

Article

Macro-Properties and Microstructures of Foam Concrete Containing Porosity Sludge Gasification Particles

Manman Yang ^{1,2}, Zhiyong Li ³, Yunlei Wang ², Kele Wang ¹, Juntao Ma ² and Fenglan Li ^{1,*}

¹ Xuchang Innovation Center of Low-Carbon and Eco-Building Materials Technology, Zhongyuan Institute of Science and Technology, Zhengzhou 450042, China; yang@zykj.edu.cn (M.Y.); wangkele@zykj.edu.cn (K.W.)

² International Joint Research Lab for Eco-Building Materials and Engineering of Henan, North China University of Water Resources and Electric Power, Zhengzhou 450045, China; wangyunlei1999@163.com (Y.W.); majuntao@ncwu.edu.cn (J.M.)

³ Zhengzhou Wastewater Purification Co., Ltd., Zhengzhou 450045, China; lizhiyonghyb@163.com

* Correspondence: lifenglan@zykj.edu.cn

Abstract

Aiming to enhance environmental sustainability and cost-effectiveness, a new foam concrete was created by utilizing sludge gasification particles (SGPs) as a partial replacement of cement. This study assessed the impact of SGPs content (0–30%) on the dry density, compressive and flexural strengths, drying shrinkage, thermal conductivity and pore structures of foam concrete. The results indicate that the designed foam concrete met the A07 density grade and FC3~FC2 strength grade as per the technical specification of foam concrete in China code JGJ/T 341, while the thermal conductivity was 33.3% lower than the standard requirement. The inclusion of SGPs led to a reduction in compressive strength by 35.2–52.6% and in flexural strength by 28.6–42.8%, while it resulted in a notable improvement in drying shrinkage with a reduction of 7.5–32.2%, and in thermal insulation performance with an increase of 17.3–23.4%. The foam concrete reached optimal performances with an SGPs content of 10%. Microscopic analysis revealed that SGPs increased the porosity and average pore diameter while altering the pore morphology towards large and more irregular shapes. These findings suggest that SGPs with optimal content can contribute to producing low-carbon, thermally efficient, and dimensionally stable foam concrete that is suitable for sustainable construction.

Keywords: foam concrete; sludge gasification particles; drying shrinkage; thermal conductivity; pore structure; mechanical property



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1. Introduction

In recent years, with increasing attention to the ecological sustainability of environment and global climate, the use of energy-efficient and low-carbon materials has become a cornerstone of construction policies worldwide [1,2]. As is known, the construction industry has high resource consumption and carbon emissions, accounting for 36% of global energy consumption and 39% of CO₂ emissions [3,4]. Therefore, innovative solutions are urgently required to align with decarbonization targets. Foam concrete or cellular concrete is a lightweight, porous cementitious material with an artificially entrained porous structure [5–7], having a porosity over 50%, a density less than 1600 kg/m³, higher thermal insulation, and an inherent reaction to fire [8]. It is a promising candidate for use in structural and non-structural applications to improve comfort in buildings with lower energy

consumption and higher environmental friendliness [9–11]. However, it is prone to cracking due to the significant drying shrinkage (0.6–1.2%) and volume instability, hindering its widespread application [12,13].

Current strategies to mitigate the disadvantages of foam concrete focus on optimizing water to cement ratio [13,14], adding mineral admixtures such as fly ash, silica fume and alkali slag [15–17], introducing functional aggregates [18–20], or admixing polyethylene powder [21]. Among them, aggregate modification in appropriate particle dosing presents particularly compelling advantages to maintain mechanical properties with reduced cement content and shrinkage [8,22,23]. However, critical tradeoffs are involved in its practical implementation, since excessive aggregates compromise mechanical integrity, and conventional sand additives face segregation issue caused by density mismatches [24]. This drives a growing interest in lightweight aggregates (LWAs) to solve this kind of technical problem. LWAs, including expanded perlite and glass sand [6], recycled waste and byproducts [7], expanded clay aggregate [25] and other kinds [26], benefit hygroscopic variants, causing a 20–40% reduction in shrinkage with internal curing. Solid waste derivatives such as recycled glass and fly ash microspheres lead to a 30% reduction in cement with a slight impact on mechanical performances [6,7,27]. Porous architectures (biochar) enhance thermal insulation via multiscale pore coupling [28]. However, the production of LWAs also faces more critical constraints, such as the geographical limitations of natural LWAs like pumice, the intensive energy consumption of artificial LWAs sintered over 800 °C, and the strength degradation over 50% for waste-derived aggregates with a weakened interfacial transition zone [29]. It is urgently required to find LWAs with a combination of environmental sustainability, low carbon production, and multi-functional performance enhancements.

As such, the utilization of sludge in municipal sewage plants to produce LWAs comes into focus as a means of addressing environmental protections, since urban sludge management faces a growing challenge with global annual production exceeding 100 million tons [30]. A sludge pyrolysis gasification technology has been developed which can convert 90% of sludge mass into reusable byproducts at 500–700 °C, creating sludge gasification slags [30,31]. Through a process of crushing and screening, sludge gasification particles (SGPs) are made for application in building construction [32,33]. Researches demonstrated that SGPs have lightweight characteristics with porosity and moderate strength, and can improve thermal resistance by 18% when used as a fine aggregate in mortars compared to river sand and manufactured sand [32,33]. When applied in cement-stabilized macadam, SGPs presented a superior water absorption–desorption capacity, with a significant synergistic effect on cement hydration to maintain the compressive strength of the macadam [34,35]. For autoclaved aerated concrete, a 65% SGPs substitution achieved a density reduction (569 kg/m^3) while maintaining strength [36]. Meanwhile, SGPs can be used for preparing the backfill concrete, completely replacing the coarse and fine aggregates used in conventional concrete [37], and producing high-strength concrete for structural engineering [38]. This laid the foundation for the application of SGPs in lightweight-aggregate concrete.

Therefore, SGPs like LWAs, with an internal curing function, have the potential to improve the volume stability with reduced shrinkage in foam concrete. This creates an innovative product of foam concrete with SGPs as a constituent, enhancing the cracking resistance to shrinkage and the thermal isolation. Focusing on this target, this paper presents an experimental study to assess the effects of different contents of fine SGPs on the properties of foam concrete. Using a stereomicroscope and image processing technology, the micro structure of foam concrete was quantitatively analyzed to explore the modification mechanism of SGPs with irregular morphology and surface porosity. The findings provide

a support of the utilization of SGPs in a new foam concrete, reaching a targeted design of stabilized bubble networks in designed foam concrete.

2. Experimental Work

2.1. Materials

2.1.1. Properties of Cement

The cement was ordinary commercial Portland cement of grade 42.5 MPa. The main chemical compositions were determined using the methods specified in China code GB/T 12960 [39], and results are summarized in Table 1. The basic physical properties were determined using the methods specified in China code GB/T 175 [40], and results are summarized in Table 2.

Table 1. Main chemical composition and content of cement.

Chemical Composition	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	SO ₃	K ₂ O
Content/%	20.61	4.03	62.07	3.25	4.15	2.13	0.84

Table 2. Basic physical properties of cement.

Specific Surface Area (m ² /kg)	Apparent Density (kg/m ³)	Setting Time (min)		Flexural Strength (MPa)		Compressive Strength (MPa)	
		Initial	Final	3 d	28 d	3 d	28 d
353	3046	219	275	4.6	8.5	27.1	46.2

2.1.2. Character of SGP

The original SGPs obtained from a sewage treatment plant in Zhengzhou is shown in Figure 1a. It was crushed and sieved through a 2.36 mm sieve. The crushed SGPs are shown in Figure 1b. In accordance with the specifications of China code GB/T 17431.2 [41], the basic physical properties and the sieve analytic curve of SGPs are presented in Table 3 and Figure 2. The distribution of particle size of SGPs was basically uniform.

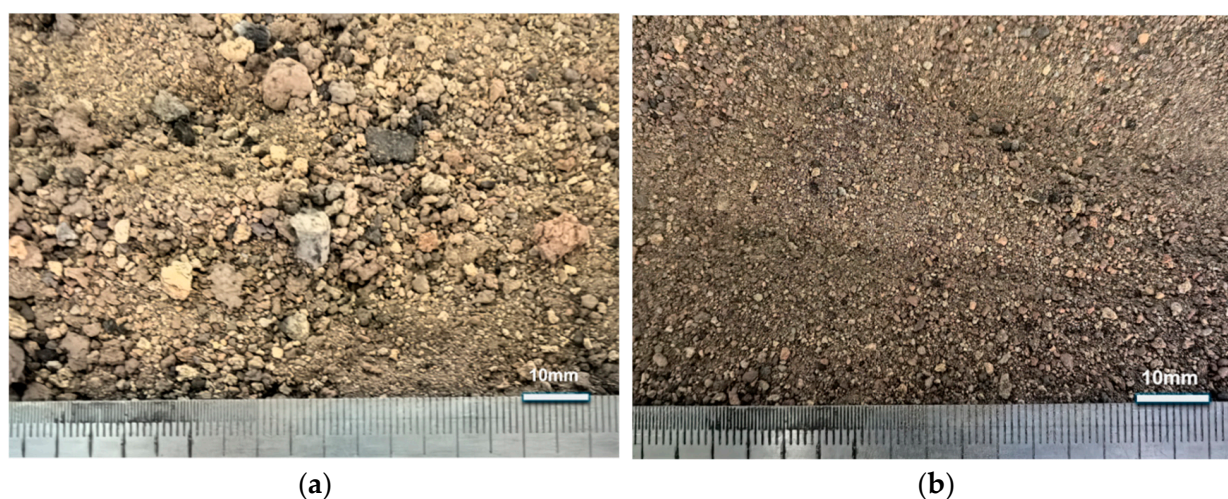


Figure 1. Photos of original and treated SGPs. (a) Undisturbed particle; (b) particles after crushing and screening.

Table 3. Basic physical properties of SGPs.

Aggregate	Fineness Modulus	Apparent Density (kg/m ³)	Bulk Density (kg/m ³)	Saturated Surface-Dry Water Absorption (%)
SGP	2.0	2094	1073	5.47

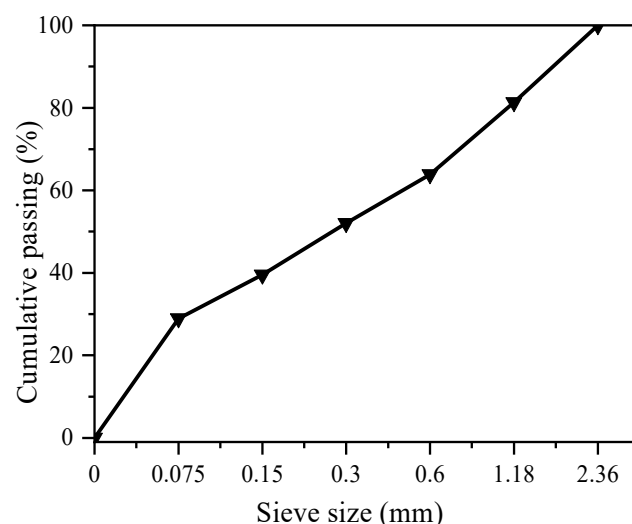


Figure 2. Sieve analytic curve of SGPs.

Figure 3 depicts the microstructure of SGPs detected using Zeiss Gemini Sigma 300 scanning electron microscopy (SEM) (Carl Zeiss AG, Germany), which shows that the interior of SGPs is highly porous and the pore size is mostly between approximately 20 and 200 μm . The high porosity explains its high absorption rate and low apparent density. The chemical components of SGPs were measured with the grounded powder referencing the specification for testing the constituents of cement specified in China code GB/T 12960 [39], and results are listed in Table 4. Figure 4 shows the XRD results of SGPs which include quartz, feldspar and hematite. The narrow and intense peaks of quartz indicate high crystallinity of SGPs, and the appearances of broaden peaks and humps reveal the amorphous phases contained in SGPs.

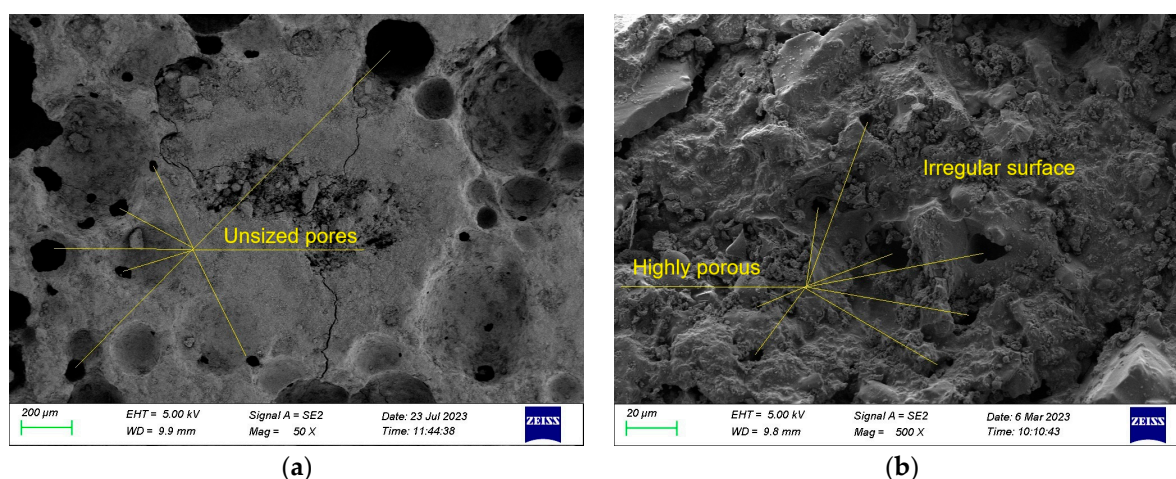


Figure 3. SEM morphology of SGP: (a) unsize pores; (b) highly porous and irregular surface.

Table 4. Main chemical composition of SGPs (by weight, %).

Chemical Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	MnO	TiO ₂	P ₂ O ₅
Content (%)	47.27	15.23	4.66	3.65	7.31	1.48	2.14	0.1	0.56	11.67

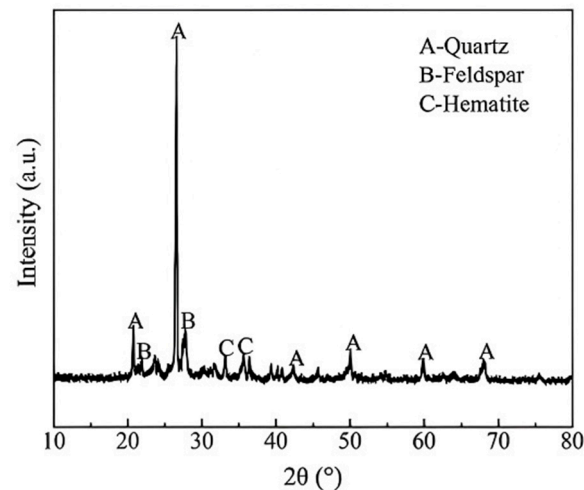


Figure 4. XRD analysis of SGP.

2.1.3. Properties of Superplasticizer and Foaming Agent

A high-performance polycarboxylate superplasticizer was used with a solid content of 35.6% and a water reduction of 30%.

A composite ether foaming agent was used with properties listed in Table 5. The foaming agent was diluted with tap water at a ratio of 1:80 in a plastic container, using the physical foaming method by cement paste stirring machine to prepare the foam for foam concrete.

Table 5. The performance index of foaming agent.

Solubility (%)	Bulk Density (g/L)	pH	Dilution Ratio	Settlement After 1 h (mm)	Bleeding Rate After 1 h (%)
100	32–44	7.5	1:80	21	32

2.2. Preparation of Foam Concrete

The foam concrete was designed with a dry density of $700 \pm 50 \text{ kg/m}^3$ at a grade A07 according to China code JGJ/T 341 [42]. The water to cement ratio was 0.35. With a similar expected dry density of foam concrete with/without SGPs, and referencing existing studies on foam concrete with lightweight aggregates or polyethylene powder at comparable dry density [21,26], the content of SGPs replacing cement varied for 10%, 20% and 30% total mass of cement-water mixtures (Table 6), while the corresponding specimens were denoted as SGFC_10, SGFC_20 and SGFC_30. Meanwhile, the basement of foam concrete produced with cement paste and foam was used as a reference, denoted as CFC. The superplasticizer was employed at 0.5% of cement dosage.

Table 6. Mix proportion design of foam concrete.

Symbol	SGP Mass Fractions (%)	Cement (kg/m ³)	SGP (kg/m ³)	Water (kg/m ³)	Foam (kg/m ³)	Superplasticizer (kg/m ³)
CFC	0	583.3	0	204.1	58.34	2.92
SGFC_10	10	513.9	69.3	179.8	59.63	2.57
SGFC_20	20	459.3	124.1	160.7	60.66	2.30
SGFC_30	30	415.1	168.1	145.3	61.48	2.07

The flow chart of test block preparation is shown in Figure 5. The molds were covered with plastic sheets and cured for 48 h before demolding. After removal from molds, the specimens were placed in a standard curing room for 28 days.

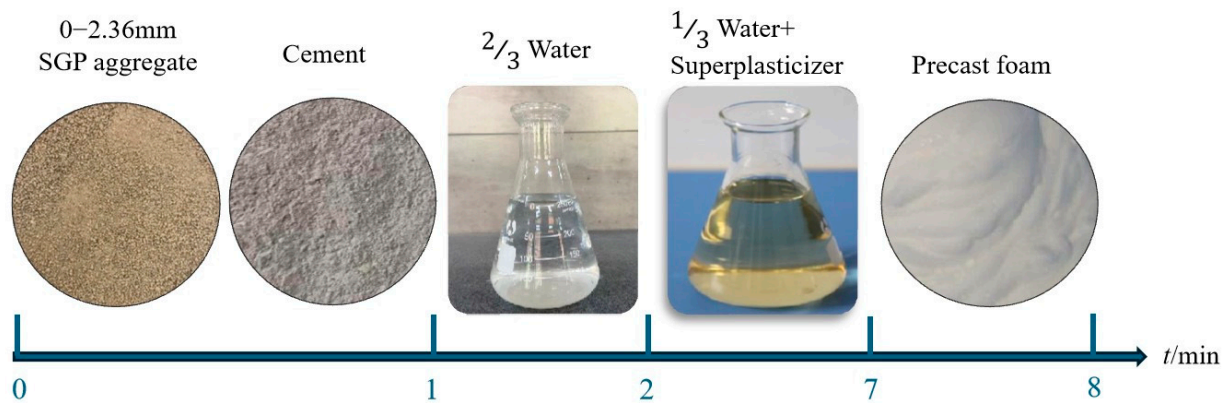


Figure 5. Mixing procedure of foam concrete.

2.3. Test Methods

2.3.1. Test for Dry Density

The dry density of foam concrete was determined in accordance with the China code JGJ/T 341 [42]. The specimens were the cubes with a dimension of 100 mm, three of them as a group. The dry mass was recorded when the specimens were dried to constant mass in an oven at temperature $(60 \pm 5)^\circ\text{C}$, the dry density was calculated with the mass divided by volume of specimen.

2.3.2. Tests for Mechanical Properties

The compressive and flexural strengths of foam concrete were evaluated at the curing age of 7 and 28 days, following the standards outlined in China code GB/T 17671 [43]. The mechanical property testing equipment is shown in Figure 6a. Using $40\text{ mm} \times 40\text{ mm} \times 160\text{ mm}$ prism specimens, three of them as a group, the flexural strength was determined on a 5 kN cement mortar strength testing machine under a loading rate of $(50 \pm 10)\text{ N/s}$, the average of a group was used as the test result. Upon completion of the flexural strength test, the fractured halves of the specimens were tested on the 200 kN pressure testing machine with a loading rate of $(2.4 \pm 0.2)\text{ kN/s}$, the average of six results were used to assess compressive strength.

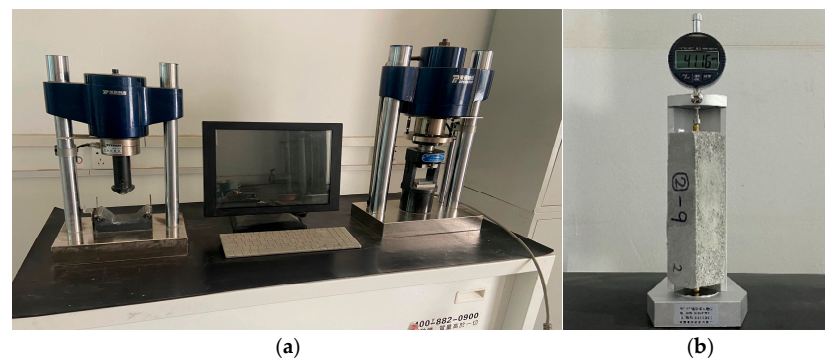


Figure 6. Tests for mechanical properties and drying shrinkage of foam concrete: (a) compressive and flexural testing machine; (b) drying shrinkage test.

2.3.3. Test for Drying Shrinkage

The drying shrinkage of foam concrete was detected using prism specimens of $40\text{ mm} \times 40\text{ mm} \times 160\text{ mm}$, two specimens as a group, following the procedure specified in China code GB/T 11969 [44]. After removing the mold, specimens were immersed in a water tank at a temperature of $(20 \pm 2)^\circ\text{C}$ for 72 h, and then they were removed from the water, and wiped off surface moisture to measure initial length. After that, they were placed in a curing box with a temperature of $(20 \pm 2)^\circ\text{C}$ and a relative humidity of $(45 \pm 5)\%$. The

drying shrinkage rates of foam concrete were measured at curing age of 3, 7, 14, 21, 28, 56, 90 days, respectively (Figure 6b).

2.3.4. Test for Thermal Conductivity

The thermal conductivity of foam concrete was tested using a Hot Disk Analyzer (Hot Disk AB, Gothenburg, Sweden) with the transient plane heat source method [45]. The 5501 F1 probe of the analyzer was placed between two cubic specimens with dimensions of 40 mm, as shown in Figure 7. The detection depth was set to 12.5 mm with a period of 160 s. The average of two test results was taken as the thermal conductivity.

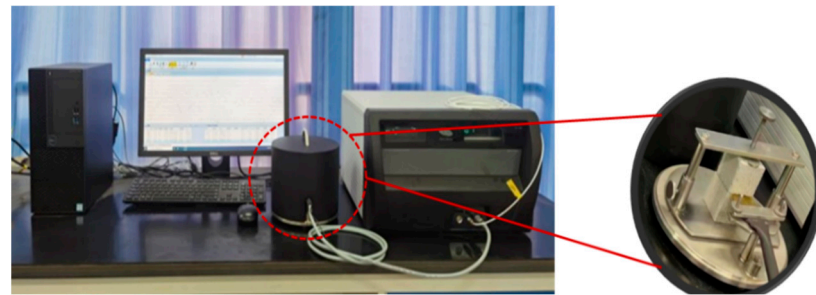


Figure 7. Hot Disk thermal conductivity analyzer.

2.3.5. Pore Structure Detection and Analysis

The internal structure of foam concrete was detected using porosity analysis, pores distribution test and scanning electron microscopy (SEM). The porosity analysis and pore distribution tests employed an XTL-BM-8TD stereomicroscope (Shanghai BM Optical Instruments Manufacturing Co., Ltd., Shanghai, China) and Image-Pro Plus image (IPP) analytic software 1.0. The foam concrete was cut and polished (Figure 8a), and the samples were dried and blackened. The pores of the samples were filled with nano-calcium carbonate powder, creating high-contrast black/white observation surface to make accurate image analysis (Figure 8b). The sample images were taken by XTL-BM-8TD stereomicroscope (Figure 8c) [46]. These images were processed and analyzed using IPP. The pore structure (Figure 8d) was investigated using SEM, as shown in Figure 8e, after curing for 28 days.

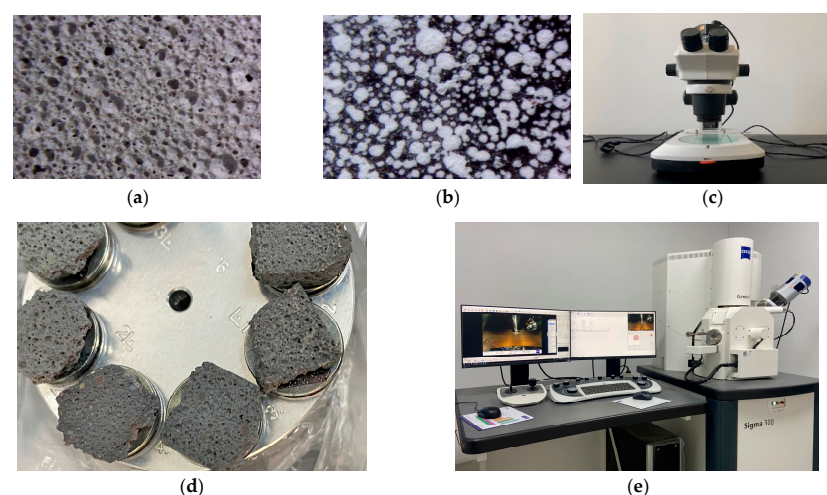


Figure 8. Pore structure detection and SEM analysis: (a) polished section; (b) pore-filled section; (c) XTL-BM-8TD stereomicroscope; (d) SEM samples; (e) SEM equipment.

3. Results and Analyses

3.1. Dry Density of Foam Concrete

The tested dry density of foam concrete with 0, 10%, 20% and 30% SGPs was 702 kg/m³, 698 kg/m³, 677 kg/m³ and 681 kg/m³. They all fall into the range 650~750 kg/m³ specified for the dry density of A07 foam concrete in China code JGJ/T 341 [42]. This indicates that the mix proportion design of foam concrete reached the target A07 grade of dry density. Meanwhile, a tendency exists on dry density, which decreases with the increased content of SGPs, although samples in this study reached similar density.

3.2. Mechanical Properties of Foam Concrete

Figure 9 shows the test results of compressive and flexural strengths of foam concrete, with standard deviations within 0.15~0.25 MPa for compressive strength, and 0.05~0.09 MPa for flexural strength. They all fall into the limit specified in China code JGJ/T 341 [42]. Generally, the strengths increased with the curing age because of the continuous cement hydration, whereas they both gradually decreased at the same curing age with an increase in SGP content. Compared with CFC at a curing age of 28 days, the SGFC_10, SGFC_20, and SGFC_30, respectively, decreased in compressive strength by 35.2%, 42.1%, and 52.6%, and in flexural strength by 28.6%, 35.7%, and 42.8%. This indicates that although the SGPs can provide strength as a skeleton of foam concrete, the partial replacement of cement with SGPs directly reduces the amount of cement for available hydration, leading to a weakened matrix of set cement. Meanwhile, the incorporation of SGPs destabilizes the pore structure in fresh mixture, causing smaller pores to coalesce into larger ones to reduce the load-bearing capacity of hardened foam concrete. This is similar with the observation in the foam concrete with sand as an admixture [23]. As the results, the final strengths of foam concrete came from the combined effect of these two functions, presenting a degradation over an enhancement.

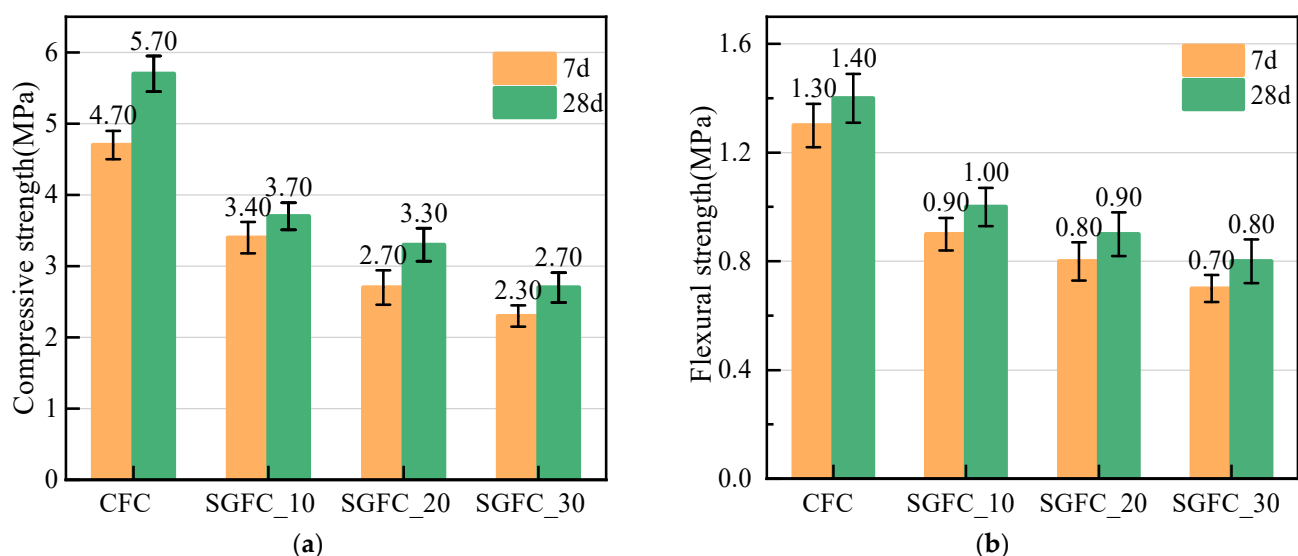


Figure 9. Effect of SGPs content on compressive and flexural strengths of foam concrete: (a) compressive strength; (b) flexural strength.

As per the specification of China code JGJ/T 341 [42], the strength grade of foam concrete with 0%, 10%, 20%, and 30% SGPs, respectively, satisfies FC5, FC3, FC3 and FC2 strength grades.

3.3. Drying Shrinkage of Foam Concrete

The effect of SGP content on the drying shrinkage of foam concrete is shown in Figure 10. The free water consumption and evaporation of foam concrete in the early stage of cement hydration caused a gradual increase in internal pressure in capillary pores, resulting in a sharp increase in shrinkage of foam concrete in the first 7 days [47]. With continuous hydration of cement and evaporation of free water, the relative humidity in the pores of foam concrete was close to the ambient humidity, and the drying shrinkage gradually slowed down. Therefore, drying shrinkage mostly occurred within the first 56 days, and minorly increased afterward.

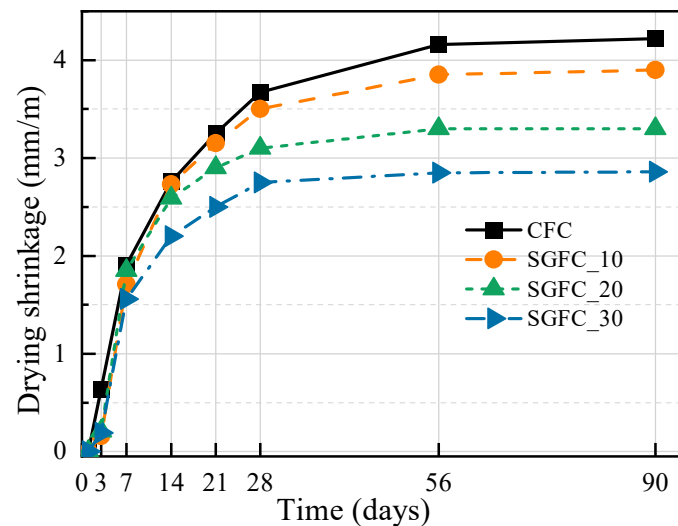


Figure 10. Effect of SGPs content on the drying shrinkage of foam concrete.

The drying shrinkage of foam concrete was insignificantly affected by the addition of SGPs at the early curing age before 7 days, whereas it gradually decreased with the increase in SGP content after the curing age of 14 days. At the curing age of 90 d, SGFC_10, SGFC_20, and SGFC_30 had a decrease in drying shrinkage by 7.5%, 21.0%, and 32.2%, compared to referenced CFC. Generally, the foam concrete with a higher content of SGPs had a marked decrease in drying shrinkage, whereas that with 10% SGPs presented a similar shrinkage development with the increase in curing age.

The shrinkage reduction can attribute to the presence of SGPs with two beneficial actions. One is to build a rigid skeleton to constrain the matrix deformation of foam concrete [19]. Another is the internal curing effect with porose microstructures, which stores mixing water in early age with a high capacity of water absorption, and gradually release water afterwards with its desorption capacity, mitigating the capillary moisture gradients to compensate the pore drying shrinkage. The mechanisms are similar to those of lightweight aggregates in foam concrete [22]. Therefore, with a reduction in cement used to prepare foam concrete, the incorporation of SGP benefits to improve the drying shrinkage of foam concrete.

3.4. Thermal Conductivity of Foam Concrete

Figure 11 shows the influence of SGP content on the thermal conductivity of foam concrete. SGFC_10, SGFC_20, and SGFC_30 had a decrease in thermal conductivity by 23.4%, 21.5%, and 17.3% compared to referenced CFC. This reduction can be attributed to SGPs, which increased the internal pores of foam concrete to prolong the heat conduction path with more tortuous, hindering the efficiency of heat conduction of foam concrete [48]. However, although adding the SGPs could create a decrease in thermal conductivity

of foam concrete, higher content of SGPs resulted in an increase tendency. When SGP content was 10%, the thermal conductivity of foam concrete was as low as 0.15 W/(m·K). When SGP content reached to 30%, the thermal conductivity of foam concrete increased to 0.16 W/(m·K). This indicates that a rational content of SGPs can improve the micro-structure of foam concrete with an even pore distribution, while a high content SGPs will increase the interface between SGPs particles and cement paste, leading to the pores merging and connecting with each other to increase the connection path of internal heat transfer, finally showing an increase in thermal conductivity [21].

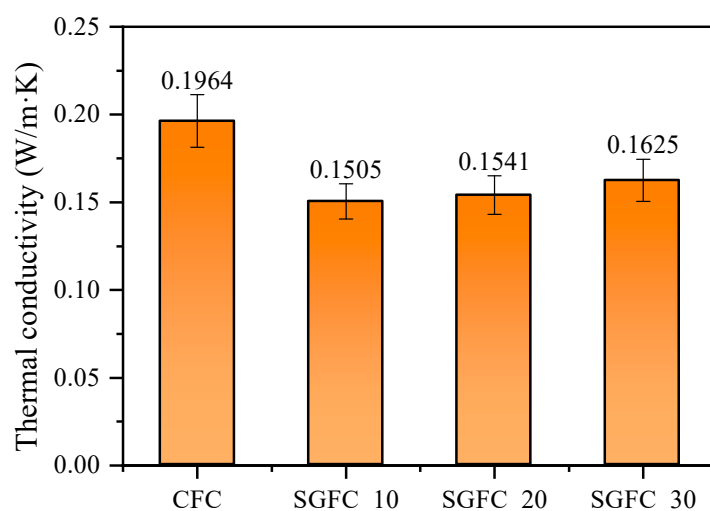


Figure 11. Measured thermal conductivity of foam concrete.

As per the specification of China code JGJ/T 341 [42], the thermal conductivity of foam concrete at A07 density grade should not be over 0.225 W/(m·K). Therefore, the foam concrete with 10%, 20%, and 30% SGPs is superior in thermal insulation to standard requirements. Relatively, foam concrete with 10% SGPs reached a maximum reduction of 33.3% in thermal conductivity compared with the requirement.

3.5. Micro-Pore Structure of Foam Concrete

The mechanical properties, drying shrinkage, thermal conductivity and other properties of foam concrete relate to the porosity and the shape, size and distribution of pores in foam concrete. Normally, foam concrete with a uniform pore distribution exhibits better mechanical properties [49]. Based on the image-taking and -processing steps in the method section, the microscopic images of foam concrete samples are shown in Figure 12. Where Figure 12a shows the referenced foam concrete CFC, Figure 12b–d shows the foam concretes with 10%, 20%, and 30% SGPs. From these figures, the pores of foam concrete distributed more unevenly with the increase in SGP content. This can be further confirmed by the pore size distribution based on number of the foam concrete, as shown in Figure 13, which indicates that the inclusion of SGPs can destabilize the pores in fresh mixture, causing the smaller voids to merge into larger ones, because the increasing SGP content leads to a decreased portion of the large pores overall.

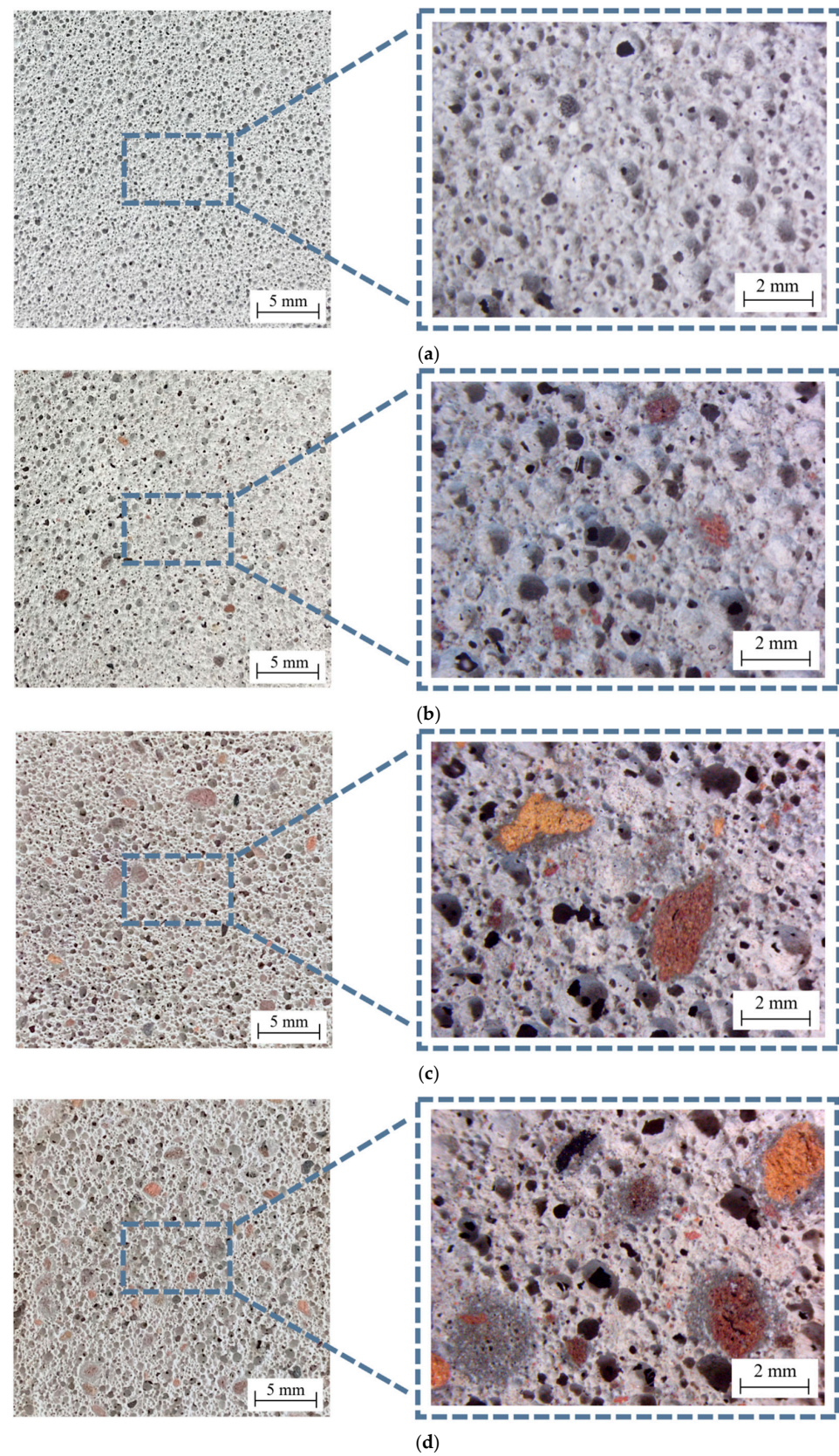


Figure 12. Microscopic images of the cross-section of foam concrete samples: (a) CFC; (b) SGFC_10; (c) SGFC_20; (d) SGFC_30.

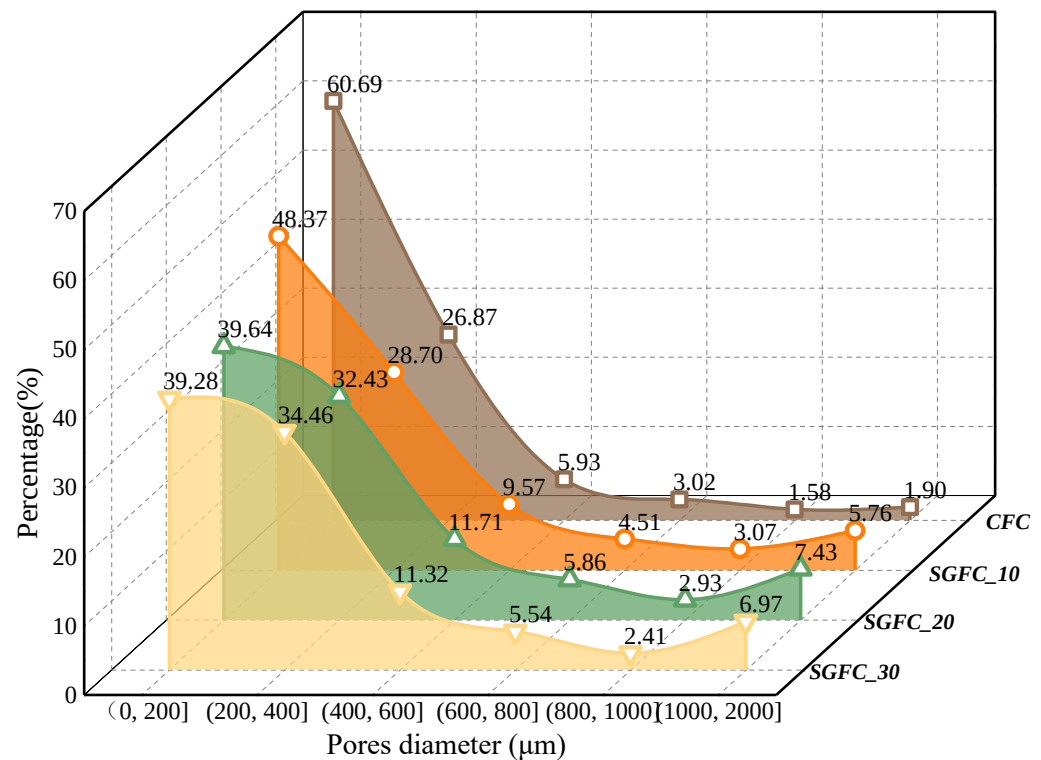


Figure 13. Pore size distribution of foam concrete.

Figure 14 presents the statistical average and median pore sizes of foam concrete. The average pore size was 337 μm , 405 μm , 448 μm and 487 μm , while the median pore size D50 was 167 μm , 207 μm , 248 μm and 252 μm for the foam concrete with the SGP content of 0, 10%, 20% and 30%, respectively. This indicates that the incorporation of SGPs had a significant effect on the pore size of foam concrete. In referenced CFC, a considerable number of 60.69% of pores were observed with a pore diameter less than 200 μm . With an increase in SGPs content, the pores with a size less than 200 μm in foam concrete gradually decreased, while those pores larger than 200 μm gradually increased, resulting in foam concrete with pores increased in the average and median sizes. It is notable that the average and medium pore sizes of SGFC_10 are almost equivalent to that of referenced CFC, resulting in the interesting macro properties. This quantitative evidence further demonstrates that the change of pore distribution caused by the inclusion of SGPs can destabilize the foam pores in fresh mixture, leading to smaller foam pores to merge into larger ones. The effects of SGPs on the fine and uniform pore structure of foam concrete can be reflected on its macroscopic properties, as reported for the foam concrete with other aggregates [49,50]. Therefore, even SGPs may provide strength as a skeleton, the larger pore size reduces the strength of foam concrete [50]. This is correlated with the strength tests results reported in Figure 6.

The shape of pores is also a factor affecting the performance of foam concrete, where irregular pores reduce strength and uniformity. The roundness value, defined as the ratio of maximum to minimum diameter of same pore, is typically used to quantify which the pore cross-section approaches a circle [21]. A larger roundness value means a pore with more irregular shape. The roundness of foam concrete is shown in Figure 15. The average roundness value of the CFC, SGFC_10, SGFC_20, and SGFC_30 was 1.49, 1.55, 1.71, and 1.72, respectively. This indicates that the pores of foam concrete became irregular with the increase in SGP content, which was more obvious in foam concrete with an SGP content over 10%. This is because SGPs cause the internal pores of the foam concrete to gradually develop from independent spherical pores with small volumes to interconnected

and irregularly shaped larger pores. From CFC to SGFC_30, with a decrease in cement content and an increase in SGP content, the bubble maintenance ability in cement slurry gradually weakened, and the foam structure was insufficient to wrap aggregates during the forming process [24], resulting in a decrease in pore regularity and an increase in the average roundness.

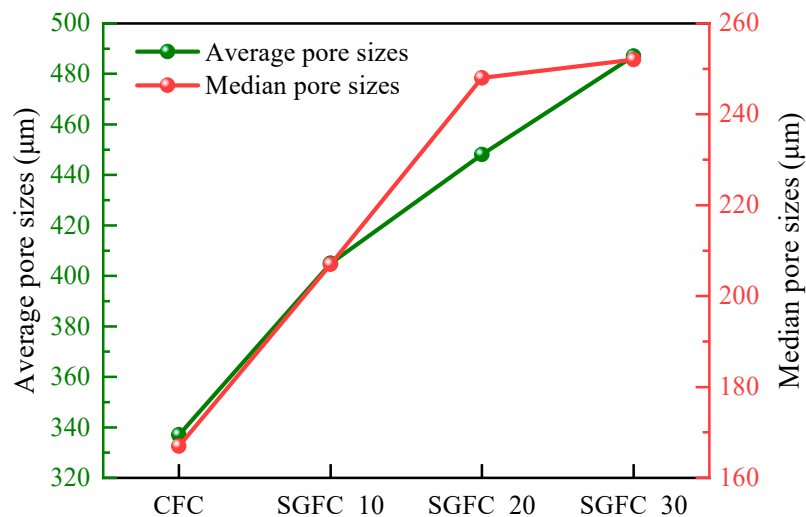


Figure 14. Average and median pore sizes of the foam concrete.

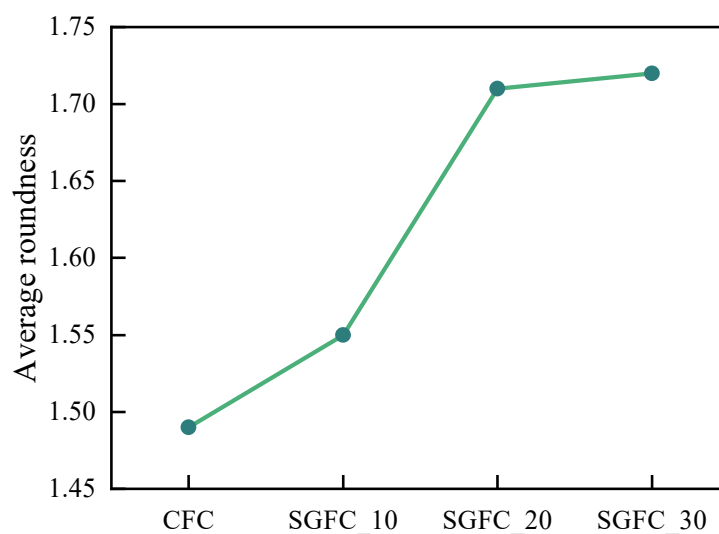


Figure 15. The roundness of the foam concrete.

Figure 16 shows the morphology of foam concrete with different contents of SGPs, detected by SEM at different magnifications. The pore distribution of foam concrete CFC was relatively uniform, and most pores were small with regular shape. After adding SGPs in foam concrete, the pores were more connected. With the increase in SGPs content, the small pores with regular shape in foam concrete became irregular and large pores. This corresponds to the change in pore size distribution in Figure 13 and the change in pore roundness value in Figure 15. Moreover, the decrease in compressive strength of foam concrete with the increase in SGPs content, shown in Figure 9, primarily comes from the pore coalescence and interfacial weakening, while the increase in thermal conductivity with the increase in SGPs content, shown in Figure 11, is induced by the increased pore connectivity.

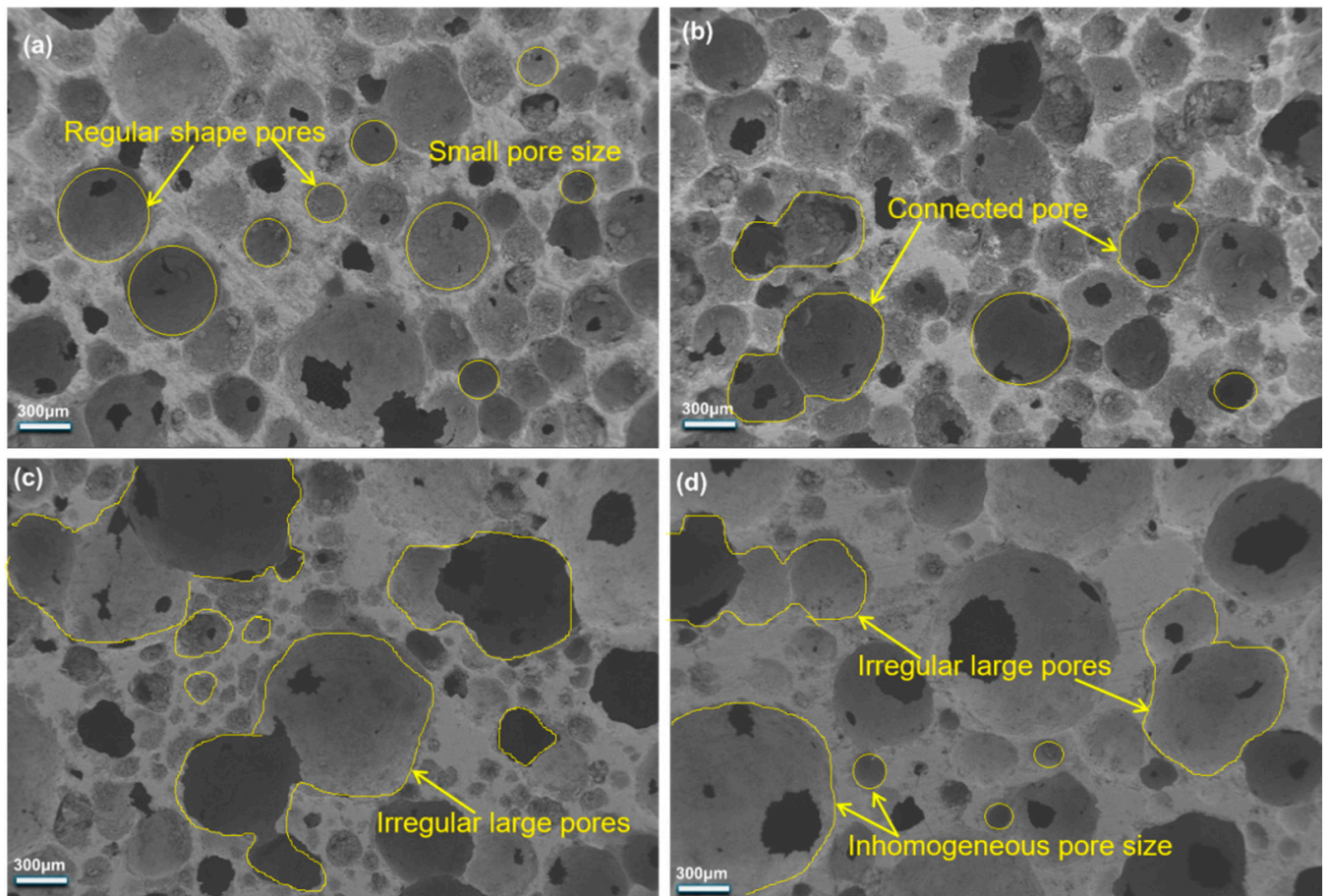


Figure 16. Morphology of the foam concrete: (a) regular shape pores; (b) connected pores; (c) irregular large pores; (d) inhomogeneous pore size.

Figure 17 shows the porosity in relation to the dry density of foam concrete. Compared with referenced CFC, the addition of SGPs leads to increased porosity of foam concrete, leading to SGFC_10, SGFC_20, and SGFC_30 with an increased porosity of 26.8%, 17.9% and 10.7%, whereas the dry density of foam concrete presents a decrease with the increase in SGP content. This means that the dry density highly relates to SGP content, differing from that the density and porosity are inversely proportional to each other for foam concrete without SGPs [42,49]. Meanwhile, as seen in Figure 3, a certain number of pores contained in SGPs also increases the number of pores in foam concrete, thereby increasing the porosity. However, when SGP content increased to 20% and 30%, the pores in the unit area of foam concrete were less than those of SGPs, showing a decrease in porosity of foam concrete. Nevertheless, the addition of SGPs increases the porosity of foam concrete with a decrease in solid phase, and the thermal conductivity of foam concrete is much lower than that of cement matrix and other solid phases. This gives the foam concrete a significant advantage over conventional concrete in terms of its thermal insulation. However, it should be noted that when SGP content exceeds 20%, the phenomenon of foam merging and defoaming occurs during mixing, resulting in a decreasing trend in porosity. Therefore, a rational content of SGPs is needed to make foam concrete with better thermal insulation performance [51].

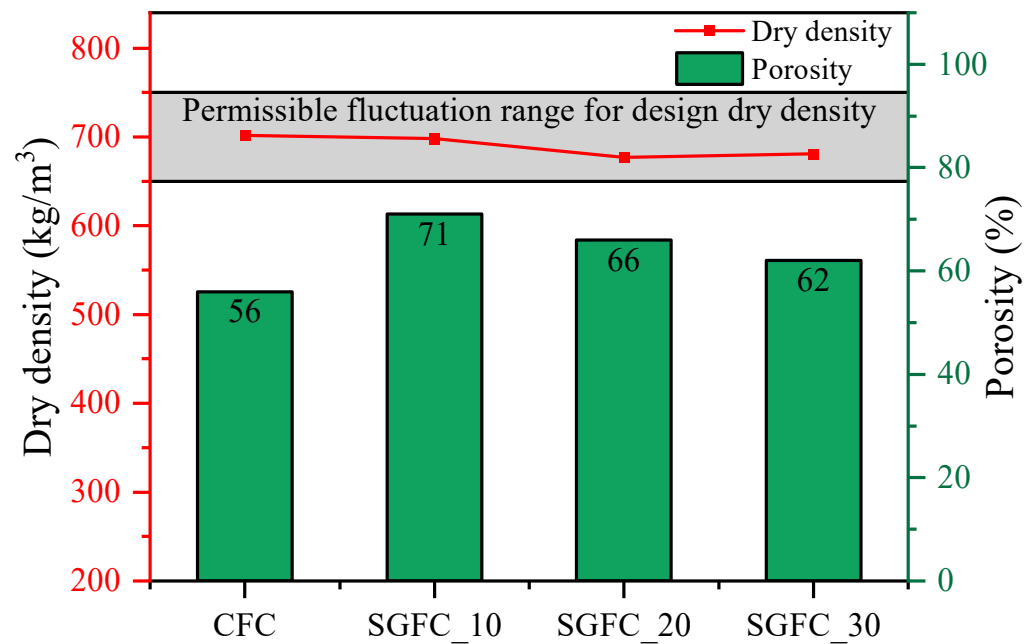


Figure 17. The porosity of the foam concrete.

4. Conclusions

The effects of SGPs content on the micro and macro properties of foam concrete were investigated in this study. Conclusions can be drawn as follows:

- (1) The foam concrete achieved the target density grade of A07. With an increase in SGP content from 0% to 30%, the compressive and flexural strengths of foam concrete decreased, while lower drying shrinkage and thermal conductivity were observed. The compressive strength had a decrease of 35.2–52.6%, and the flexural strength had a decrease of 28.6–42.8%. The drying shrinkage reached a reduction of 7.5–32.2%, and the thermal conductivity presented a decrease of 17.3–23.4%.
- (2) With an increase in SGP content from 0% to 30%, the average pore diameter of foam concrete had an increase of 44.5%, while the pores less than 200 μm decreased in percentage from 60.69% to 39.28%, and those over 200 μm increased by 21.41%. The pore roundness increased from 1.49 to 1.72, indicating a transition from isolated spherical pores to interconnected irregular pores.
- (3) The mechanisms of SGPs functions in foam concrete can be explained with two aspects: an enhanced volume stability through a combination of skeletal restraint and internal curing effect, and a reconstruction of pore structures with connected pores of larger diameter. Therefore, a trade-off should be decided between strength reduction and shrinkage/thermal improvements.
- (4) Aimed at developing a low-carbon and environmentally friendly building material, the foam concrete can be produced with an optimal content of 10% SGPs. This provides a foam concrete with a strength grade of FC3 and a decrease of 33.3% in thermal conductivity compared to standard requirements, and an equivalent drying shrinkage with a decrease of 7.5% at a curing age of 90 days.
- (5) The effects of SGPs on strength, shrinkage and thermal insulation of foam concrete were studied for the first time. The mechanisms involved between strength reduction and shrinkage/thermal improvements are necessary to be fully explored in the future. A potential practical application can be expected on producing foam concrete with an optimal content of SGPs.

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