics in the construction industry. The amount of carbon dioxide in the air has increased by almost 45% since the turn of the century [1]. In the setting of the worldwide climate shift, the construction industry is considering an option for normal-strength concrete to alleviate its extreme self-weight and substantial carbon discharge linked with the fabrication of cement [2]. Thus, the application of green energy-saving building materials to reinstate conventional building materials has turned out to be the standard practice [3]. Because of this, the construction industry must deal with an additional challenge: the creation of

concrete-based materials that are both durable and environmentally friendly [4]. It is crucial to prevent corrosion and sulfate attacks on the steel bars used in reinforced concrete [5]. Because of this, water and ions can easily pass through the material's pores. Concrete cracks can be attributed to several factors, but one of the most well-known is drying shrinkage [6].

Lightweight foamed concrete (LFC) is considered a green building material, porous in nature, which gives it several benefits such as being light in self-weight, having excellent thermal insulation properties, environmental safeguards, good fire resistance performance, and a low cost [7–10]. LFC has a greater strength-to-weight ratio with bulk density ranging from 550 to 1950 kg/m^3 than normal-strength concrete [11]. This distinction leads to a decrease in the total dead load of the structural components as well as the manufacturing and labor costs during transportation and construction [12]. LFC is extensively employed as filling material, non-loadbearing panels, and insulation material for exterior walls [13,14]. In turn, to fabricate this highly porous cellular structure of LFC, small air bubbles of varying sizes are created into the freshly blended materials, most often by the chemical or mechanical foaming method [15]. Essentially, the material ingredient to produce LFC is the same as normal strength concrete that used Portland cement, aggregate, and water [16]. Though only fine sand (aggregate) is utilized in the fabrication of LFC. Moreover, lightweight filler or reinforcement such as rice husk ash or polypropylene fiber can be combined with LFC base mix to expand its characteristics [17].

The ability of a long-lasting structure to withstand weathering, chemical attack, abrasion, and other degrading processes while requiring minimal maintenance is as significant as the structure's ability to withstand loads applied to it [18]. Although LFC has several advantages in terms of thermal performance, acoustic properties, and economic aspects of construction, the material's brittle behavior remains a significant disadvantage for seismic and other applications where flexibility is necessary due to its high porosity and the connectivity of the voids that can permit the access of adverse matters into the LFC medium [19]. Additionally, LFC poses some drawbacks such as low strength, a large amount of entrained air, poor toughness, and brittle material which has restricted its usage in engineering and building construction. Accordingly, LFC is deemed inappropriate for major load-bearing structural components. However, the recent invention of polypropylene fiber as an additive in concrete has offered a scientific framework for addressing these shortcomings [20]. Due to its enhanced mechanical properties, low permeability, and increased resistance to chemical and mechanical attacks, concrete offers several advantages in its application. Although concrete's behavior is largely determined by its compressive strength, its tensile strength is essential for its beauty and longevity [21]. Comparatively, the tensile strength of concrete is considerably lower. Therefore, fibers are typically added to the basic matrix to improve its flexural tensile strength, crack-arresting mechanism, and post-cracking ductility [22].

Steel fiber-strengthened concrete is extensively employed in numerous civil engineering works owing to ease in production, high performance, and cost-effectiveness. Nevertheless, some findings testified that irregular inclusion of steel fiber in the concrete led to adverse impacts on the workability of fresh mix leading to the weak adhesion of steel fibers with cementitious matrix causing in porous concrete and a reduction in the strength's parameter [23]. Alternatively, the concrete properties can be enhanced with the inclusion of fibrous materials. In recent years, polymeric fiber has been used to modify concrete with the intention to improve its durability, thermal and mechanical performances [24]. In general, the reinforcement of brittle building materials using fibers has been recognized since ancient times. In addition to natural fibers such as jute, bamboo, kenaf, oil palm, coir, rice husk and sugarcane bagasse, synthetic fibers such as polypropylene, and polyethylene have also been utilized to strengthen concrete [25]. Similarly to all synthetic fibers, polypropylene fiber is inexpensive, abundantly accessible, and of uniform quality [26]. It should be pointed out that the addition of synthetic fibers to concrete improves the toughness, flexural strength, tensile strength, and impact strength as well as the mode of failure of concrete, which has resulted in a dramatic increase in their use in the construction of structures. When a crack appears in concrete, it causes a disruption in the material's spatial continuity and

causes steel to corrode via a process known as the micro-cell mechanism [27]. Microcracks form quickly from the exterior to the interior, increasing the permeability of the concrete. In addition to lowering the quality of the concrete and making it unsightly, microcracks render construction unfeasible [28]. Cracks with a width of less than 0.3 mm are generally considered acceptable and do not adversely damage the structure. However, they have the potential to develop into structural cracks as time passes. A crack width that is bigger than 0.3 mm might be problematic and will affect its durability performance. Therefore, it is crucial to lessen the crack's diameter, which might be performed by mixing polypropylene fibers into the concrete.

A substantial amount of study has been conducted to investigate the effect of polypropylene fiber addition on the fresh, mechanical, and durability qualities of concrete. Kamal et al. [29] investigated the mechanical properties of self-compacted fiber-reinforced concrete. They attempted to find the optimal proportion of steel and polypropylene fibers to achieve greater mechanical strength. Polypropylene fiber's compressive strength increased by 13%, whereas steel fibers increased by 37%. The impact resistance of polypropylene fibers increased by 22%, while steel fibers improved by 67%. Rai and Singh [30] explored the consistency and variability in steel-polypropylene hybrid fiber-reinforced concrete's impact strength. They noticed that the hybrid fiber-reinforced concrete surpassed its mono-fiber equivalent in terms of performance.

Moreover, Toutanji et al. [31] scrutinized the permeability of chloride ions in concrete as well as their resistance to the impact of polypropylene fiber-reinforced silica fume concrete. Their research used polypropylene fibers with lengths of 12 and 19 mm and volume percentages of 0%, 0.1%, 0.3%, and 0.5%. A portion of the cement was substituted with silica fume at 5% and 10% concentrations. According to the findings of the study, the inclusion of polypropylene fiber and silica fume improved the impact resistance of concrete. Next, the impact resistance of high-strength FRC containing steel, polypropylene, and polyethylene fibers was studied by Zhang et al. [32]. When compared to concrete, which had polyethylene and polypropylene fibers, both utilized at 1%, their investigation indicated that steel fibers with 1% of volume and fiber combinations of steel and polypropylene fiber for 0.75% and 0.25%, respectively, could resist the projectile impact well.

Moreover, Kiran and Zai [33] examined how fiber-reinforced concrete slabs responded to impact loads. In high-performance concrete, they used polypropylene and carbon fibers, and they discovered that the mechanical properties were improved by combining the two fibers. The study employed polypropylene fibers with a density of 900 g/m^3 and carbon fibers with 0.5% content. Amancio et al. [34] explored the functionality of polypropylene fiber-reinforced concrete at high temperatures. They performed the trial on M30 concrete for 30 min while adding three distinct fiber variations and four different temperatures. When concrete is exposed to high temperatures, they discovered that the use of polypropylene fibers in the concrete can reduce and prevent spalling.

As far as LFC is concerned, not much research has been conducted to investigate the potential utilization of polypropylene fiber in LFC for durability and mechanical properties improvement. However, there were few investigations executed to observe the use of polypropylene fiber in LFC. Hazlin et al. [35] reported that the addition of 0.05% by volume of polypropylene fiber in LFC increased its tensile strength by 35% and 40% for densities of 1600 kg/m^3 and 1800 kg/m^3 correspondingly. According to Ngo and Huynh [36], 1% polypropylene fiber in LFC is the ideal weight fraction to attain good mechanical properties. They found that with 1% addition of polypropylene fiber increased the compressive and flexural strength. The flexural strength enhancement was more significant in comparison to compressive strength. Though Bing et al. [37] found that adding PP fiber to LFC improved its compressive strength, Falliano et al. [38] found that the percentage of PP in LFC had no discernible effect on its strength. So, further research is needed to shed light on this debate.

It should be pointed out that the addition of polypropylene fiber to LFC bridges the cracks and prevents further expansion. More forces and energy are needed to tear out or shatter the fibers to cause the beam to deflect more. In addition to maintaining the structural

integrity of the concrete, this technique increases the structural member's ability to take more weight without cracking. The load-deflection curve now has a lengthy post-peak lowering component. Steel reinforcement bars in concrete have a similar advantageous effect since they function as continuous, lengthy fibers. However, the advantage of short discontinuous polypropylene fibers is that they are evenly mixed and spread throughout the concrete [39]. Moreover, concrete can generate a three-dimensional random distribution network structure when polypropylene fiber is added, which effectively prevents the formation and progression of microcracks. The longevity of concrete can be increased by adding polypropylene fiber since it can stop water and other damaging ions from entering it. Furthermore, due to fewer through cracks in the concrete, the resist-permeability of the concrete can be increased by adding polypropylene fiber.

From the above review, there is a huge potential to utilize polypropylene fiber in cement-based material for properties modification and enhancement. Additionally, the research on the durability and mechanical properties of polypropylene fiber-reinforced concrete mainly focused on the normal strength concrete. The effect of polypropylene fiber inclusion in LFC for engineering properties enhancement has not been very well explored. Thus, this research concentrates on establishing the mechanical and durability properties of low densities of LFC reinforced with PTBF. LFC densities of 500, 700, and 900 kg/m^3 were produced with varying weight fractions of PTBF and the composites' properties were investigated.

2. Materials and Methods

This section explains the constituent materials to produce LFC, mix proportions and laboratory test procedures. First, the preparation of materials is discussed thoroughly. After that, the mix proportions, mixing methods, and experimental approaches for the LFC samples reinforced with polypropylene twisted bundle fiber (PTBF). This research was designed to explore the effect of PTBF at six different weight fractions (0.0%, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5%) on LFC properties. Three low densities of LFC were prepared specifically 500 kg/m^3, 700 kg/m^3 and 900 kg/m^3. The low densities of LFC were considered in this research because it has extremely low durability and mechanical properties and it can benefit from the reinforcement with PTBF. Three main properties have been investigated which were durability and mechanical properties. For durability properties, four main parameters were investigated such as workability, density, water absorption capacity and porosity. In terms of mechanical properties, three main aspects have been scrutinized such as axial compressive strength, splitting tensile strength, and flexural strength. Next, the correlation between durability and mechanical properties was determined to quantify the degree to which the two parameters are related.

2.1. Materials

The basic materials used in this study were Portland cement conforming to British Standard BS12 [40] and fine river sand was sieved passing through 600 microns sieve with a specific weight of 2.59 g/cm^3 and particle sizes of 0.15–2.36 mm adhered to British Standard BS882 [41]. Stable foam with a density of 70 kg/m^3 was created using a protein-based surfactant which was attenuated with a ratio of 1:34. The surfactant was produced and supplied by DRN Technologies Sdn Bhd. Protein foams are agents that are mostly formed from hydrolyzed proteins that exist naturally in the environment. In order to make the foam concentration, they are mixed together with foam stabilizers, which are often metal salts; bactericides; corrosion inhibitors; freeze protection additives; and solvents. Protein foam agents result in a stable foam that has a strong resilience to heat and excellent resistance to burn-back. Fluorochemicals added to fluoro-protein foams improve their effectiveness by increasing the spreading velocity of the foams and, as a result, the pace at which flames are extinguished. Because of this, increased fuel tolerance also implies higher foam stability and increased productivity. The protein-based surfactant was then aerated using a Portafoam TM-1 foam generator system to produce stable foam. This

system runs from an air compressor and consists of a main generating unit, a foaming unit, and a lancing unit.

In this study, polypropylene twisted bundle fiber (PTBF) was selected to be employed in LFC. The PTBF was produced and supplied by Weifang Ectachem Co. Ltd., China. It should be pointed out that PTBF was opted for due to being reasonably priced, inert in high pH cementitious setting, and easy to disperse. The PTBF has an equivalent diameter of 0.25 mm, 37 mm in length, and a density of 0.975 g/cm^3 as shown in Figure 1. The PTBF was added to the LFC with varying weight fractions of 0.0%, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5%. The physical and mechanical attributes of the PTBF are shown in Table 1.



Figure 1. Polypropylene twisted bundle fiber (PTBF) of 37 mm in length.

Table 1. Physical and mechanical attributes of polypropylene twisted bundle fiber (PTBF).

Properties	Value
Length	37 mm
Equivalent diameter	0.25 mm
Aspect ratio (L/D)	148
Density (g/cm^3)	0.975
Young's modulus	5.25 GPa
Tensile strength	575 MPa
Elongation at break	3.18%
Thermal conductivity	0.28 W/mK
Specific heat capacity	1287 J/kgK
Melting temperature	175 °C

2.2. LFC Mix Design

In this research, three different low densities LFC of 500, 700, and 900 kg/m^3 were prepared. The cement-to-filler (sand) ratio employed was fixed at 1:1.5 and constant water to the cement of 0.45 was employed for all mixes. A total of 18 mixes were made. The LFC samples were cured by moisture curing and exposed for 7, 28, and 56 days. Table 2 shows the LFC mixture proportions made. Each batch of LFC with different densities was created using an LN-100 mixer. Prior to adding water and PTBF, the cement and fine aggregate (sand) were first thoroughly dry-mixed until they were homogeneous. The foaming agent was then produced using the foaming generator (Portafoam TM-1), which turned the protein into foam. The foam was then put into the mixer and blended for no longer than 10 min to ensure that it had not broken down and turned to water.

Table 2. Mixture proportions of LFC.

Density (kg/m^3)	PTBF (%)	Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Foam (kg/m^3)	PTBF (kg/m^3)
500	0.0	194.1	291.2	87.4	46.3	0.0
500	0.5	194.1	291.2	87.4	46.3	3.1
500	1.0	194.1	291.2	87.4	46.3	6.2
500	1.5	194.1	291.2	87.4	46.3	9.3
500	2.0	194.1	291.2	87.4	46.3	12.4
500	2.5	194.1	291.2	87.4	46.3	15.5
700	0.0	266.3	399.5	119.9	40.0	0.0
700	0.5	266.3	399.5	119.9	40.0	4.1
700	1.0	266.3	399.5	119.9	40.0	8.3
700	1.5	266.3	399.5	119.9	40.0	12.4
700	2.0	266.3	399.5	119.9	40.0	16.5
700	2.5	266.3	399.5	119.9	40.0	20.6
900	0.0	338.6	507.9	152.4	33.8	0.0
900	0.5	338.6	507.9	152.4	33.8	5.2
900	1.0	338.6	507.9	152.4	33.8	10.3
900	1.5	338.6	507.9	152.4	33.8	15.5
900	2.0	338.6	507.9	152.4	33.8	20.7
900	2.5	338.6	507.9	152.4	33.8	25.8

After the mixing was complete, a slump test was conducted. This was carried out in accordance with the guidelines outlined in British Standard BS 1881-102 [42]. The wet density was then measured to confirm that the estimated wet density was accurate. This was performed to guarantee that the mixture will reach the proper density. After completion, the freshly cast LFC was placed in the mold and left there for 24 h at room temperature. The LFC samples were demolded and moisture-cured in plastic containers with water after one day. The LFC substrates were removed from the plastic containers at ages 7, 28, and 56 days and placed in an oven for oven drying at 105 ± 2 °C for 24 h before testing. Prior to the test, the samples were given an average 2 h cooling period. The samples are cooled to determine their dried density. The development of concrete's strength and durability depends significantly on curing. Following the placement and completion of the LFC samples, curing occurs. It also entails maintaining the desired temperature and moisture levels for protracted periods of time. All the specimens in this study experienced constant moisture curing.

2.3. LFC Preparation

All LFC specimens were prepared in the laboratory by using a 20 dm^3 horizontal type mixer at 25 °C and under the mixing speed of 40 r/min as shown in Figure 2. The process is detailed as follows:

(1) The foaming agent composed of protein was diluted with water at a ratio of 1:34. Using a high-pressure pump, the dilution was introduced into the foamer's bucket. The dilution was put in the foaming apparatus and exposed to high-pressure air generated by an air compressor in order to create homogenous fine bubbles.

(2) Cement, fine sand, PTBF, and water were placed into the concrete mixer and mixed for approximately 3 min. The relative viscosity of each fresh LFC was measured immediately after mixing. An appropriate amount of foam (Figure 2a) was subsequently introduced into the mortar slurry and mixed for another 3 min until a well-blended slurry and homogenous mix was produced (Figure 2b).

(3) The LFC slurry was then poured into molds (cube, prism, and cylinder), leveled with a steel ruler, and then placed in a room at 20 ± 5 °C with relative humidity (RH) of 60% as shown in Figure 3. The specimens were removed from the molds after 24 h and stored in a fog room (20 ± 2 °C; RH > 95%) for curing purposes.



(**a**) (**b**)

Figure 2. Preparation of LFC mixture. (**a**) preparation of stable foam. (**b**) adding foam into mortar slurry.



Figure 3. LFC slurry was then poured into molds.

2.4. Details of Experimental Tests

To establish the mechanical and durability properties of LFC reinforced with varying weight fractions of PTBF, several tests were executed such as compression test, flexural test, splitting tensile test, flow table test, porosity test, and water absorption test. This section will explain in detail about these experimental tests.

2.4.1. Compression Test

The axial compression test was carried out to establish the potential strength of the LFC mixes from which it is sampled. It tests the capacity of the LFC specimen to endure a load before undergoing failure. It facilitates verifying whether correct mix proportions of diverse LFC mix proportions of different materials were employed to attain the required strength. In this study, the axial compression test was accomplished in compliance with the British Standards BS 12390-3 [43] with a continual rate of 0.03 mm/s. Cubic samples of 100 × 100 × 100 mm in size were prepared. The compression test was executed on days 7, 28 and 56. The result was taken from the average of three LFC samplings. Figure 4 visualizes the compression test setup.

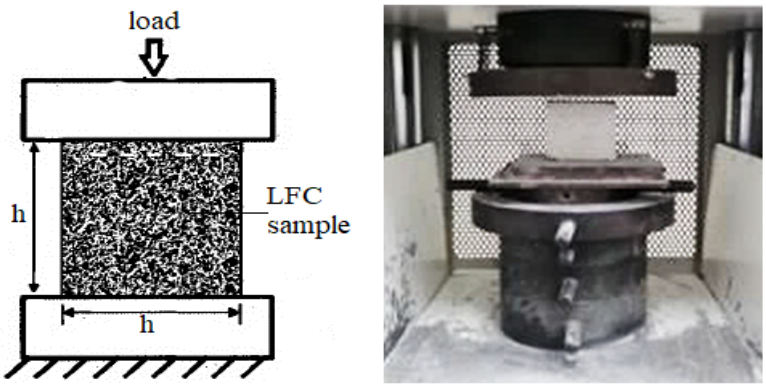


Figure 4. Setup for compression test.

2.4.2. Flexural Test

The flexural test was performed to establish the strength needed to bend a prism and verifies the stiffness of LFC. In other words, it is the utmost stress just before it yields in a flexural test. To determine the influence of PTBF on the flexural strength of LFC, a three-point flexural test was conducted conforming to British Standards 12390-5 [44] as shown in Figure 5. The LFC specimens were fabricated into 100 × 100 × 500 mm and each flexural strength test is carried out with 3 prisms. The flexural tests were performed after standard curing of 7, 28 and 56 days.

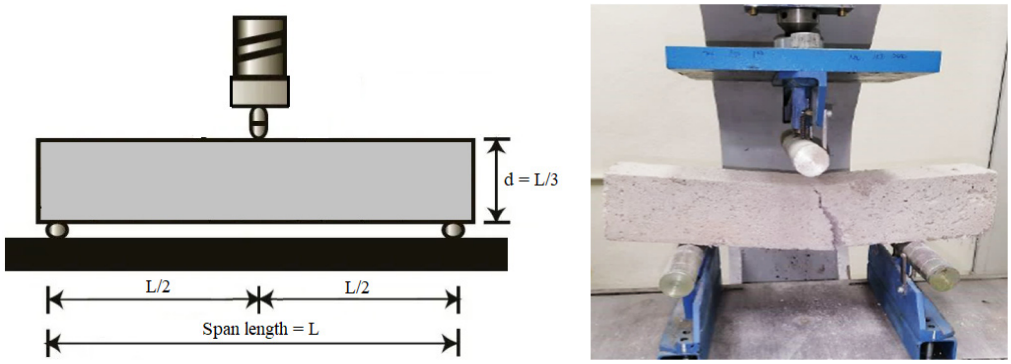


Figure 5. Apparatus for three-point bending test.

2.4.3. Splitting Tensile Test

The splitting tensile strength of LFC is one of the fundamental and crucial properties which significantly influence the size and magnitude of cracking in concrete. The LFC specimen is not commonly expected to withstand direct tension owing to its brittle nature as well as low tensile strength. In this research, the splitting tensile strength test was achieved in line with the British Standards 12390-6 [45]. A cylinder LFC specimen with a diameter of 100 mm and height of 200 mm was utilized and the test was performed on days 7, 28 and 56. Figure 6 shows the apparatus for the splitting tensile strength test.

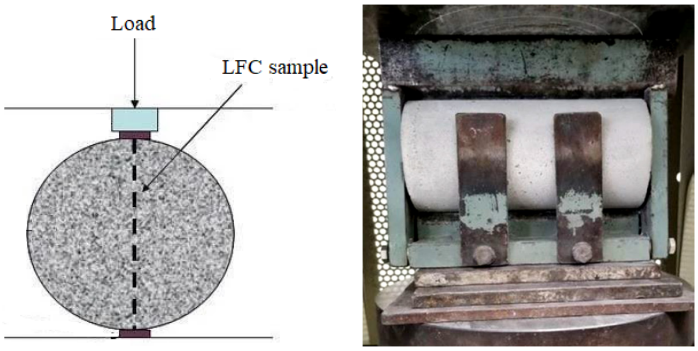


Figure 6. Splitting tensile test apparatus.

2.4.4. Flow Table Test

This test was executed to ascertain the influence of PTBF addition on the workability of LFC. The workability was determined by the spreadability using a long cylinder (diameter of 76.2 mm × height of 152.4 mm) as shown in Figure 7a [46]. The average spread diameter of the LFC mixes was determined once the LFC stopped flowing. Figure 7b displays the measurement of the spreadability of LFC.



(**a**) (**b**)

Figure 7. Flow table test. (**a**) long cylinder. (**b**) measurement of spreadability.

2.4.5. Porosity Test

Porosity is the number of pores in LFC and typically expelled in volume percent. The porosity of LFC has an influence on the durability, mechanical and thermal properties in many aspects. It also permits various harmful elements into the LFC. In reinforced LFC, the salt will destroy the reinforcing bar and rust growing and splitting the LFC. Therefore, it is crucial to determine the porosity of LFC with the inclusion of PTBF. The porosity test was performed via the vacuum-saturated method. The cylinder specimens were cast with a size of 45 mm in diameter and 50 mm in height. This test was executed on day 28 by submerging the LFC specimens into a vacuum desiccator.

2.4.6. Water Absorption Test

The water absorption capability of LFC is directly related to its resistance to water penetration, which plays a crucial role in numerous weakening mechanisms and keeps many detrimental causes from the environment. The water absorption of LFC enables the

transport of oxygen, chloride and carbon dioxide, which triggers the corrosion of reinforcing steel in LFC. In this study, the water absorption test was performed in accordance with the British Standards BS 1881-122 [47]. Cylinder LFC specimens of 75 mm in diameter and 100 mm in height were prepared.

3. Results

3.1. Slump Flow

The slump flow results for the three densities considered in this research are shown in Figure 8. As can be noticed from Figure 8, all LFC mixes had slump flow larger than 185 mm which signifies a good self-flowing ability. The control specimens had the highest slump flow of 258 mm, 250 mm and 240 mm for 500, 700 and 900 kg/m^3 densities in that order. With the insertion of PTBF in LFC, the slump flow was decreased with the increase in weight fractions of PTBF. Comparing the slump flow values of the different LFC mixes, when 2.5% of PTBF was added to the mix, it led to the lowest slump flow. The recorded slump diameters were 200 mm, 190 mm and 185 mm for 500, 700 and 900 kg/m^3 densities correspondingly. The decline in the slump flow of LFC with the addition of PTBF was possibly prompted by the weakening of resistance between the structures of the mix and contraction of the free water amount as PTBF tend to absorb water, which elucidates the decrease of slump diameter consistently to the presence of PTBF, as their external segment present significant porosity which benefits the bond to the matrices. Moreover, the PTBF's high specific surface area accumulates the cementitious matrices in the area of the PTBF and, accordingly, enhances the LFC viscosity, which triggers a decrease in the slump flow with higher weight fractions of PTBF. This will bridge a downturn in the LFC slump diameter due to the free flow of the intermittent stage over the capacity of the stable spreading form, eliminating the air bubbles in the cementitious matrix. Along with fine filler (sand), the mortar also needs to cover the plane PTBF membrane. This indicates supplementary filling mortar is needed to cover the additional zone of PTBF, consequently, further cement slurry is necessary for greasing which causes the slump flow of LFC to be decreased as the weight fraction of PTBF was raised from 0.5% to 2.5%. In addition, PTBF augments the interior abrasion between LFC components causing more cement matrix to lessen the inner resistance, leading to a decrease in LFC workability [48]. A comparable discovery had been described that the workability of concrete diminished as the fiber's weight fraction was boosted [49].

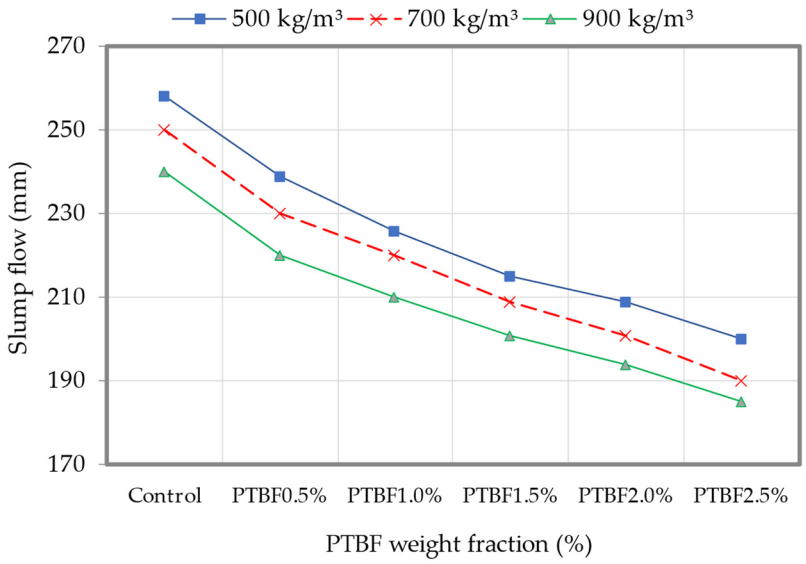


Figure 8. Slump flow of LFC with different weight fractions of PTBF.

3.2. Density

Figure 9 demonstrates the influence of varying weight fractions of PTBF on the dry density of LFC. The results revealed that the dry density of LFC diminishes as the weight fractions of PTBF increase from 0.5% to 2.5% for all three densities as compared to the control LFC. The greatest dry density of LFC was acquired at 0.0% inclusion of PTBF (control specimen) while the least density was achieved at 2.5% inclusion of PTBF in LFC. The decrease in dry density of LFC mixed with higher weight fractions of PTBF was due to difficulty in the compaction process which causes absorbent LFC, leading to a reduced dry density of LFC as associated with the control specimen. For the entire LFC mixes with the addition of varying weight fractions of PTBF, the final dry densities were within the appropriate acceptance of ± 50 kg/m^3. For example, the differences between final dry densities and targeted dry densities of 500 kg/m^3 density were ± 2 kg/m^3, ± 6 kg/m^3, ± 11 kg/m^3, ± 20 kg/m^3, ± 26 kg/m^3 and ± 33 kg/m^3 for mixes Control, PTBF0.5%, PTBF1.0%, PTBF1.5%, PTBF2.0% and PTBF2.5%, respectively. The final dry density of LFC will completely impact the durability and mechanical properties.

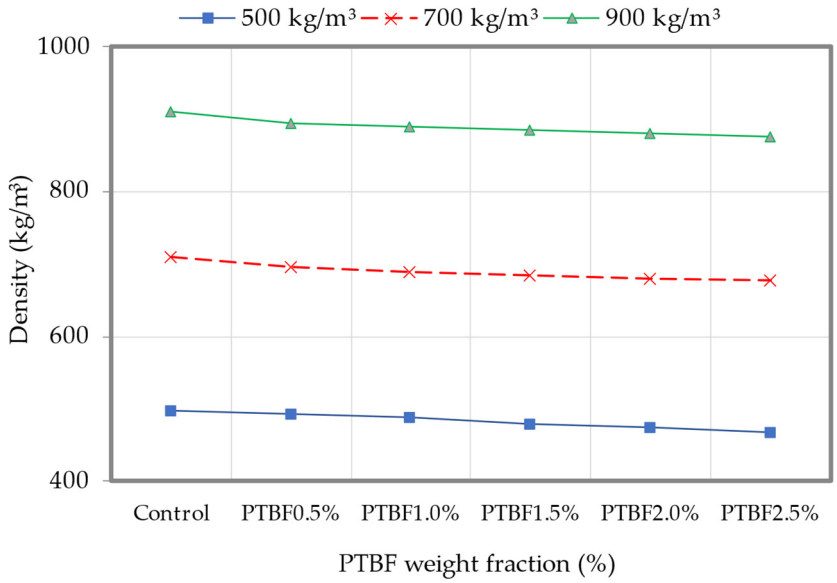


Figure 9. Dry density of LFC with different weight fractions of PTBF.

3.3. Porosity

Figure 10 visualizes the porosity of LFC with varying PTBF weight fractions. Generally, the LFC porosity improves steadily with the presence of PTBF up to 2.5% weight fraction. LFC mix with 2.5% PTBF attained the optimal values of porosity with approximately a 12% decrease in comparison with the control LFC sample for all three densities considered in this research. This is possibly due to the great packing capacity of PTBF in the cementitious matrix of LFC. The 500 kg/m^3 density LFC mix with 2.5% of PTBF recorded a porosity of 65.5% while the control sample achieved a porosity value of 74.5%. Within the LFC fresh state condition, its surface moisture was quickly vaporizing with substantial dry shrinkage, and microcracks were certainly formed on the surface [50]. When PTBF was included in LFC mixes, the segregation can be diminished as well as decreasing the water evaporation [51]. Furthermore, PTBF can efficiently inhibit the propagation of cracks emerging from the outside to the inside of LF.

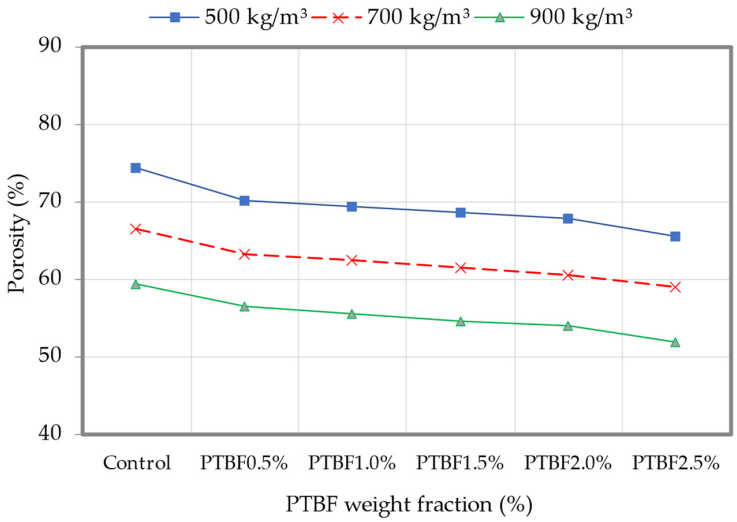


Figure 10. Porosity of LFC with different weight fractions of PTBF.

3.4. Water Absorption

Figure 11 establishes the LFC water absorption results with different weight fractions of PTBF. It was apparent that the water absorption capacity of LFC intensified with the boost of the weight fractions of PTBF from 0.5% to 2.5%. Optimal water absorption was attained with the inclusion of 2.5% of PTBF for all three densities assessed in this study. It should be pointed out that the LFC with the presence of PTBF in the mix has fewer cracks formation, and the cracks in LFC were less significant and finer than the LFC without the addition of PTBF. This implies that the presence of PTBF can play an important role to lessen the risk of microcrack merging in LFC and considerably enhance the water absorption capacity of LFC. The concrete water penetration depth declined with the inclusion of polypropylene fiber [52]. Additionally, fine fibers have noticeable inhibition of micropores in concrete, while coarse fibers have more noticeable macropores inhibition in concrete [53]. Moreover, the LFC mixed with fine and coarse polypropylene fiber has greater impenetrability than the LFC with single-diameter polypropylene fiber. There was a reduction in the water absorption capacity by up to 45% with the presence of polypropylene fiber, implying that the impermeability of concrete was considerably improved [54].

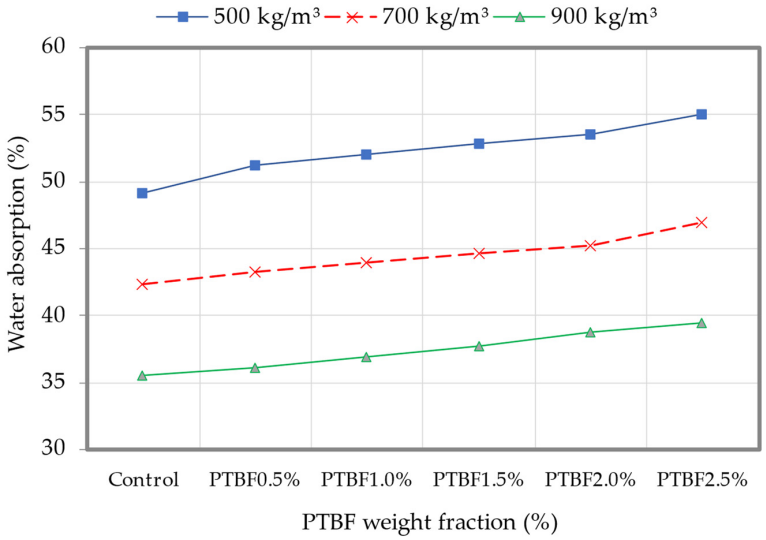


Figure 11. Water absorption of LFC with different weight fractions of PTBF.

3.5. Compressive Strength

Figures 12–14 reveal the compressive strength results of 500, 700 and 900 kg/m^3 densities correspondingly with the insertion of various weight fractions of PTBF. In general, the inclusion of PTBF into LFC enhanced compressive strength. For 500 and 700 kg/m^3 densities, the ideal weight fraction of PTBF was 1.5%, while for the 900 kg/m^3 density, the optimal weight fraction was 2.0%. With the inclusion of PTBF in LFC, there was a reduction in the entrapped air void, capillary pores, and entrained air voids, which amplify the LFC's compressive strength. The LFC compressive strengths with the inclusion of PTBF on day 7, 28 and 56 surpassed the control specimen strength, regardless of its density. The optimal compressive strengths accomplished at day 56 were 1.74, 3.93 and 6.02 N/mm^2, with the inclusion of a 1.5% and 2.0% weight fractions of PTBF for the 500, 700 and 900 kg/m^3 densities, respectively, in comparison to the control specimen, which only achieved compressive strengths of 1.05 N/mm^2 (500 kg/m^3), 2.31 N/mm^2 (700 kg/m^3), and 3.35 N/mm^2 (900 kg/m^3). When an optimal weight fraction of PTBF is uniformly dispersed in LFC cement paste, the hydrated products of cement amass around the PTBF due to their superior surface energy which acts as nucleation spots [55]. The PTBF grasps tensile energy as the LFC shrinks, through the boundary between the PTBF and LFC cementitious matrix and disperses this energy to the neighboring matrix to reduce concentrated tensile stress which leads to an intensification of the resistance to crack. After reaching their compressive peak strength, PTBF-reinforced LFC specimens were able to sustain loads at progressively higher strains. This was explained by the fact that the PTBF reinforcement stopped cracks from expanding by constructing connecting bridges on the concrete, resulting in more structurally sound specimens. When the weight fraction of PTBF in the LFC cementitious matrix surpassed 2.0%, poor PTBF dispersal in the LFC matrix leads to a balling effect which causes a degraded impact of scattering the tensile stress from the LFC vicinity to another area PTBF surface [56]. This explanation supports the reason why there was a decline in compressive strength when the weight fractions of PTBF exceeded 2.0%.

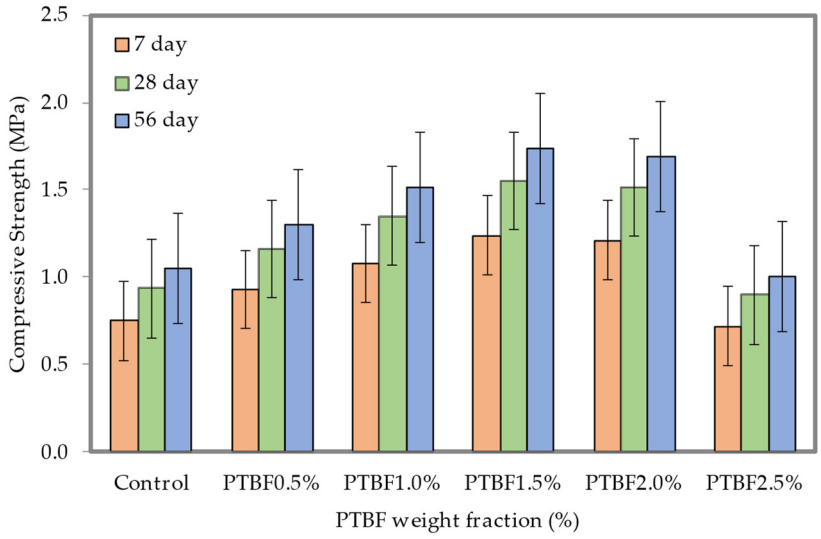


Figure 12. Compressive strength of 500 kg/m^3 density LFC with different weight fractions of PTBF.

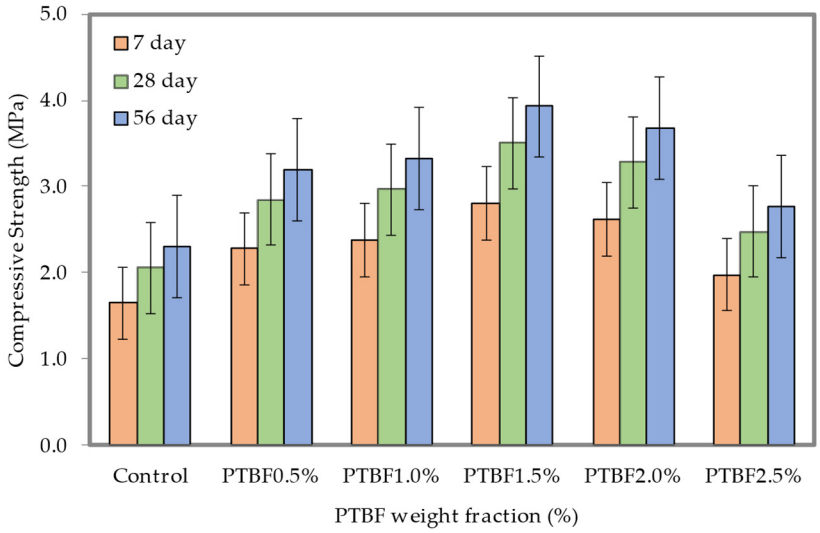


Figure 13. Compressive strength of 700 kg/m^3 density LFC with different weight fractions of PTBF.

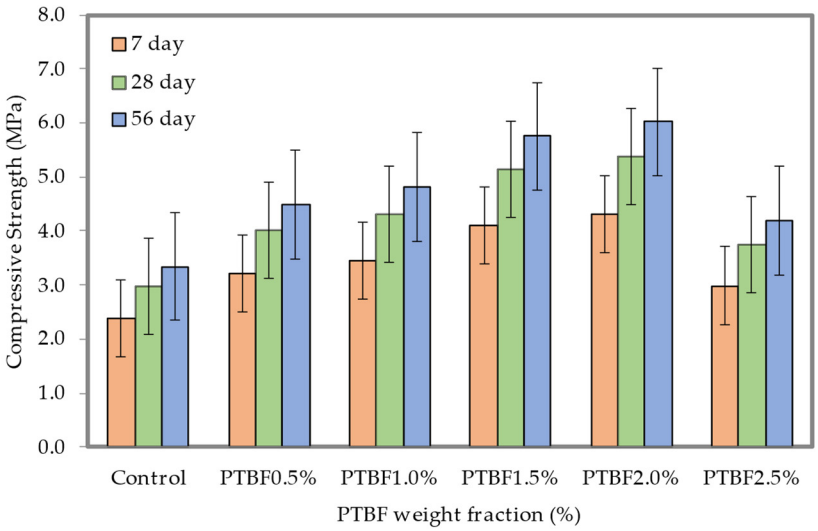


Figure 14. Compressive strength of 900 kg/m^3 density LFC with different weight fractions of PTBF.

3.6. Flexural Strength

Figures 15–17 establish the flexural strength results of 500, 700, and 900 kg/m^3 densities correspondingly with the varying weight fractions of PTBF. As can be noticed from Figures 16–18, the presence of PTBF in LFC improved flexural strength. For the 500 and 700 kg/m^3 densities, the best weight fraction of PTBF was 1.5%, while for the 900 kg/m^3 density, the ideal weight fraction was 2.0%. The LFC flexural strengths with the presence of PTBF on day 7, 28 and 56 surpassed the control specimen flexural strength, regardless of its density. The ideal flexural strengths attained at day 56 were 0.49, 0.89, and 1.44 N/mm^2, with the addition of 1.5% and 2.0% weight fractions of PTBF for the 500 kg/m^3, 700 kg/m^3, and 900 kg/m^3 densities, respectively, in comparison to the control specimen, which only attained flexural strengths of 0.29 N/mm^2 (500 kg/m^3), 0.53 N/mm^2 (700 kg/m^3), and 0.80 N/mm^2 (900 kg/m^3). PTBF is a hydrophilic material; hence it has excellent adhesion with the cement paste. Beyond the 2.0% weight fraction of PTBF, the flexural strength of LFC decreased dramatically for all three densities considered in this study. If the volume fractions of PTBF were too high, the flexural strength will be reduced, which is because the PTBF is difficult to scatter evenly and trigger agglomeration. In the process of crack spread out, the PTBF will gradually remove the matrix until the bond strength is entirely outstripped.

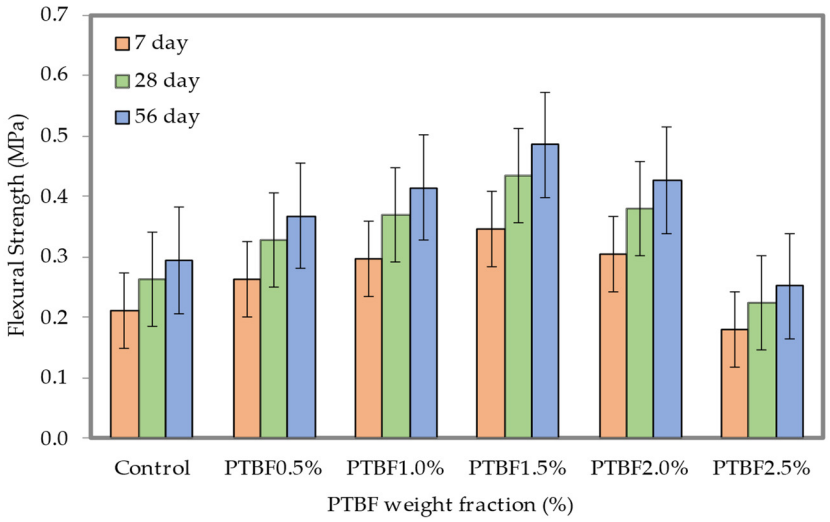


Figure 15. Flexural strength of 500 kg/m^3 density LFC with different weight fractions of PTBF.

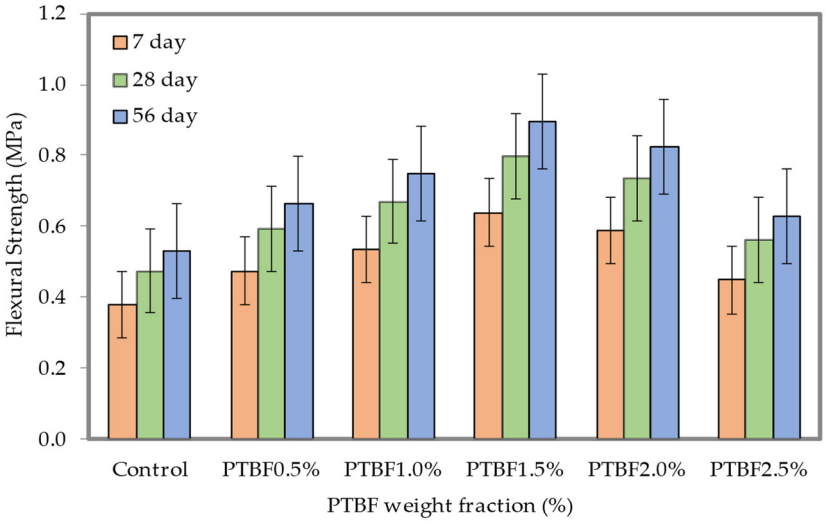


Figure 16. Flexural strength of 700 kg/m^3 density LFC with different weight fractions of PTBF.

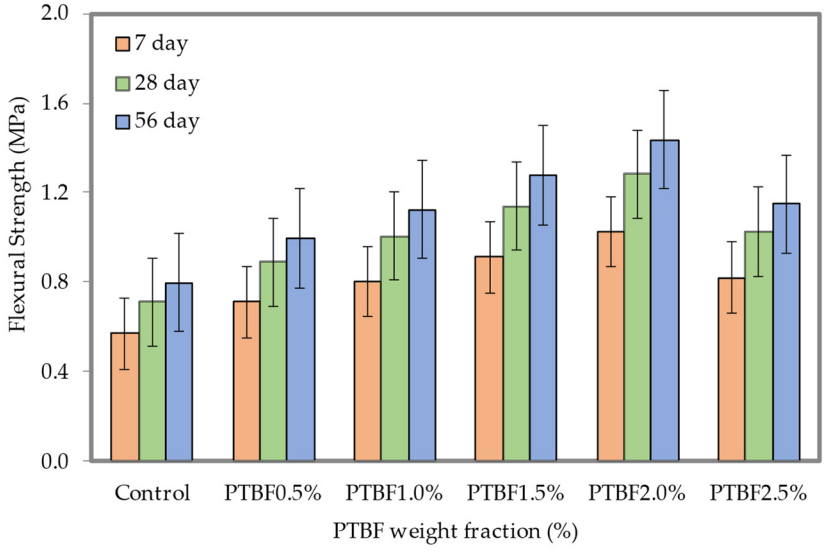


Figure 17. Flexural strength of 900 kg/m^3 density LFC with different weight fractions of PTBF.

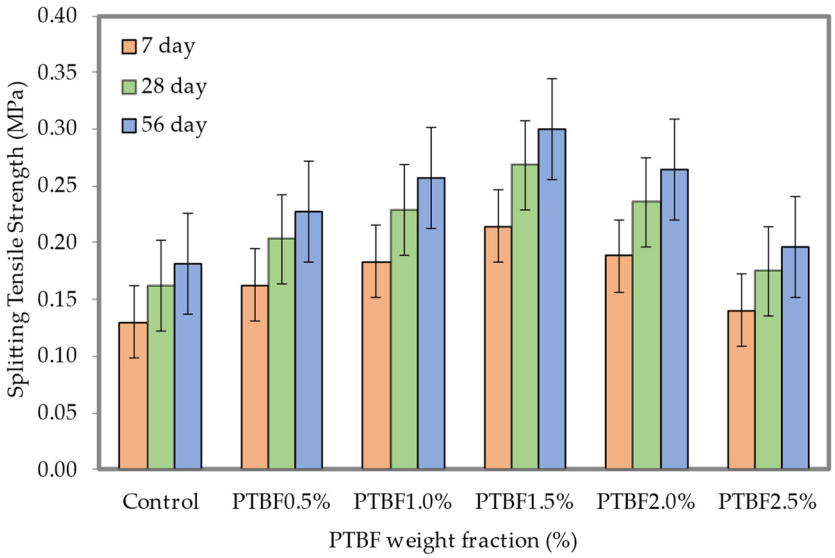


Figure 18. Tensile strength of 500 kg/m^3 density LFC with different weight fractions of PTBF.

3.7. Splitting Tensile Strength

The influence of varying weight fractions of PTBF on splitting tensile strength of 500, 700 and 900 kg/m^3 densities are shown in Figures 18–20. It is noticeable from the whole trend that with the rise of PTBF weight fractions, the splitting tensile strength of entire LFC densities at different ages all display an upward trend. Generally, the splitting tensile strength increases steadily with the rise in the weight fractions of PTBF up to 1.5% (for densities of 500 kg/m^3, 700 kg/m^3) and 2.0% (for 900 kg/m^3 density). The optimal splitting tensile strengths accomplished at day 56 were 0.30, 0.55, and 0.78 N/mm^2, with the inclusion of a 1.5% and 2.0% weight fractions of PTBF for the 500, 700, and 900 kg/m^3 densities, respectively, in comparison to the control specimen, which only achieved compressive strengths of 0.18 N/mm^2 (500 kg/m^3), 0.34 N/mm^2 (700 kg/m^3), and 0.49 N/mm^2 (900 kg/m^3). The enhancement of splitting tensile strengths was achieved for the three densities considered in this research because of the greater LFC robustness assisted by the existence of PTBF.

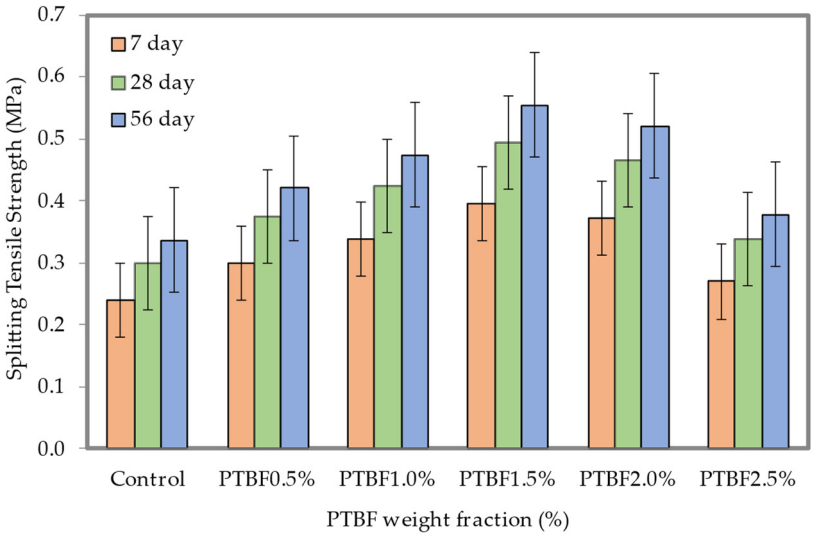


Figure 19. Tensile strength of 700 kg/m^3 density LFC with different weight fractions of PTBF.

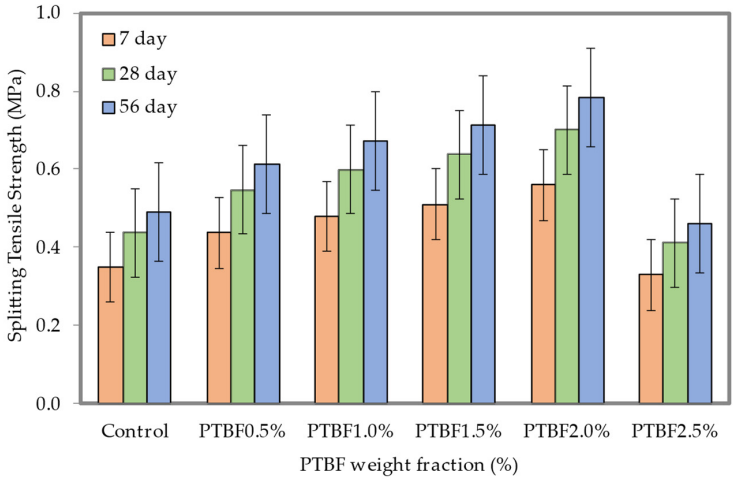


Figure 20. Tensile strength of 900 kg/m^3 density LFC with different weight fractions of PTBF.

4. Discussion

4.1. Correlation between Water Absorption and Porosity

Figure 21 reveals the connection between the LFC water absorption capacity and its porosity. A straight relationship transpires between the LFC water absorption and porosity with varying weight fractions of PTBF which specifies that as the LFC water absorption expands, the porosity expands as well. Dispersal of free water in the LFC develops at the outward section and emerges into the LFC matrix's deepest segment. Additionally, internal water absorption may have a minor impact on the porosity of FC. The R-squared value of 0.8711 indicates that there is a clear linear association between the LFC water absorption capacity and its porosity.

Figure 22 reveals the morphology of the control LFC specimen of 900 kg/m^3 density. It was obvious that there were many large and interconnected pores which led to high water absorption and porosity values. With the inclusion of 2.5% FP, it enhances the compactness of the LFC and reduces the number of large and interconnected pores. As can be noticed from Figure 23, the internal structure becomes denser and homogenous microstructure was attained as the FF were embedded in the cementitious matrix and at the same time reduces the LFC water absorption capacity and porosity values [57].

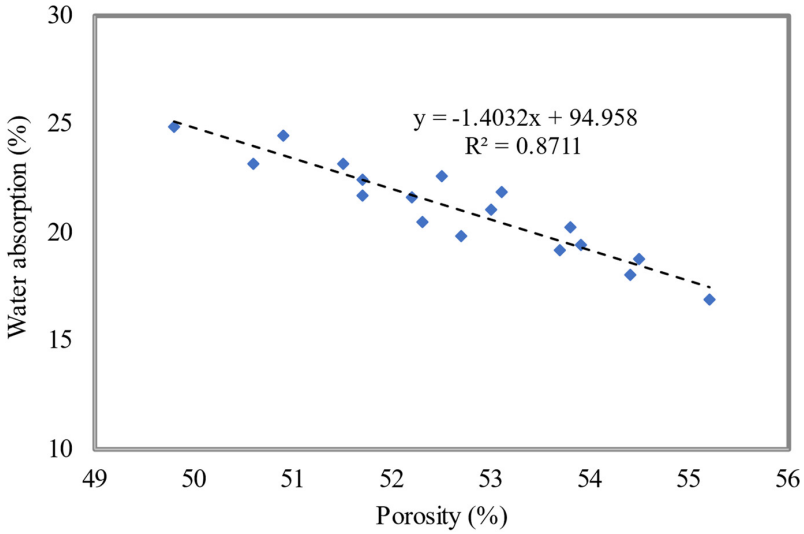


Figure 21. Relationship between water absorption and porosity.

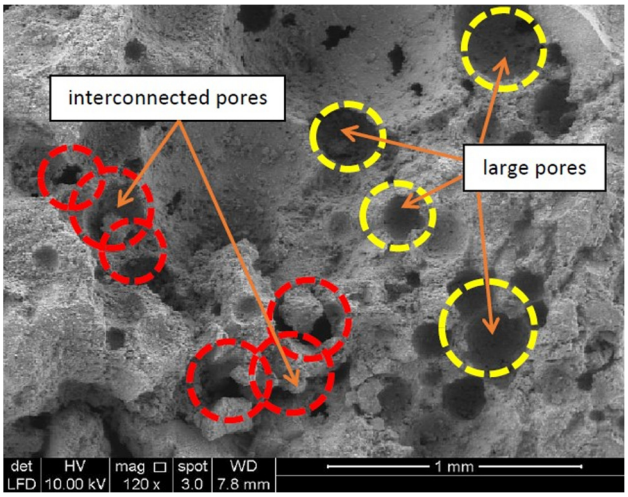


Figure 22. SEM micrograph of control LFC (no addition of fiber).

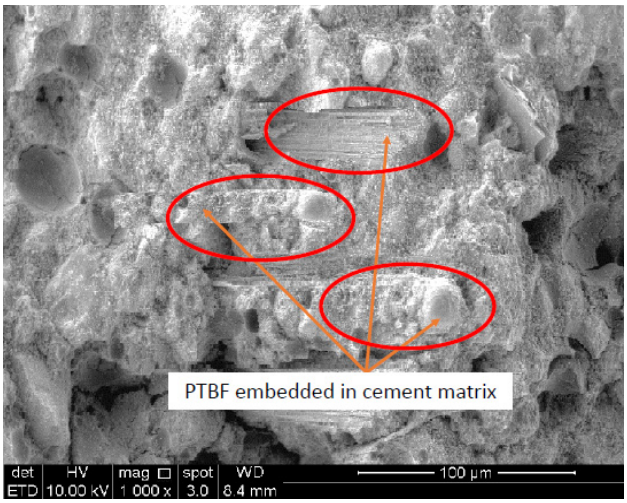


Figure 23. SEM micrograph of LFC with 2.5% PTBF.

4.2. Correlation between the Compressive and Flexural Strengths

A correlation between the compressive and flexural strengths was executed for the 900 kg/m^3 LFC density. All curing periods were considered for this analysis. Figure 24 proves the connection between the flexural and splitting tensile strengths of LFC with different weight fractions of PTBF. It apparently discovered that a direct expanding relationship can be distinguished in compressive strength and flexural strength of LFC [58,59]. From Figure 24, it can be seen that an R-squared value of 0.9444 was obtained, which indicates a highly linear relationship between the two strength parameters, signifying that variations in the predictors are interrelated to deviations in the response variable and that the attained prediction models explain much of the variability of the response. The connection explains that the flexural strength of LFC grows with improving compressive strength. This regression model allows the approximation of the LFC flexural strength from its compressive strength, for the range investigated in this exploration.

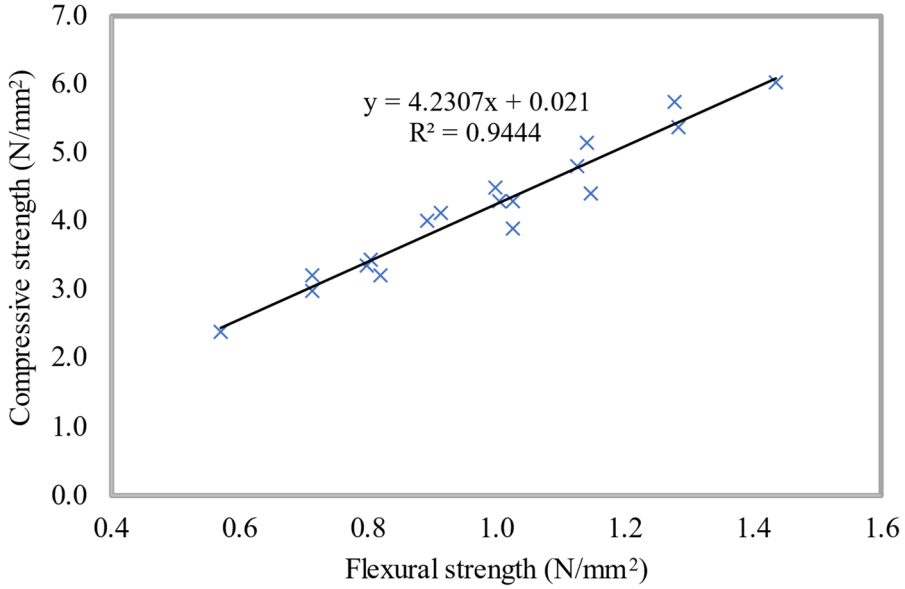


Figure 24. Relationship between the flexural and compressive strengths for 900 kg/m^3 density.

There was evidence of PTBF pull-out from the matrix after the flexural test was completed, indicating that the extra stress transmitted to the PTBF was exceptionally strong, culminating in PTBF rupture as shown in Figure 25. Even though the PTBF was shattered and foamed concrete matrix was broken, it can still hold the basic shape. The existence of PTBF in LFC plays a vital role in bolstering the LFC cementitious matrix and altering the material's physical attributes from a brittle condition to a ductile state [60]. Integrating an appropriate weight fraction of PTBF can efficiently upsurge the flexural strength of LFC because an appropriate volume of PTBF can bond with the hydration products and unhydrated constituents in the LFC matrix to build a three-dimensional network structure, which can create a subsidiary effect and enhance the flexural strength of LFC [61].

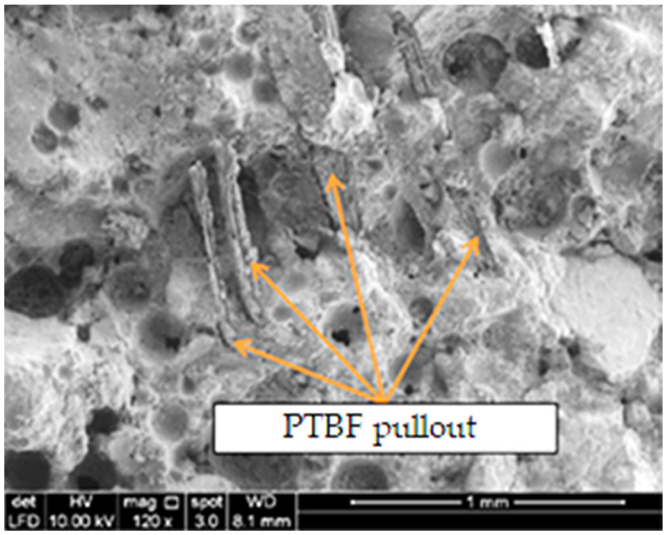


Figure 25. Sign of PTBF pullout after flexural test.

4.3. Correlation between the Compressive and Splitting Tensile Strengths

Figure 26 shows the viable connection between the splitting tensile and compressive strengths of 900 kg/m^3 density LFC with varying weight fractions of PTBF. The splitting tensile strength of LFC was mapped against the compressive strength. Corresponding to

Figure 26, the dissemination of data corroborates that a good relationship between splitting tensile and compressive strengths of LFC does exist. The splitting tensile strengths for all curing periods increased with increasing compressive strength in a similar trend. A great linear association is apparent with an R-squared of 0.9056. For the entire specimens tested in this study, the splitting tensile strength of LFC was approximately 14% of its compressive strength [62,63].

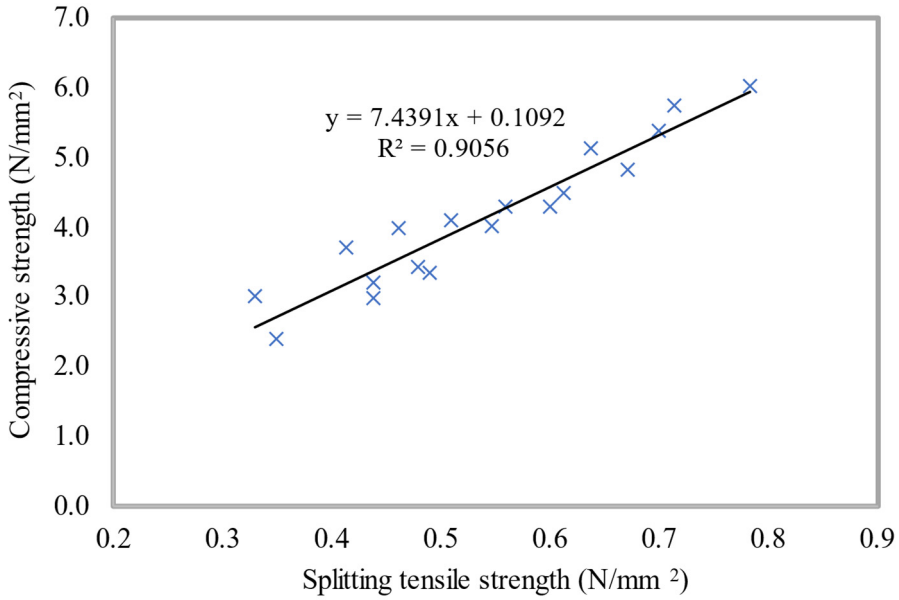


Figure 26. Relationship between the compressive and tensile strengths for 900 kg/m^3 density.

As shown in Figure 27, the impediment of the propagation of cracks in LFC was reduced more obviously with the optimal weight fraction of PTBF. It should be pointed out that at low strains, a linear-elastic behavior was seen, followed by a sudden decrease in stress corresponding to the first crack (matrix failure) and the onset of the plastic region under flexural loading. The material can sustain a proportion of its maximal flexural strength when displacement increases in the plastic zone, which is mostly due to frictional slip and pullout behavior [64]. Furthermore, the area under the curve for the PP fiber-reinforced mixes rose as the fiber percentage increased. During the LFC hardening process, the PTBF will progressively form a fiber grid skeleton inside the LFC, which can enhance the brittle state of the LFC matrix by governing the growth and propagation of cracks when it is exposed to external tensile stress so that it does not lead to an explosive failure. When the PTBF weight fractions were between 1.5% and 2.0%, it is apparent that the fiber can be uniformly dispersed, thus boosting the bonding strength between the cement matrix and the PTBF. The dissemination of the PTBF in the LFC matrix is almost homogeneous without significant accumulation occurrence. The plastic deformation of LFC under tensile load ensues after the presence of the first crack, and before that, it shows elastic linear tension [65]. However, when the PTBF was added to LFC, it will play a fastening role when LFC cracks, so that the matrix elastic modulus will not immediately drop to zero when the direct boundary strain is achieved. PTBF will carry all the stress when cracks emerge, and then slowly transmit it to the matrix [66–68].

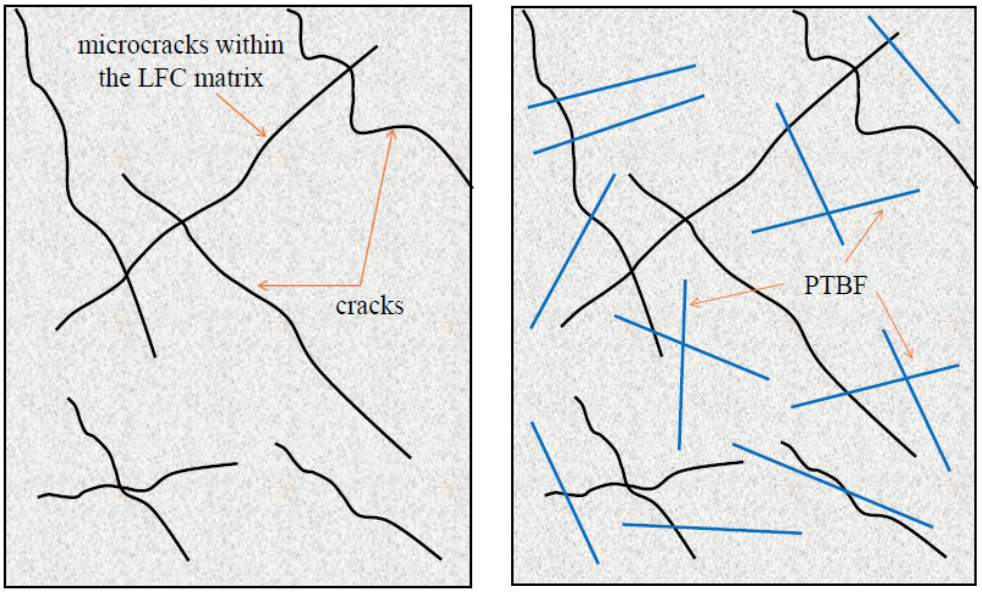


Figure 27. Schematic diagram of PTBF impeding LFC cracks (**a**) cracks and microcracks occur within the LFC cementitious matrix. (**b**) PTBF restricted the propagation of cracks and microcracks.

5. Conclusions

Based on this experimental investigation, the subsequent conclusions are drawn:

1. Slump flow is reduced when PTBF is added to LFC because the fibers form a spatial network and the cement paste used to cover them is burned. Nonetheless, all LFC mixtures had a slump flow bigger than 185 mm, indicating strong self-flowing ability.
2. The LFC dry density reduces as the PTBF weight fractions increase from 0.5% to 2.5% associated with the control specimen. The highest LFC dry density was obtained for the control specimen (0.0% PTBF) whereas the lowest density was obtained at 2.5% PTBF inclusion. The decrease in dry density at higher weight fractions of PTBF was due to the complexity of the compaction process which results in porous LFC.
3. The LFC porosity progresses progressively with the PTBF addition up to 2.5%. LFC mixed with 2.5% PTBF accomplished the ideal porosity with approximately a 12% decrease in comparison with the control LFC specimen for all three densities considered in this research. This is probably due to the excellent PTBF packing capability in the cement matrix of LFC.
4. The water absorption of LFC increased with the rise in weight fractions of PTBF from 0.5% to 2.5%. The ideal water absorption capacity was accomplished with the addition of 2.5% of PTBF. LFC with the existence of PTBF in the mix has fewer cracks, and the cracks were less significant and finer than the LFC without the addition of PTBF. A linear relationship exists between the LFC water absorption capacity and its porosity for various PTBF weight fractions, indicating that as the LFC water absorption increases, the porosity increases as well.
5. The presence of PTBF in LFC augmented the flexural, compressive and splitting tensile strengths of LFC. For 500 and 700 kg/m^3 densities, the optimal weight fraction of PTBF was 1.5%, while for the 900 kg/m^3 density, the optimal weight fraction was 2.0%. With the inclusion of PTBF in LFC, there was a reduction in the entrapped air void, capillary pores, and entrained air voids, which boost the LFC's strength properties. Beyond the 2.0% PTBF weight fraction, the LFC compressive, flexural and splitting tensile strengths diminished significantly. If the PTBF weight fractions were too high, the PTBF is difficult to disperse uniformly and causes agglomeration.

6. Compressive strength and flexural strength of LFC can be distinguished by a direct expanding relationship, which denotes a highly linear relationship between the two strength parameters. The relationship demonstrates that the flexural strength of LFC increases with enhancing compressive strength. Additionally, the distribution of data supports the existence of a strong correlation between the splitting tensile and compressive strengths of LFC. In a similar pattern, the splitting tensile strengths rose with increasing compressive strength for all curing durations.

Author Contributions: Conceptualization, M.A.O.M., M.M.A.B.A., R.A.R.; methodology, M.A.O.M., P.V.; formal analysis, A.V.S., P.V.; technology development, P.P., P.R., M.S.B.; resources, M.M.A.B.A., R.A.R., M.N.M.N.; data curation, M.S.B., P.P., M.N.M.N.; writing—original draft preparation, M.A.O.M.; writing, review and editing, A.V.S., P.R.; funding acquisition, M.S.B., P.V. All authors have read and agreed to the published version of the manuscript.

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References

1. Chica, L.; Alzate, A. Cellular concrete review: New trends for application in construction. *Constr. Build. Mater.* **2019**, *200*, 637–647. [CrossRef]
2. Dhasindrakrishna, K.; Pasupathy, K.; Ramakrishnan, S.; Sanjayan, J. Progress, current thinking and challenges in geopolymer foam concrete technology. *Cem. Concr. Compos.* **2021**, *116*, 103886. [CrossRef]
3. Mydin, M.A.O.; Phius, A.F.; Sani, N.; Tawil, N.M. Potential of Green Construction in Malaysia: Industrialised Building System (IBS) vs Traditional Construction Method. *E3S Web Conf.* **2014**, *3*, 01009. [CrossRef]
4. Sadeghian, O.; Moradzadeh, A.; Mohammadi-Ivatloo, B.; Abapour, M.; Anvari-Moghaddam, A.; Lim, J.S.; Marquez, F.P.G. A comprehensive review on energy saving options and saving potential in low voltage electricity distribution networks: Building and public lighting. *Sustain. Cities Soc.* **2021**, *72*, 103064. [CrossRef]
5. Sadineni, S.B.; Madala, S.; Boehm, R.F. Passive Building Energy Savings: A Review of Building Envelope Components. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3617–3631. [CrossRef]
6. Dey, V.; Bonakdar, A.; Mobasher, B. Low-velocity flexural impact response of fiber-reinforced aerated concrete. *Cem. Concr. Compos.* **2014**, *49*, 100–110. [CrossRef]
7. Prakash, R.; Raman, S.N.; Subramanian, C.; Divyah, N. Eco-friendly fiber-reinforced concretes. In *Handbook of Sustainable Concrete and Industrial Waste Management*; Woodhead Publishing: Sawston, UK, 2022; pp. 109–145.
8. Mohamad, N.; Iman, M.A.; Othuman Mydin, M.A.; Samad, A.A.A.; Rosli, J.A.; Noorwirdawati, A. Mechanical properties and flexure behaviour of lightweight foamed concrete incorporating coir fibre. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *140*, 012140. [CrossRef]
9. Serri, E.; Suleiman, M.Z.; Mydin, M.A.O. The effects of oil palm shell aggregate shape on the thermal properties and density of concrete. *Adv. Mat. Res.* **2014**, *935*, 172–175. [CrossRef]
10. Mohamad, N.; Samad, A.A.A.; Lakhiar, M.T.; Othuman Mydin, M.A.; Jusoh, S.; Sofia, A.; Efendi, S.A. Effects of Incorporating Banana Skin Powder (BSP) and Palm Oil Fuel Ash (POFA) on Mechanical Properties of Lightweight Foamed Concrete. *Int. J. Int. Eng.* **2018**, *10*, 69–76. [CrossRef]
11. Ganesan, S.; Othuman Mydin, M.A.; Sani, N.M.; Che Ani, A.I. Performance of polymer modified mortar with different dosage of polymeric modifier. *MATEC Web Conf.* **2014**, *15*, 01039. [CrossRef]
12. Song, P.S.; Hwang, S.; Sheu, B.C. Strength properties of nylon- and polypropylene-fiber-reinforced concretes. *Cem. Concr. Res.* **2005**, *35*, 1546–1550. [CrossRef]
13. Ebrahimi, K.; Daiezadeh, M.J.; Zakertabrizi, M.; Zahmatkesh, F.; Korayem, A.H. A review of the impact of micro- and nanoparticles on freeze-thaw durability of hardened concrete: Mechanism perspective. *Constr. Build. Mater.* **2018**, *186*, 1105–1113. [CrossRef]
14. Nambiar, E.K.K.; Ramamurthy, K. Air-void characterisation of foam concrete. *Cem. Concr. Res.* **2007**, *37*, 221–230. [CrossRef]

15. Othuman Mydin, M.A.; Mohamed Shajahan, M.F.; Ganesan, S.; Sani, N.M. Laboratory investigation on compressive strength and micro-structural features of foamed concrete with addition of wood ash and silica fume as a cement replacement. *MATEC Web Conf.* **2014**, *17*, 01004. [CrossRef]
16. Zhou, Y.; Bu, R.; Yi, L.; Sun, J. Heat Transfer Mechanism of Concurrent Flame Spread over Rigid Polyurethane Foam: Effect of Ambient Pressure and Inclined Angle. *Int. J. Therm. Sci.* **2020**, *155*, 106403. [CrossRef]
17. Chung, S.-Y.; Lehmann, C.; Elrahman, M.A.; Stephan, D. Pore characteristics and their effects on the material properties of foamed concrete evaluated using Micro-CT images and numerical approaches. *Appl. Sci.* **2017**, *7*, 550. [CrossRef]
18. Dhasindrakrishna, K.; Ramakrishnan, S.; Pasupathy, K.; Sanjayan, J. Collapse of fresh foam concrete: Mechanisms and influencing parameters. *Cem. Concr. Compos.* **2021**, *122*, 104151. [CrossRef]
19. Falliano, D.; Parmigiani, S.; Suarez-Riera, D.; Ferro, G.A.; Restuccia, L. Stability, flexural behavior and compressive strength of ultra-lightweight fiber-reinforced foamed concrete with dry density lower than 100 kg/m^3. *J. Build. Eng.* **2022**, *51*, 104329. [CrossRef]
20. Jiang, J.; Lu, Z.; Niu, Y.; Li, J.; Zhang, Y. Study on the preparation and properties of high-porosity foamed concretes based on ordinary Portland cement. *Mater. Des.* **2016**, *92*, 949–959. [CrossRef]
21. Oren, O.H.; Gholampour, A.; Gencel, O.; Ozbakkaloglu, T. Physical and Mechanical Properties of Foam Concretes Containing Granulated Blast Furnace Slag as Fine Aggregate. *Constr. Build. Mater.* **2020**, *238*, 117774. [CrossRef]
22. Gencel, O.; Bilir, T.; Bademler, Z.; Ozbakkaloglu, T. A Detailed Review on Foam Concrete Composites: Ingredients, Properties, and Microstructure. *Appl. Sci.* **2022**, *12*, 5752. [CrossRef]
23. Mansouri, I.; Shahheidari, F.S.; Hashemi, S.M.A.; Farzampour, A. Investigation of Steel Fiber Effects on Concrete Abrasion Resistance. *Adv. Concr. Constr.* **2020**, *9*, 367–374.
24. Chajec, A.; Sadowski, L. The Effect of Steel and Polypropylene Fibers on the Properties of Horizontally Formed Concrete. *Materials* **2020**, *13*, 5827. [CrossRef] [PubMed]
25. Hilal, A.A.; Thom, N.H.; Dawson, A.R. Pore Structure and Permeation Characteristics of Foamed Concrete. *J. Adv. Concr. Technol.* **2014**, *12*, 535–544. [CrossRef]
26. Zhou, X.Y.; Yang, D.Y.; Zhu, C.X.; Wang, T.Z.; Zhao, X.T.; Liu, M. Durability of multi-scale polypropylene fiber reinforced concrete based on pore structure analysis. *Mater. Sci. Eng. J.* **2022**, *40*, 110–115.
27. Farhad, A.; Ronny, G. Experimental investigation into the properties of self-compacting rubberised concrete incorporating polypropylene and steel fibers. *Int. Fed. Struct. Concr.* **2018**, *20*, 267–281.
28. Karimipour, A. Effect of untreated coal waste as fine and coarse aggregates replacement on the properties of steel and polypropylene fibres reinforced concrete. *Mech. Mater.* **2020**, *150*, 103592. [CrossRef]
29. Kamal, M.M.; Safan, M.A.; Etman, Z.A.; Kasem, B.M. Mechanical properties of self-compacted fiber concrete mixes. *HBRC J.* **2014**, *10*, 25–34. [CrossRef]
30. Rai, B.; Singh, N.K. Statistical and experimental study to evaluate the variability and reliability of impact strength of steel-polypropylene hybrid fiber reinforced concrete. *J. Build. Eng.* **2021**, *44*, 102937. [CrossRef]
31. Toutanji, H.A. Properties of polypropylene fiber reinforced silica fume expansive-cement concrete. *Constr. Build. Mater.* **1999**, *13*, 171–177. [CrossRef]
32. Zhang, M.H.; Sharif, M.S.H.; Lu, G. Impact resistance of high-strength fiber reinforced concrete. *Mag. Concr. Res.* **2007**, *9831*, 199–210. [CrossRef]
33. Kiran, T.; Ali Khan, S. Behaviour of Fibre Reinforced Concrete Slabs Under Impact Loads. *Int. J. Curr. Res.* **2017**, *9*, 60349–60354.
34. Amancio, F.A.; De Carvalho Rafael, M.F.; De Oliveira Dias, A.R.; Bezerra Cabral, A.E. Behavior of concrete reinforced with polypropylene fiber exposed to high temperatures. *Procedia Struct. Integr.* **2018**, *11*, 91–98. [CrossRef]
35. Hazlin, A.R.; Iman, A.; Mohamad, N.; Goh, W.I.; Sia, L.M.; Samad, A.A.A.; Ali, N. Microstructure and Tensile Strength of Foamed Concrete with Added Polypropylene Fibers. *MATEC Web Conf.* **2017**, *103*, 01013. [CrossRef]
36. Ngo, S.H.; Huynh, T.P. lightweight foamed concrete reinforced with different polypropylene fiber contents. *J. Sci. Technol. Civ. Eng.* **2022**, *16*, 128–139. [CrossRef]
37. Bing, C.; Zhen, W.; Ning, L. Experimental research on properties of high-strength foamed concrete. *J. Mater. Civ. Eng.* **2012**, *24*, 113–118. [CrossRef]
38. Falliano, D.; De Domenico, D.; Ricciardi, G.; Gugliandolo, E. Compressive and flexural strength of fiber-reinforced foamed concrete: Effect of fiber content, curing conditions and dry density. *Constr. Build. Mater.* **2019**, *198*, 479–493. [CrossRef]
39. Gencel, O.; Kazmi, S.M.S.; Munir, M.J.; Kaplan, G.; Bayraktar, O.Y.; Yarar, D.O.; Karimi Pour, A.; Ahma, M.R. Influence of bottom ash and polypropylene fibers on the physico-mechanical, durability and thermal performance of foam concrete: An experimental investigation. *Constr. Build. Mater.* **2021**, *306*, 124887. [CrossRef]
40. *BS 12*; Specification for Portland Cement. British Standards Institute: London, UK, 1996.
41. *BS 882*; Specification for Aggregates from Natural Sources for Concrete. British Standards Institute: London, UK, 1992.
42. *BS 1881-102*; Testing Concrete. Method for Determination of Slump. British Standards Institute: London, UK, 1983.
43. *BS 12390-3*; Testing Hardened Concrete. Compressive Strength of Test Specimens. British Standards Institute: London, UK, 2011.
44. *BS EN 12390-5*; Testing Hardened Concrete. Flexural Strength of Test Specimens. British Standards Institute: London, UK, 2019.
45. *BS EN 12390-6*; Testing Hardened Concrete. Tensile Splitting Strength of Test Specimens. British Standards Institute: London, UK, 2009.

46. Brady, K.C.; Watts, G.R.A.; Jones, M.R. *Specification for Foamed Concrete*; Transport Research Laboratory: Great Britain, UK, 2001.
47. *BS 1881-122*; Testing Concrete. Method for Determination of Water Absorption. British Standards Institute: London, UK, 1983.
48. Hilal, A.A.; Thom, N.H.; Dawson, A.R. The use of additives to enhance properties of pre-formed foamed concrete. *Int. J. Eng. Technol.* **2015**, *7*, 286–293. [CrossRef]
49. Hou, L.; Li, J.; Lu, Z.; Niu, Y. Influence of foaming agent on cement and foam concrete. *Constr. Build. Mater.* **2021**, *280*, 122399. [CrossRef]
50. Wang, J.; Dai, Q.; Si, R.; Guo, S. Mechanical, durability, and microstructural properties of macro synthetic polypropylene (PP) fibre-reinforced rubber concrete. *J. Clean. Prod.* **2019**, *234*, 1351–1364. [CrossRef]
51. Tambichik, M.A.; Abdul Samad, A.A.; Mohamad, N.; Mohd Ali, A.Z.; Othuman Mydin, M.A.; Mohd Bosro, M.Z.; Iman, M.A. Effect of combining Palm Oil Fuel Ash (POFA) and Rice Husk Ash (RHA) as partial cement replacement to the compressive strength of concrete. *Int. J. Integr. Eng.* **2018**, *10*, 61–67. [CrossRef]
52. Ramezanianpour, A.A.; Esmaeili, M.; Ghahari, S.A.; Najaf, M.H. Laboratory study on the effect of polypropylene fiber on durability, and physical and mechanical characteristic of concrete for application in sleepers. *Constr. Build. Mater.* **2013**, *44*, 411–418. [CrossRef]
53. Guo, Z.Q. Experimental Study on the Impermeability of Multi-Scale Polypropylene Fibre Concrete. Master's Thesis, Chongqing University, Chongqing, China, 2018.
54. Behfarnia, K.; Behravan, A. Application of high performance polypropylene fibers in concrete lining of water tunnels. *Mater. Des.* **2014**, *55*, 274–279. [CrossRef]
55. Othman, R.; Jaya, R.P.; Muthusamy, K.; Sulaiman, M.; Duraisamy, Y.; Abdullah, M.M.A.B.; Przybył, A.; Sochacki, W.; Skrzypczak, T.; Vizureanu, P.; et al. Relation between Density and Compressive Strength of Foamed Concrete. *Materials* **2021**, *14*, 2967. [CrossRef] [PubMed]
56. Zhang, Z.; Wang, H. The pore characteristics of geopolymer foam concrete and their impact on the compressive strength and modulus. *Front. Mater.* **2016**, *3*, 38. [CrossRef]
57. Jitchaiyaphum, K.; Sinsiri, T.; Chindaprasirt, P. Cellular lightweight concrete containing pozzolan materials. *Procedia Eng.* **2011**, *14*, 1157–1164. [CrossRef]
58. Aziz, I.H.; Abdullah, M.M.A.; Salleh, M.A.A.M.; Yoriya, S.; Abd Razak, R.; Mohamed, R.; Baltatu, M.S. The investigation of ground granulated blast furnace slag geopolymer at high temperature by using electron backscatter diffraction analysis. *Arch. Metall. Mater.* **2022**, *67*, 227–231.
59. Paleu, C.C.; Munteanu, C.; Istrate, B.; Bhaumik, S.; Vizureanu, P.; Bălţatu, M.S.; Paleu, V. Microstructural Analysis and Tribological Behavior of AMDRY 1371 (Mo–NiCrFeBSiC) Atmospheric Plasma Spray Deposited Thin Coatings. *Coatings* **2020**, *10*, 1186. [CrossRef]
60. Seker, B.; Gökçe, M.; Toklu, K. Investigation of the effect of silica fume and synthetic foam additive on cell structure in ultra-low density foam concrete. *Case Stud. Constr. Mater.* **2022**, *16*, e01062.
61. Song, Y.; Lange, D. Influence of fine inclusions on the morphology and mechanical performance of lightweight foam concrete. *Cem. Concr. Compos.* **2021**, *124*, 104264. [CrossRef]
62. Loghin, C.; Nicolaiov, P.; Ionescu, I.; Hoblea, Z. Functional Design of Equipment for Individual Protection. *Manag. Technol. Chang.* **2009**, *2*, 693–696.
63. Ailenei, E.C.; Ionesi, S.D.; Dulgheriu, I.; Loghin, M.C.; Isopescu, D.N.; Maxineasa, S.G.; Baciu, I.-R. New Waste-Based Composite Material for Construction Applications. *Materials* **2021**, *14*, 6079. [CrossRef] [PubMed]
64. Tolêdo Filho, R.D.; Joseph, K.; Ghavami, K.; England, G.L. The use of sisal fibre as reinforcement in cement-based composites. *Rev. Bras. Eng. Agric. Ambient.* **1999**, *3*, 245–256. [CrossRef]
65. Khitab, A.; Serkan Kırgız, M.; Nehdi, M.L.; Mirza, J.; de Sousa Galdino, A.G.; Karimi Pour, A. Mechanical, thermal, durability and microstructural behavior of hybrid waste-modified green reactive powder concrete. *Constr. Build. Mater.* **2022**, *344*, 128184. [CrossRef]
66. Amran, M.; Fediuk, R.; Vatin, N.; Huei Lee, Y.; Murali, G.; Ozbakkaloglu, T.; Klyuev, S.; Alabduljabber, H. Fibre-Reinforced Foamed Concretes: A Review. *Materials* **2020**, *13*, 4323. [CrossRef]
67. Mydin, M.A.O.; Abdullah, M.M.A.B.; Mohd Nawi, M.N.; Yahya, Z.; Sofri, L.A.; Baltatu, M.S.; Sandu, A.V.; Vizureanu, P. Influence of Polyformaldehyde Monofilament Fiber on the Engineering Properties of Foamed Concrete. *Materials* **2022**, *15*, 8984. [CrossRef]
68. Ariffin, N.; Abdullah, M.M.A.B.; Zainol, M.R.R.M.A.; Baltatu, M.S.; Jamaludin, L. Effect of Solid to Liquid Ratio on Heavy Metal Removal by Geopolymer-Based Adsorbent. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *374*, 012045. [CrossRef]

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