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RESEARCH

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Development and microstructural characterization of ultra-lightweight aggregate concrete incorporating different sizes of polypropylene fibers

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Abstract

In this study, ultra-lightweight concrete with an oven-dry density of 800 kg/m^3 was produced using expanded glass as the lightweight aggregate. Polypropylene fibers of different sizes were incorporated into the specimens to examine their effects on the material properties, such as drying shrinkage and flexural strength. The target dry density was achieved by applying the packing density concept to optimize the mix grading and calculate the content of each concrete component. Specimens with different ratios of short and long fibers were produced. Their fresh state, mechanical performance, and physical properties were extensively analyzed using various methods, including X-ray micro-computed tomography to examine the microstructure. The experimental results indicated a significant reduction in drying shrinkage for the fiber incorporated specimens, dependent on the fiber length and content. The compressive strength of the specimens exceeded 12 MPa. Moreover, the inclusion of polypropylene fibers notably enhanced the flexural strength by approximately 60%, while the lower density contributed to substantially reduced thermal conductivity by up to 26%, which is beneficial for thermal insulation. These results confirm that polypropylene fibers can be used to produce ultra-lightweight concrete with self-leveling properties, without compromising mechanical and physical performance.

Keywords Ultra-lightweight concrete, Polypropylene fiber, Fresh state, Mechanical properties, Thermal conductivity, Drying shrinkage

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1 Introduction

Recently, significant attention has been devoted to improving the insulation efficiency of buildings and reducing energy consumption, to address the associated environmental concerns. Buildings account for approximately 40% of the global energy consumption, mainly to satisfy the thermal comfort requirements of occupants, and contribute to over 33% of global emissions (Tyagi et al., 2016). Therefore, enhancing the thermal performance of buildings is a critical requirement in many regions. Furthermore, reducing energy use in the construction field constitutes a significant step for mitigating climate change and ensuring sustainability

(Perez-Lombard et al., 2008). In general, thermal energy flows from a warmer area to a cooler one. During winter, thermal energy moves from the interior to the exterior of a building, whereas in summer, heat is transferred from the exterior to the interior through the walls, resulting in significant heat energy loss. Thermal wall insulation is crucial for reducing this heat transfer and, consequently, the rate of energy consumption. Several insulating materials have been developed to minimize heat loss from various structures and to meet structural requirements (Al-Homoud, 2005; Hill et al., 2018; Papadopoulos, 2005; Schiavoni et al., 2016). Lightweight concrete is a promising construction material in this regard due to its low thermal conductivity and acceptable mechanical performance.

Lightweight concrete, characterized by its reduced density, low thermal conductivity, and reasonable mechanical properties, is defined in EN 206 as a construction material with a dry density between 800 and 2000 kg/m^3 (Chung et al., 2018; Mehta & Monteiro, 2015). Its excellent resistance to high-temperature exposure has enabled its widespread use in various structural in various structural elements, such as beams, columns, slabs, and walls (Chen & Liu, 2008; Lotfy et al., 2014). This material can be produced using either artificial or natural lightweight aggregates or with a foaming agent (foamed concrete), and it can serve both nonstructural and structural purposes (Korat et al., 2013; Neville, 2012). Lightweight aggregate concrete (LWAC) generally exhibits better mechanical performance than foamed concrete at the same density level Chung et al. (2019). Several types of artificial lightweight aggregates, such as expanded clay or expanded glass, have been developed to minimize material density. The density of lightweight concrete is a key parameter influencing its thermal performance (Cavalline et al., 2017). At a given density level, variations in the mineralogical and physical characteristics of the aggregate material can change the thermal insulation efficiency of LWAC by up to 25% (Yu et al., 2015). Several studies have demonstrated that the mechanical properties and thermal insulation of LWAC exhibit a significant correlation with its density (Abd Elrahman et al., 2019; Neville, 2012). However, despite the several benefits of LWAC, such as reduced mass and enhanced thermal insulation (Hassanpour et al., 2012), its compressive and tensile strengths are lower than those of conventional concrete. A systematic approach for optimally proportioning the components of lightweight concrete to balance structural performance and thermal conductivity is yet to be devised (Yu et al., 2015). Consequently, producing lightweight concrete that can simultaneously achieve low density, suitable mechanical properties, and effective thermal insulation remains a significant challenge (Yu et al., 2016).

One of the drawbacks of lightweight concrete is increased drying shrinkage at early ages compared with conventional concrete (Alexander Bogas et al., 2014). In this regard, several researchers have focused on the role of fibers, particularly polypropylene fiber (PPF), in reducing shrinkage and enhancing the flexural behavior of concrete (Choumanidis et al., 2016; Mazaheripour et al., 2011; Wu et al., 2016). Various types of fibers have been used for this purpose, including steel, synthetic materials, and some natural fibers (Afroughsabet & Ozbakkaloglu, 2015; Hamoush et al., 2010; Khaloo et al., 2014; Madhavi et al., 2014; Qian & Stroeven, 2000). The flexural behavior of fiber-reinforced concrete depends on the type, aspect ratio, and content of fiber. Although some studies have explored the use of PPF in lightweight concrete (Badogiannis et al., 2019; Gencel et al., 2011; Mazaheripour et al., 2011; Nahhas, 2013), most investigations have focused on steel fibers (Altun & Aktas, 2013; Hassanpour et al., 2012; Mohamed et al., 2023), and only a few studies investigated the effect of polypropylene fibers on specific properties of lightweight concrete. Considering that the primary benefit of lightweight concrete is density reduction, employing polymer-based fibers instead of the comparatively denser steel fibers proves advantageous in reducing the specific gravity of the material. In addition, even the studies that have employed PPF have not considered the parameters of the fibers. Hence, the effects of different aspects of PPFs on the characteristics of lightweight concrete must be investigated further for a better understanding of the performance of lightweight concrete. Furthermore, fibers have been incorporated primarily into LWAC with densities of 1400 to 1800 kg/m^3; the effect of fibers on ultra-lightweight aggregate concrete (ULWAC), which has densities less than 800 kg/m^3, has rarely been investigated (Roberz et al., 2017; Sikora et al., 2020; Yu et al., 2015).

The main objective of this study was to develop homogeneous and stable ultra-lightweight concrete with a density of about 800 kg/m^3, incorporating PPF to enhance the mechanical and physical properties of the material. To achieve this, the mixtures were optimized using the packing density concept, i.e., maximizing the content of lightweight aggregate with low density while minimizing the content of high density cementitious materials. Expanded glass aggregate (Liaver®) was selected due to its high ratio of mechanical properties/density compared with other natural and commercially available artificial lightweight aggregates (Abd Elrahman et al., 2019; Chung et al., 2021). To improve the flexural properties and reduce shrinkage, PPF was also incorporated. The characteristics of the fibers, including length and type,

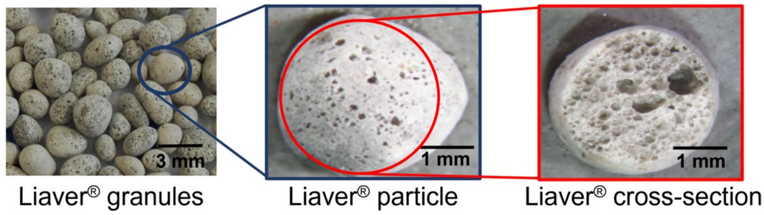

Fig. 1 Characteristics of the expanded aggregate (Liaver.®)

can affect the material performance. Therefore, polypropylene fibers with different lengths were used in different proportions to examine their effects on the material properties. To mitigate the high risk of segregation and bleeding due to the very low density of the produced concrete, chemical admixtures were used to ensure mixture homogeneity in the fresh state. The fresh-state, mechanical, shrinkage, and thermal properties of the proposed materials were comprehensively investigated, and these properties were correlated with microstructural characteristics, including pore structures, analyzed using X-ray micro-computed tomography (micro-CT). The obtained results were carefully analyzed to establish comprehensive guidelines for designing PPF-incorporated LWAC with optimal workability, strength, and thermal performance, thereby enabling the proposed materials to be utilized for a wide range of applications.

2 Sample preparations

2.1 Raw materials

This study investigated the influence of PPF on the properties of LWAC, which has a theoretical dry density of 800 kg/m^3. To produce LWAC with such low density, EN 13055-compliant expanded glass (Fig. 1) supplied by Liaver® GmbH (Ilmenau, Germany), was used due to its superior physical and mechanical properties relative to other commercially available lightweight aggregates (Abd Elrahman et al., 2019; Chung et al., 2017). Six different sizes of the Liaver® aggregate were used: 4–8 mm, 2–4 mm, 1–2 mm, 0.5–1 mm, 0.25–0.5 mm, and 0.1–0.3 mm. The physical and mechanical properties of the aggregates, as measured and provided by the manufacturer, are presented in Table 1. In this table, the particle density and crushing resistance vary according to the aggregate sizes, while water absorption measured according to BS EN 1097-6 shows consistent values across different Liaver® sizes. As the primary binder, CEM III/A42.5 N-LH, as defined in the EN 197-1 standard, was selected for its low hydration rate; its very low thermal conductivity is also beneficial in minimizing the hydration heat in lightweight concrete. Type F fly ash (FA) and microsilica (SF), compliant with EN 450-1 and EN 13263-1, respectively, were incorporated to enhance the workability of the concrete without increasing the hydration heat or introducing micro-cracking. Fig. 2 presents the particle size distribution of the fine materials used, and Table 2 presents their physical properties and chemical composition.

Table 1 Properties of the aggregate

Liaver®	Size	Particle density [kg/m^3]	Crushing resistance [N/mm^2]	Water absorption [wt.%]
Liaver®	4–8 mm	300	> 1.9	13.6
Liaver®	2–4 mm	320	> 2.2	14.4
Liaver®	1–2 mm	350	> 2.4	15.8
Liaver®	0.5–1 mm	420	> 2.6	15.4
Liaver®	0.25–0.5 mm	540	> 2.9	14.8
Liaver®	0.1–0.3 mm	800	> 3.5	14.1

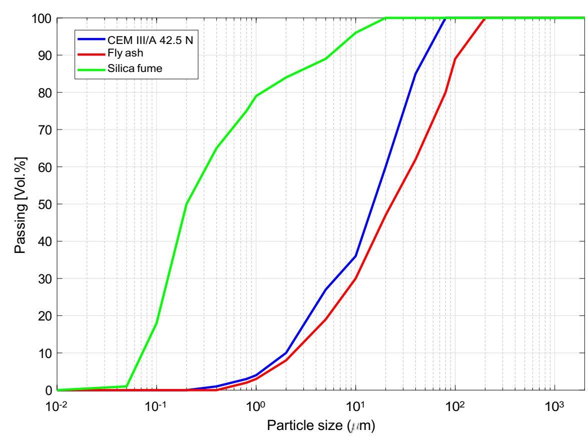

Fig. 2 Particle size distribution of the fine materials

LWAC often experiences severe dry shrinkage due to the porous nature and lower elastic modulus of the lightweight aggregate used, particularly at early ages. The inclusion of fibers can mitigate this issue by reducing the cracking associated with high dry shrinkage. PPF (density of 0.91 g/cm^3) in two sizes—short fibers at 6 mm (SPP) and long fibers at 12 mm (LPP), both with a diameter of 0.031 mm—were supplied by Sika GmbH (Stuttgart,

Table 2 Physical properties and chemical composition of the fine materials

Material	SiO_2	CaO	Fe_2O_3	Al_2O_3	MgO	K_2O	Na_2O	SO_3	Specific density [g/cm^3]
CEM III/A42.5N	29.1	49.1	1.1	8.8	4.9	0.7	0.18	3.4	3.06
Fly ash	49.2	3.1	7.6	27.6	2.1	5.0	0.9	0.7	2.29
Silica fume	98.4	0.2	0.01	0.2	0.1	0.2	0.15	0.1	2.2

Germany). LWAC tends to exhibit low workability due to the reduced mass of the aggregate. It is also very sensitive to compaction and vibration in its fresh state, showing a high tendency to bleed and segregate due to the density difference between the cement matrix and the lightweight aggregates. The inclusion of PPF tends to reduce the workability even further. To address these challenges and ensure sufficient workability for the produced concrete, a polycarboxylate ether superplasticizer (Viscocrete 1051, Sika), with a density of 1.04 g/cm^3 according to the EN 934-2 standard, was utilized. In addition, a viscosity-enhancing admixture, methyl hydroxyethyl cellulose (Tylose MH 15000 YP4, Sika), was employed to stabilize the fresh mixture and enhance its homogeneity. The dosages of the superplasticizer and viscosity enhancer were adjusted by trial and error during mixing to achieve a stable fresh mixture with the desired consistency class of F3 as specified in EN 206-1.

2.2 Mixture proportioning and sample production

The concrete mixture was designed with an aim to increase the packing density of the lightweight aggregate and thereby minimize the void volume between aggregate particles. This approach increased the volume of the low-particle-density aggregates while reducing the volume of the high-density-cement paste, thus allowing for the targeted density of 800 kg/m^3 to be achieved. The challenge lies in producing ultra-lightweight concrete with sufficient strength while maintaining a reduced density. As shown in Table 1, the crushing strength and density of the lightweight aggregates decreased as the aggregate size increased. Hence, appropriate proportions of each aggregate size needed to be selected to maximize the compressive strength of the LWAC by including the optimal aggregate contents for achieving the targeted density. The well-known Andreasen and Andersen (Abd Elrahman & Hillemeier, 2014; Yu et al., 2013) model was used to calculate the volume of aggregate in each size fraction, as follows:

$$P(D) = \frac{D_a^q - D_{\min}^q}{D_{\max} - D_{\min}^q} \quad (1)$$

where *P(D)* represents the total volume of particles passing through a sieve of size *D*, D_{max} is the maximum size of the particles, D_{min} is the minimum size of the particles, and q is the distribution factor. Higher distribution factors result in coarser mixtures with reduced workability, which are unsuitable for fiber-incorporated lightweight concrete as it already suffers from poor workability. Therefore, a q value of 0.4 was selected to balance dense aggregate packing with an adequate workability. Due to the high packing density of the aggregate skeleton, a specific amount of cement paste would be necessary to coat the particles and ensure the required workability. However, if the binder contained only cement, a large amount (550 kg/m^3) of binder would be required, which could increase the hydration heat, leading to internal micro-cracking and a significant reduction in strength, especially in this type of low-thermal conductivity concrete. To mitigate these issues, the cement content in the binder was reduced to 440 kg/m^3 (80 wt.-%); instead, FA (10 wt.-%) was added as its spherical particles improve workability and reduce hydration heat, while SF (10 wt.-%) was added as its fine particles enhance particle cohesion in the fresh state.

Nine concrete mixes, as listed in Table 3, were prepared to assess the influence of fibers on the mechanical performance and volumetric changes of lightweight concrete. A reference mix without fibers (denoted as 'LWC') was prepared to ensure that the mixture proportioning would satisfy the targeted dry density and to compare the other mixes with different fiber compositions, denoted as 'LWCF'. Each specimen containing fibers is designated with two numbers: the first number indicates the volume fraction of the short fiber, and the second number indicates the volume fraction of the long fiber. Two of the mix designs included only long fibers, while two included only short fibers, with concentrations of 0.5 and 1 vol.-%. The remaining four mixes contained a combination of both fiber types, with the proportions of short and long fibers adjusted to maintain total fiber volumes of either 0.5 or 1 vol.-%. For all mixes, the water/binder ratio was maintained at 0.36, with additional water added to compensate for aggregate absorption.

Table 3 Mixture proportions of LWAC with different fiber contents (unit: [kg/m^3])

Mix	Liaver®						Cement	SF*	FA**	SPP	LPP
	4–8 [mm]	2–4 [mm]	1–2 [mm]	0.5–1 [mm]	0.25–0.5 [mm]	0.1–0.3 [mm]					
LWC	35.6	28.1	24.1	23.39	21.29	23.9	440	55	55	–	–
LWCF0-0.5	35.6	28.1	24.1	23.39	21.29	23.9	440	55	55	–	4.55
LWCF0-1	35.6	28.1	24.1	23.39	21.29	23.9	440	55	55	–	9.1
LWCF0.5–0	35.6	28.1	24.1	23.39	21.29	23.9	440	55	55	4.55	-
LWCF1-0	35.6	28.1	24.1	23.39	21.29	23.9	440	55	55	9.1	-
LWCF0.75–0.25	35.6	28.1	24.1	23.39	21.29	23.9	440	55	55	6.83	2.28
LWCF0.25–0.25	35.6	28.1	24.1	23.39	21.29	23.9	440	55	55	2.28	2.28
LWCF0.25–0.75	35.6	28.1	24.1	23.39	21.29	23.9	440	55	55	2.28	6.83
LWCF0.5–0.5	35.6	28.1	24.1	23.39	21.29	23.9	440	55	55	4.55	4.55

*SF: microsilica, **FA: fly ash

(a) (b)

Fig. 3 Measurement of material properties: **a** flexural strength measurement, **b** thermal property evaluation using a hot disk

3 Properties and characterization

3.1 Evaluation of concrete properties

The existence of fibers in fresh concrete hinders the free movement of particles and consequently reduces the workability of the material. In this study, the properties of fresh concrete were evaluated by measuring the slump flow, which serves as a consistency indicator, as specified in EN 12350-6. In addition, the dry shrinkage of lightweight concrete represents a critical issue due to the reduced elastic modulus of lightweight aggregate compared with normal-weight aggregate. The influence of different types and dosages of PPF on the dry shrinkage performance of the lightweight concrete mixes was investigated. Dry shrinkage measurements were conducted in accordance with DIN 52450 (Graff–Kaufmann) on concrete samples of 40×40×160 mm^3 at intervals of 1, 3, 7, and 28 days. During these periods, the samples were cured conditions at 60% humidity and a temperature of 20±1 °C.

Subsequently, several tests were performed on the hardened specimens to assess the mechanical and physical properties of the lightweight concrete mixes. After 28 days of curing, the dry density of the lightweight concrete was determined as per EN 12390-7 using cubical samples of 150×150×150 mm^3. Compressive strength tests were conducted on similar samples in accordance with EN 12390-3 at the age of 28 days. For each mix, three samples were tested, and the average value was recorded. To investigate the effect of the PPF sizes and dosages on the tensile performance of the prepared concrete, flexural strength tests were performed on prism-shaped samples of 40×40×160 mm^3 at 28 days (Fig. 3a). The average value from three samples of each mix was considered. To evaluate the thermal insulation properties, the thermal conductivity of the specimens was measured on cubical samples of 100×100×100 mm^3 using a hot disk (Göteborg, Sweden), in compliance with ISO 22007-2 (Fig. 3b). The measurements were repeated five times for each mix, and the mean value was considered.

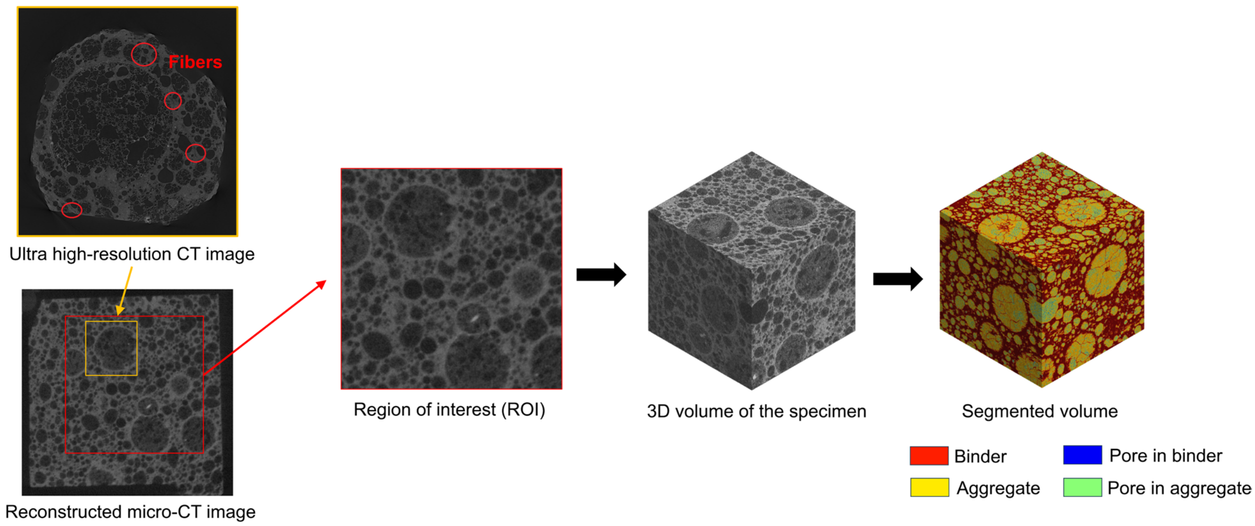

Fig. 4 Micro-CT imaging process for segmenting each component of fiber-incorporated LWAC

3.2 Micro-CT imaging process

To analyze the microstructural characteristics of the specimens, micro-CT was performed. This method allows for the examination of image-based information, including pore characteristics, without damaging the target materials. Micro-CT is particularly useful for investigating characteristics such as component porosity in LWAC (Abd Elrahman et al., 2018; Chung et al., 2021). The imaging process, which included micro-CT images at different scales, is illustrated in Fig. 4. In general, a set of cross-sectional reconstructed images are presented in grayscale, reflecting the relative densities of the components. In the ultra-high-resolution image, the PPFs are highlighted with the red circles; however, this image covers only a limited area and may not fully represent the material being considered. Therefore, reconstructed images with a lower resolution but wider coverage were used to characterize the target specimens. To conduct a more effective investigation, an appropriate region of interest (ROI) needs to be selected. The ROI images used in this study had a resolution of 900×900 pixels with a pixel size of 16.03 μm, which is adequate for identifying micropores within specimens. Considering the image resolution, it is assumed that the PPFs are uniformly distributed in the pore and binder parts. These ROI images were stacked to create a 3D volume representing the microstructure. For a more comprehensive analysis, the volume image was segmented using the multi-thresholding and watershed approaches within the MATLAB image processing toolbox (MATLAB, 2023). This process generated segmented images that clearly display specific components, such as pores, aggregates, and the pores within each component, as shown in Fig. 4. The images obtained for each specimen enabled the detailed analysis of material characteristics, including porosity and properties related to durability.

4 Results and discussion

4.1 Workability

Workability is a crucial parameter affecting the performance, castability, and filling ability of low-density lightweight concrete. The workability of the materials was evaluated by measuring the slump flow diameter of the prepared specimens. The mixtures were designed to achieve a consistency class of F3 or higher according to EN 206-1, to ensure a high filling ability and facilitate movement. Appropriate amounts of superplasticizers and viscosity-enhancing admixtures were added to achieve the targeted flow diameter with each stable fresh mix.

Table 4 presents the measured slump values for the fiber-incorporated lightweight concrete mixes. The reference mix (LWC) exhibited a flow diameter of about 60 cm, which is considered ideal in the fresh state for this type of low-density concrete. In general, the workability of fresh concrete primarily depends on the self-weight of the material and the friction between particles. For lightweight concrete mixes, the reduced density minimizes the effect of self-weight, making particle friction the governing factor. In addition, the use of expanded glass (Liaver®) with a semi-spherical shape and smooth, glassy surface, along with a superplasticizer, helped significantly in achieving the targeted consistency class. However, the addition of PPF reduced the slump flow gradually, depending on the fiber dosage and type (short or long). As observed in Table 4, the higher fiber dosages

Table 4 Measured slump flow of different lightweight concrete mixes (unit: [mm])

Specimen	Slump flowStd.*
LWC	631.5
LWCF0–0.5	54.53
LWCF0–1	422
LWCF0.5–0	422
LWCF1–0	423
LWCF0.75–0.25	421
LWCF0.25–0.25	523
LWCF0.25–0.75	421
LWCF0.5–0.5	402.5

*Std.: standard deviation

(1.0 vol.-%) in LWCF0–1, LWCF1–0, LWCF0.25–0.75, LWCF0.75–0.25, and LWCF0.5–0.5 notably reduced the slump flow from about 60 cm to 40 cm, even with the addition of superplasticizers. At higher fiber dosages, fiber interlocking hinders the movement of fresh concrete, reducing workability, as shown in Fig. 5. The effect largely depends on the dosage and type of fiber: LWCF0–0.5 and LWCF0.25–0.25 performed better in the fresh state than mixes with higher dosages. The slump flow of LWCF0.5–0, which contained 0.5 vol.-% of short fibers, was similar to that of the samples with 1.0 vol.-% of short fibers. This indicates that the inclusion of short fibers tends to affect the workability more than the inclusion of long fibers, because a greater number of fibers are included in the sample in the former case, which creates larger fiber surfaces and exacerbates the interlocking effect. This tendency can also be confirmed by comparing the slump flow values of LWCF0.25–0.75 and LWCF0.5–0.5. The results confirm that the inclusion of fibers reduces the workability of LWAC significantly, and this trend becomes more pronounced with increasing fiber volume and greater proportions of short fibers.

4.2 Oven dry density and dry shrinkage

The targeted theoretical dry density was 800 kg/m^3, considering that the chemically bound water is in the range of 0.2–0.22 wt.-% (Taylor, 1997). The oven dry density of concrete was measured using cubical samples. All the LWAC samples were dried in an oven at 110±5°C to ensure the complete removal of evaporable water, until the mass change was within 0.2 wt.-%. Fig. 6 presents the measured dry densities of the fiber-incorporated lightweight concrete mixes. The reference mix exhibited the highest dry density among the samples, at 813 kg/m^3. With the addition of 0.5% of long fiber (e.g., LWCF0–0.5), the density decreased by 3% to about 788 kg/m^3, due to the fibers interlocking and creating voids; this compromised the efficient filling of the fresh mixture. The

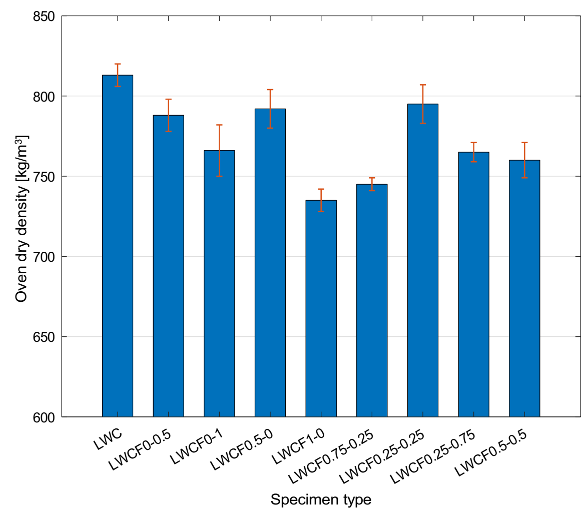

Fig. 6 Oven dry density of ultra-lightweight concrete with PPF

result was similar with the same content of short fiber (mix LWCF0.5–0). Increasing the fiber content to 1%

(a) (b)

Fig. 5 Slump flow of lightweight concrete specimens: **a** reference mix, **b** mix with PPF

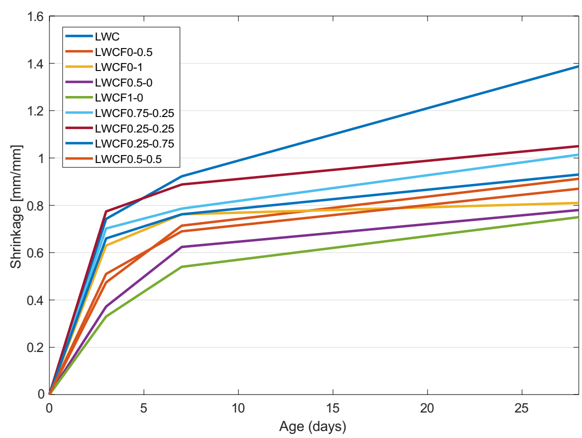

Fig. 7 Dry shrinkage of ultra-lightweight concrete with PPF

resulted in a significant reduction in concrete density for the aforementioned reason. The dry density of concrete is a material characteristic that strongly depends on the ratio between the volumes of voids and solid material. In general, the density of lightweight concrete decreases as more lightweight aggregates are incorporated, due to their lower density compared with the binder. In addition, the use of fiber can have a marginal effect on density if the optimum dosage is used with a homogeneous distribution. However, a high fiber content tends to cause clumping and internal gaps between aggregate particles, preventing the cement paste from passing through and consequently reducing the density.

A high dry shrinkage significantly limits the applicability of LWAC in construction. As in conventional concrete, the incorporation of fibers can mitigate volumetric changes in LWAC. For the shrinkage test, the Graff–Kaufmann method was used according to DIN 52450. For the measurements, three prismatic samples with dimensions of 40×40×160 mm^3 were prepared and tested directly after demolding. The concrete specimens were cured in a controlled chamber at a temperature of 20±1°C and a relative humidity of 65% during the testing period of 1, 3, 7, and 28 days. Fig. 7 shows the corresponding results for all mixes according to the curing age, which clearly indicate that the dry shrinkage increased with age for all mixes. Up to 7 days, the dry shrinkage of all mixes followed a similar trend, although the mixes with fibers tended to show slightly lower values. However, the 28-day shrinkage of the reference mix (LWC) was ~1.4 mm, which is about 40% higher than that of the fiber-incorporated mixes; this is consistent with findings from another study (Saleh et al., 2022). In general, the dry shrinkage of lightweight concrete is much higher than that of conventional concrete due to the low elastic modulus of lightweight aggregate, which plays an important role in constraining the movement of the material. The results confirmed that the incorporation of PPF significantly reduces dry shrinkage, particularly at later ages. In particular, for the same fiber content, specimens with a larger proportion of short fibers tend to have a lower dry shrinkage than those with a larger proportion of long fibers. As discussed in Sect. 4.1, the use of short fibers with the same volume provides greater interface area with the binder, effectively reducing shrinkage and hindering the free movement of the particles at all ages.

4.3 Compressive and flexural strength

The strength of materials is directly correlated with the volume of pores within them, and LWAC typically exhibits higher void contents and lower strength than traditional concrete. To overcome this limitation, careful selection of concrete constituents is required. Expanded glass was used as the lightweight aggregate due to its high crushing strength-to-density ratio compared with other alternatives, such as expanded clay or natural lightweight aggregates. Through a suitable packing algorithm, FA and SF were used to enhance workability and the cohesion of the aggregate particles with the binder, which improved the strength of the materials, as shown in Fig. 8. In addition, short and long PPFs were included to enhance the flexural performance of the LWAC.

Table 5 presents the 28-day compressive strength measured for the LWCF mixes. Among the samples considered, the LWC mix (without fibers) showed compressive strength of approximately 14.9 MPa, the highest value observed. This compressive strength, along with the dry density of the same mix (813 kg/m^3), confirms that the designed mix meets the structural application requirements outlined in EN 206 (LC12/13 and density above 800 kg/m^3). The incorporation of PPF resulted in a marginal decrease in strength for the mixes with 0.5 vol.-% of fibers. However, with higher dosages of up to 1 vol.-%, the strength decreased to about 12.3 MPa. This reduction is not directly related to the fibers themselves but rather to the secondary effects of fiber usage, such as increased clumping, interlocking, and the creation of voids within the concrete. The increased volume of voids, along with the reduced volume of the solid material, contributes to the reduction in compressive strength. Despite the decrease in strength for some mixes, all the mixes still exhibited compressive strengths higher than 12 MPa. Thus, the developed ultra-lightweight concrete is suitable for structural applications. The obtained results are comparable to those from a previous study employing specimens with similar densities (Yu et al., 2016), as shown in Fig. 9. This figure illustrates that most studies that have investigated concrete with a density of ~800 kg/m^3 report compressive strengths of 8–10 MPa. The

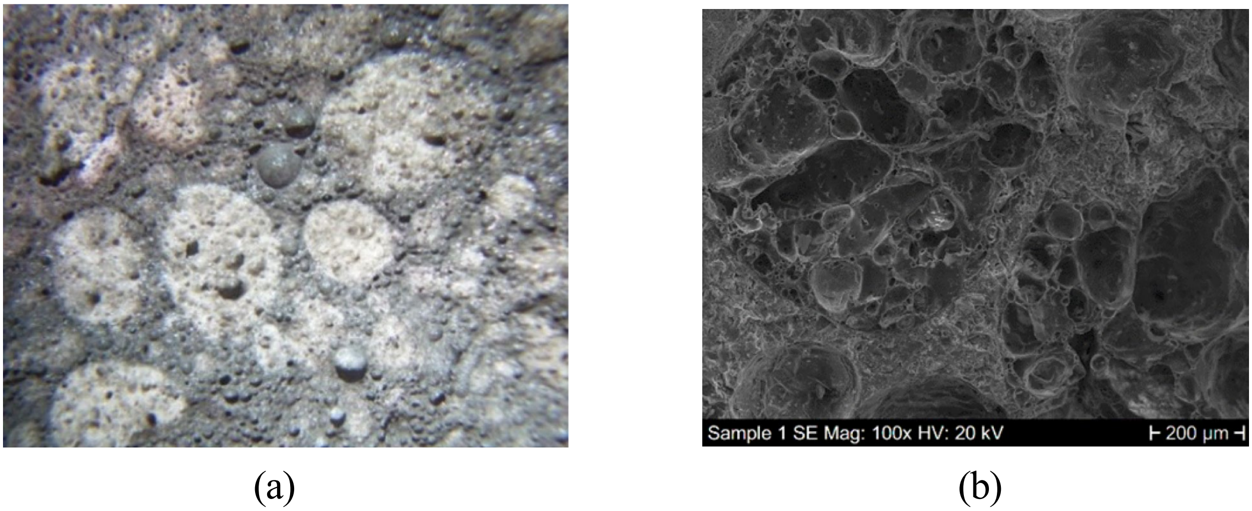

Fig. 8 Liaver® particle images confirming the adhesion between the aggregate and the binder: **a** light microscopy image, **b** scanning electron microscope image

Table 5 Compressive and flexural strength of ultra-lightweight concrete with PPF

Specimen	Strength [MPa]			
	Compressive	Std	Flexural	Std
LWC	14.9	0.8	1.92	0.08
LWCF0–0.5	14.5	0.4	2.22	0.15
LWCF0–1	13.1	0.6	2.80	0.10
LWCF0.5–0	14.0	1.1	3.01	0.08
LWCF1–0	13.7	0.5	3.24	0.15
LWCF0.75–0.25	13.1	0.5	3.28	0.10
LWCF0.25–0.25	12.7	0.9	3.21	0.20
LWCF0.25–0.75	14.2	0.6	2.92	0.12
LWCF0.5–0.5	12.3	1.0	3.29	0.09

*Std.: standard deviation

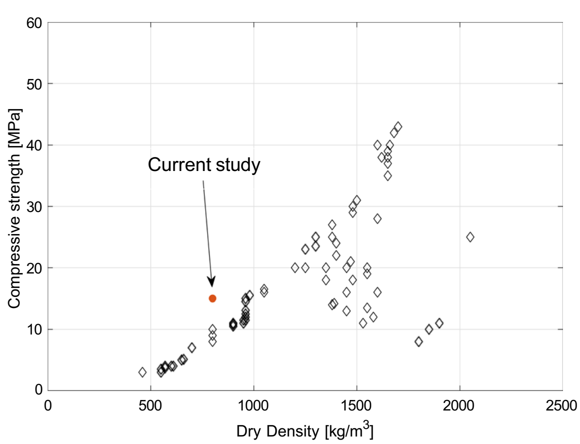

Fig. 9 Relationship of dry density and compressive strength of different lightweight concretes (Yu et al., 2016)

ultra-lightweight concrete developed in this study exhibited a compressive strength of 14 MPa, underscoring the significant role of the packing density concept in designing concrete with a specific density and high strength, even with the inclusion of fiber.

In addition to the compressive strength, the flexural strength of the concrete was measured. The flexural strength results for the LWAC mixes are presented in Table 5. Unlike with compressive strength, the incorporation of PPFs significantly improved the flexural strength in all cases. The reference mix without fibers (LWC) exhibited a flexural strength of about 1.9 MPa. With the addition of 0.5 vol.-% (LWCF0–0.5) and 1 vol.-% (LWCF0–1) of long fiber, the flexural strength increased to 2.2 MPa and 2.8 MPa, respectively. For the specimens with short fibers, the strength improvement was even more pronounced, with the values reaching 3 MPa and 3.2 MPa for dosages of 0.5 vol.-% (LWCF0.5–0) and 1 vol.-% (LWCF1–0), respectively. For the same fiber content, specimens with more short fibers contain a larger number of particles than those with more long fibers. This results in more fibers being distributed within the solid structure, which hinders crack development, as reflected in the flexural strength results for the mixes with both short and long fibers. While the influence of PPF on compressive strength was negative or marginal, it improved flexural strength by up to 60% over the reference mix. The corresponding results highlight the important role of fibers in changing the failure mode of concrete and increasing its ductility, as observed in the cross section of the broken sample obtained after the flexural test (Fig. 10b). In general, a direct correlation is observed between the compressive strength and the

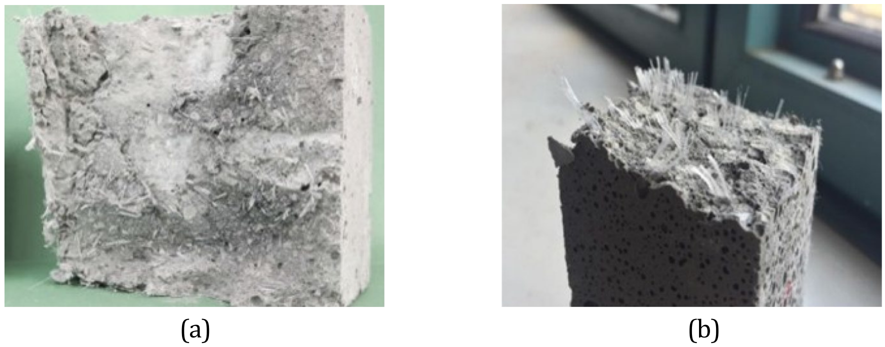

Fig. 10 Distribution of lightweight aggregates and PPF in broken specimen after **a** compressive and **b** flexural strength test

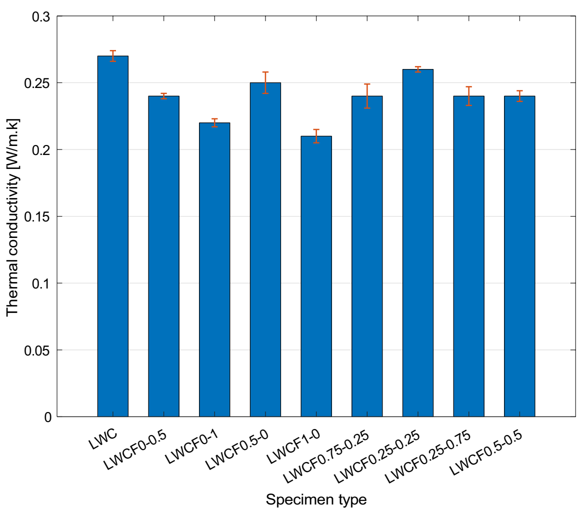

Fig. 11 Thermal conductivity of lightweight concrete with PPF

flexural strength in conventional lightweight concrete. However, the obtained results confirm that the relationship between these parameters can vary significantly depending on the type and content of fibers. The use of fibers restricts crack propagation, reduces stress concentration at crack edges, and delays crack growth, thereby improving the flexural strength of LWAC, particularly when more fibers are included for the same fiber volume.

4.4 Thermal conductivity

One of the main advantages of lightweight concrete is its superior thermal insulation. To verify this, the thermal conductivity of the specimens was measured using the Hot Disk device (Göteborg, Sweden) in accordance with ISO 22007-2. For accurate evaluation of the results and to account for the significant impact of moisture content on the thermal properties of concrete, all samples were oven dried until they reached a constant mass, before being cooled to room temperature in moisture-free conditions. Fig. 11 presents the thermal conductivity results of the mixes. The measured values ranged from 0.20 to 0.27 W/(m·K), which are significantly lower than that of conventional concrete (1.1 W/(m·K)) Neville (2012). In general, the heat flux of any material depends on the volume of the solid structure and is inversely related to the volume of internal pores. The high pore content in the lightweight aggregates led to the thermal conductivity of the LWAC being much lower than that of conventional concrete.

Among the specimens, the reference sample (LWC) exhibited the highest thermal conductivity, while the fiber-incorporated LWCF specimens exhibited lower values. For the LWCF samples, no clear trend was observed with respect to the fiber content. Instead, the thermal conductivity was primarily influenced by the dry density of the concrete; as the density decreased, the thermal conductivity also decreased due to the increased volume of pores. Although the difference was minor, the specimens with 0.5 vol.-% of short, long, or combined fibers showed higher thermal conductivity than those with 1.0 vol.-% of fibers. This suggests that a higher fiber content can enhance insulation performance by increasing the pore volume within the material.

4.5 Characterization using micro-CT

The characteristics of the LWAC samples were investigated using micro-CT data. As mentioned previously, the measured material properties of the LWAC samples were primarily related to the pore structures, and the pore characteristics of the specimens were examined using micro-CT. The image resolution was 16.03 μm, considering a representative volume element (RVE) to describe the material characteristics, which is sufficient to describe the microstructures of the specimens. The distribution of individual fibers is merged with pores, as the loss of resolution and image contrast needs be accounted for to reflect RVE. Fig. 12 shows the 3D volume of each specimen along with its pore distribution. The image on

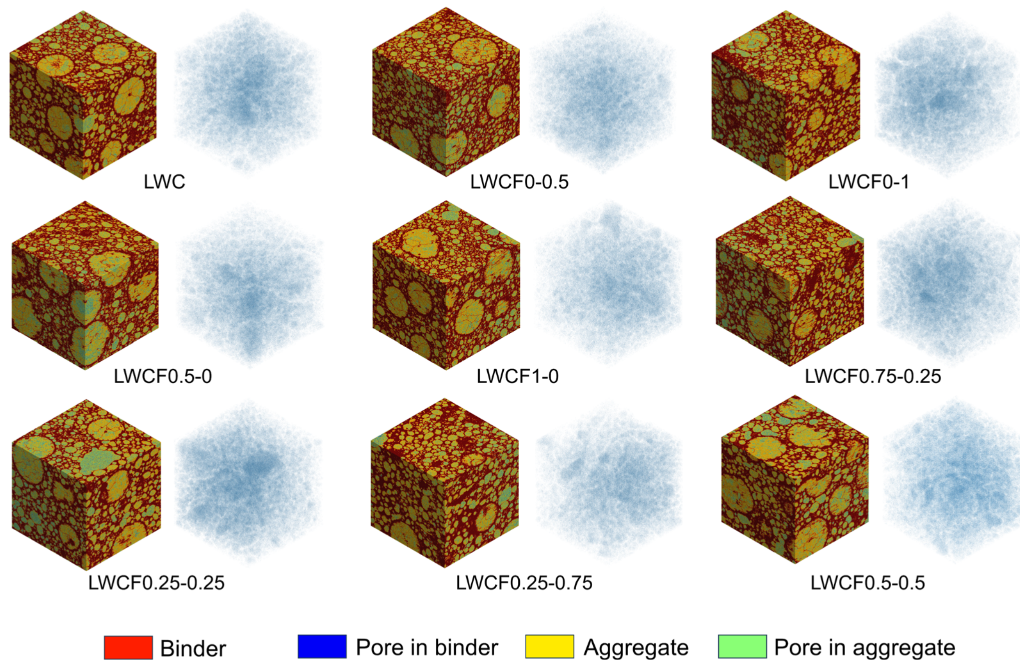

Fig. 12 Segmented RVE (left) and pores within aggregates (right) for each specimen

the left for each specimen presents the segmented volume, which is classified into four phases: binder, aggregate, pores in the binder, and pores in the aggregate. The image on the right separately shows only the pores within the lightweight aggregate particles. As seen in this figure, most of the pores were in the lightweight aggregates rather than in the binder; this indicates that the pore characteristics of LWAC strongly depend on the properties of the lightweight aggregate.

For a quantitative analysis, the porosities of the aggregate and binder were computed using the micro-CT data. Fig. 13 presents the porosity of each component in the LWCF specimens, showing that the total porosity was the lowest in the reference specimen. The dry density tended to decrease in the specimens with higher fiber contents due to the interlocking of the fibers and the creation of voids, which manifested in pores. For similar reasons, the compressive strength of the ultra-lightweight concrete specimens also decreased with increasing fiber content. These findings suggest that higher fiber contents tend to generate more pores within the material, and this tendency is reflected in the porosity observed in the total porosity and binder porosity results. Most specimens showed similar porosity in the aggregate since the amount of lightweight aggregates used was the same. In terms of binder porosity, the samples with 1 vol.-% of fibers tended to exhibit larger values, which could be due to the effects of the fibers. These results confirm that the inclusion of PPF can increase porosity.

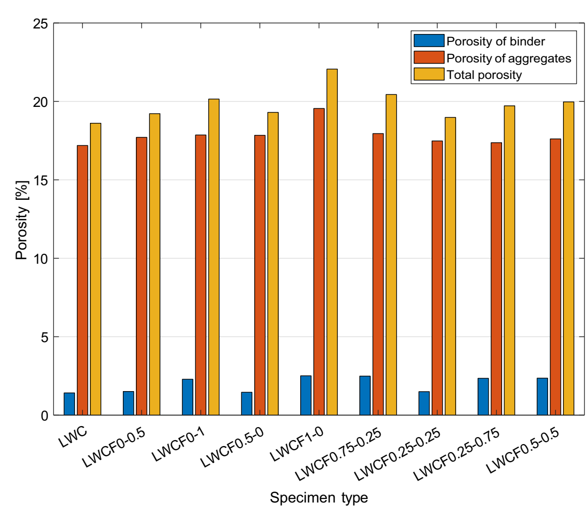

Fig. 13 Porosity distribution of each sample according to its components

For a more detailed investigation of the effects of the fibers on the pore characteristics, the tortuosity of the samples was examined. Tortuosity is an index of the complexity and indirectness of pore networks and their curvature, and it is used to characterize pore pathways in LWAC (Chung et al., 2021; Shanti et al., 2014). The smallest value of tortuosity is 1, which indicates a perfectly straight pore path, and the value increases as the pore pathway becomes more complex and indirect.

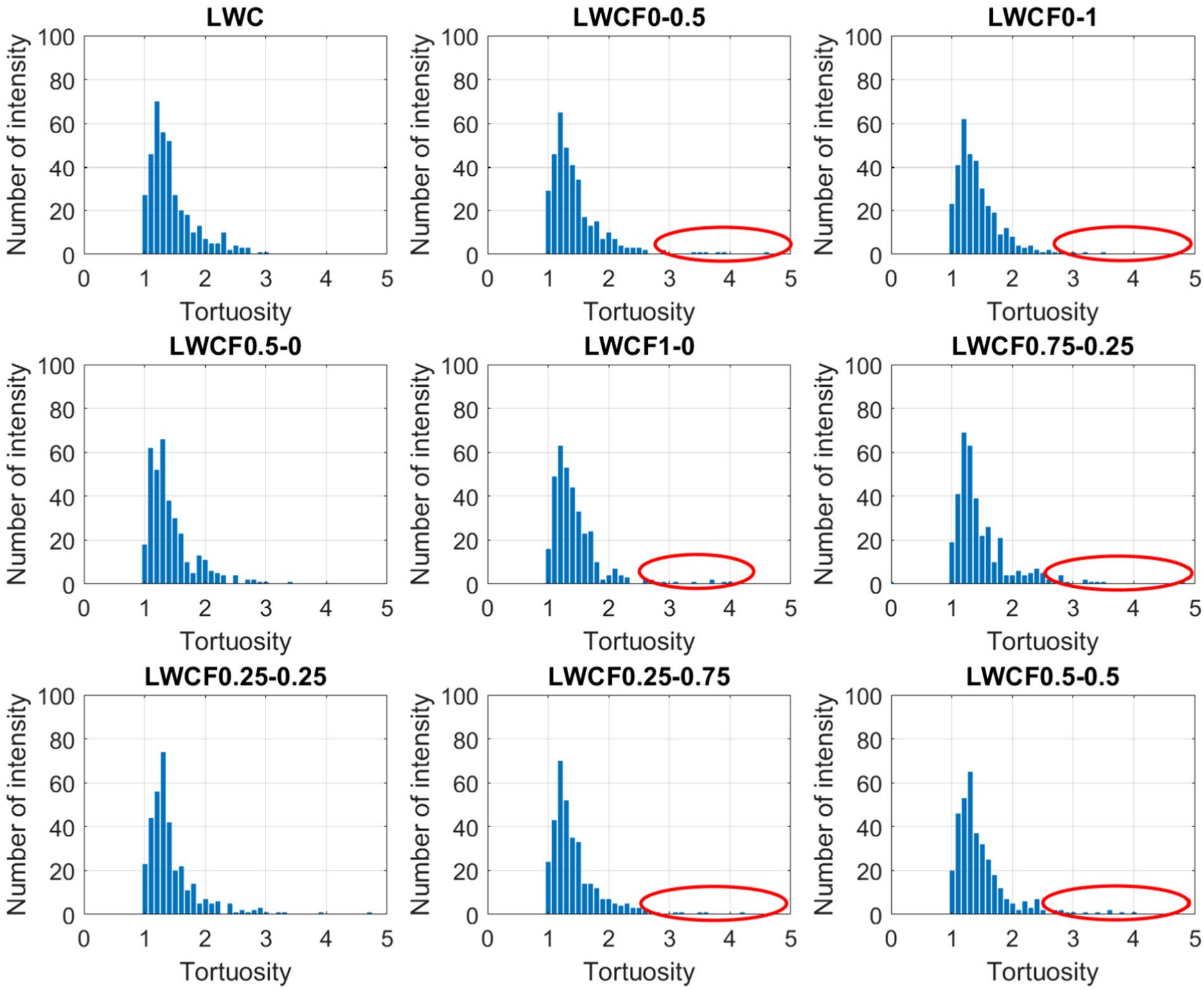

Fig. 14 Tortuosity distribution of each specimen

To compute the tortuosity, both the binder and aggregate porosities were considered together. Fig. 14 shows the tortuosity distributions depicting consistent trends across all samples. Most tortuosity values were between 1 and 2, indicating that the dominant pores can be assumed to be closed pores. However, tortuosity values larger than 3, marked in red, were observed for the specimens with PPFs, particularly with long fibers; these values indicate an indirect pore path, assumed to be interconnected pores including the fiber region. In contrast, the reference specimen rarely showed large tortuosity values. Overall, the pore characteristics, including tortuosity, confirm that PPF can act as pores and affect the pore structures within the material: this reduces the values of specific material properties, such as compressive strength and dry density, while significantly enhancing the flexural performance of LWAC.

5 Conclusions

The main objective of this study was to develop optimized ultra-lightweight concrete mixtures with a dry density of 800 kg/m^3 and with appropriate mechanical and physical performance. Several mixes were developed and evaluated, and the findings lead to the following concluding remarks:

- The packing density concept is effective for design concrete mixtures with very low density and satisfactory characteristics in the fresh and hardened states. Due to its properties, expanded glass is a suitable lightweight aggregate for achieving adequate workability and high mechanical performance.
- By optimizing the mixture proportions, the reference mix exhibited a self-leveling ability with a compres-

sive strength of approximately 15 MPa. Incorporating up to 0.5 vol.-% of PPF had marginal influence on dry density, while higher dosages led to a significant reduction in density due to the clumping and interlocking of the fibers.

- The incorporation of PPF has a marginal influence on compressive strength but significantly influence on flexural strength, which increased by about 60% in the studied specimens. In addition, the dry shrinkage was significantly reduced to about 50% of that of the reference mix when PPF was incorporated. Thermal conductivity is a material characteristic that mainly depends on density and the volumetric proportions of the solid structure and voids. Better mechanical and thermal properties can be expected from specimens with optimized proportions of long and short fibers.
- The effect of PPFs on pore characteristics, including tortuosity, was examined using micro-CT. The obtained results confirm that as PPFs with low density act as pores within specimens, their inclusion can reduce the dry density and compressive strength of the materials, which are strongly related to the pore structures.

This investigation provides a foundation for the development of very-low-density fibrous LWAC with acceptable mechanical performance for structural applications in accordance with EN standards. In addition to the current study, it is still important to investigate other aspects of lightweight concrete such as chloride diffusion and moisture transfer in various environmental conditions, which can be performed in further studies.

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S.Y.C.: ideas, methodology, validation, data curation, supervision, writing—original draft, and review & editing. S.E.O: validation, formal analysis, data curation, writing—original draft, and review & editing. P.S.: investigation, validation, and writing—review & editing. D.S.: ideas, validation, and review & editing. M.A.E: ideas, validation, conceptualization, and writing—review & editing. H.A.K.: ideas, validation, data curation, and review & editing.

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Declarations

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