Innovative Asphalt-Based Carbon Fiber Cement for Enhanced Geothermal Energy Efficiency-Impacts on Engineering Technology

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Abstract

Geothermal energy is currently being explored and developed on a large scale in response to the growing demand for global energy transition. High thermal conductivity geothermal reservoir cement is essential for raising effluent temperature, lowering development costs, and enhancing heat transfer efficiency. There is an urgent need to develop new cement systems with high thermal conductivity. The application effect of asphalt-based carbon fiber (ACF), a novel material with high thermal conductivity, in geothermal reservoir cementing is examined in this article. The findings show that by supplying reaction sites, raising the concentration of hydration products, and filling the structure's micropores, ACF facilitates the cement's hydration process. At the macroscopic level, this drastically reduces the heat transfer path and shows good heat transfer performance. Furthermore, this study's effects on research-based learning in engineering are thoroughly explained from four perspectives: undergraduate education, new instructional methods, new equipment, and student cognition. The use of G cement based on ACF in geothermal reservoir sections can improve cement heat transfer efficiency at a cheap cost and is anticipated to encourage the widespread growth of geothermal energy.

1. Introduction

With the increasing environmental issues brought about by fossil fuel consumption, geothermal energy has been widely used in power generation, heating/cooling, and agriculture for its advantages, such as stable and renewable heat sources, high energy utilization efficiency, and low carbon (Sun et al. 2024).

Geothermal resources can only be explored and developed by constructing a dependable injection-production wellbore in the formation. The most crucial engineering component to boost output and cut expenses is cementing, which is a crucial step in the construction of geothermal wells. It establishes the well's overall life cycle stability, service life, and production capability (Ahmed, Saeed, and Aman 2022). Enhancing the heat recovery efficiency of geothermal wells requires improving the cement materials" thermal conductivity in reservoir sections (Zhang and Li 2022).

Adding external materials is the most popular way to increase cement's thermal conductivity. It has been demonstrated that high thermal conductivity materials, such as steel, copper, and carbon-based fillers, can greatly increase the rate of heat transfer in cement, and accomplish the objective of increasing cement's thermal conductivity (Wei, et al. 2023; Bae, et al. 2023; Daza-Badilla, et al. 2024; Rasheed, et al. 2024). The natural flake graphite layer has a high thermal conductivity of 70~150 W/(m·K) due to its extremely active π bonds, which allow heat to be transferred by electrons. The cement's thermal conductivity rises to 1.8659 W/(m·K) when combined with iron powder and quartz sand in a 7.5:3:1 ratio (Hao et al. 2020). When the composite ratio of graphite, alumina, and steel slag powder was 7:1:3, the thermal conductivity in G cement peaked at 1.604 W/(m·K) (Ying et al. 2022). To forecast the thermal conductivity of geothermal cement, some academics have put forth mathematical models. Furthermore, it was proposed that the cement's heat conductivity is influenced by the water/cement ratio, porosity, the filler particle size and shape (Zhou et al. 2023; Yang et al. 2024).

In this study, it is impossible to overlook the detrimental effects of infill products on cement (Li et al. 2022; Wu et al. 2013). For instance, adding 7.5% graphite results in a 29% and 15% loss of compressive strength and fluidity, respectively. 15% graphite decreased compressive strength by almost 90%. On the other hand, these studies have not considered how high salinity geothermal fluids and formation temperature affect cement's hydration process and fundamental characteristics.

This study investigated using asphalt-based carbon fiber (ACF) to increase the thermal conductivity of geothermal cement. ACF costs only 1/3 as much as carbon fiber based on polyacrylonitrile-based carbon fiber and is produced from petroleum/coal tar pitch through processes such as modulation, spinning, non-melting, and carbonization. Additionally, ACF exhibits outstanding heat transfer performance, strength, and resistance to high temperatures. There are currently no reports on the use of ACF materials as thermal conductivity fillers in geothermal cementing.

This study aims to develop a novel high thermal conductivity geothermal cement based on the ACF and to promote efficient and low-cost geothermal energy development. At high temperatures or high salinity environments, the effects of ACF on thermal conductivity, compressive strength, fluidity, and density of G cement were evaluated. Then the mechanism of ACF's influence on cement was analyzed by polarizing microscopy, scanning electron microscopy (SEM), and X-ray diffraction.

2. Materials and Method

2.1 Materials

In this study, high sulfate-resistant G-grade cement was used, which was purchased from Qingyun Kangjing Building Materials Co., Ltd. (Dezhou, Shandong). This geothermal cement meets the high temperature and corrosion resistance requirements by strictly controlling the composition of its raw materials. S95 slag powder was purchased from Henan Dingnuo Purification Materials Co., Ltd. (Gongyi, Henan), made of blast furnace slag and obtained by drying, grinding, and other processes. The high-activity powder helps to improve the compressive strength of concrete, reduce the hydration heat, and reduce the early structural cracks. Asphalt-based carbon fiber powder (ACF) was purchased from Shenzhen Guosen Navigation Technology Co., Ltd., which is a powdery sample with a density of 1.76 g/cm3, a mesh number of 400, and a carbon content of ≥95%. AFC is a powder that has a resistivity of 1.5*10-3 ΩM, a diameter of 8-12 μm, and a high-temperature resistance of 450-2000 °C. The microstructure of ACF under SEM reveals rod-shaped fibers is seen in Figure 1. The unit pricing of major materials bought in small quantities are listed in Table 1; however, employing industrial-grade items bought in bulk is less expensive than that.

2.2 Methods

2.2.1 Preparation of cement

Preliminary experiments yielded the basic formula for cement: the ratio of cement and mineral powder was 6:4, and the water-cement ratio was 0.6. The experimental group consisted of cement mixed with 2.5%-20% ACF.

Three phases are involved in the preparation and curing of cement: 1. In the cement slurry mixer, the ash components (cement powder, S95 slag, and ACF) were mixed for two minutes. 2. To create the cement slurry, 60% solid mass water was added to

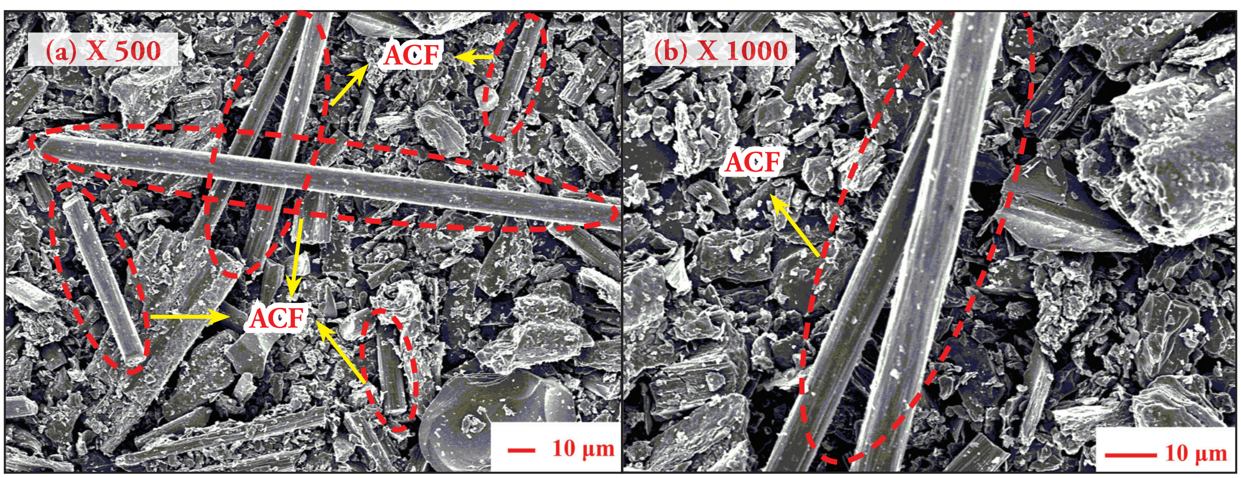

Figure 1. The SEM images of ACF: (a) magnify ×500; (b) magnify ×1000.

Table 1. Material cost.

Material	G cement	S95 slag	ACF
Unit-prices	4000 (¥/t)	5000 (¥/t)	150 (¥/kg)

the mixer, mixed for 120 seconds at low speed while the ash components were added gradually, and then agitated for another 120 seconds at high speed. 3. After pouring the cement slurry into the 40 mm x 40 mm x 40 mm triple test mold, it was cured for 72 hours at 40, 60, 80, and 100° C in a water bath. Additionally, the cement was cured in 2.5%, 5%, 7.5%, and 10% concentrations of salt water to simulate the impact of high-salinity geothermal water on cement.

2.2.2 Thermal conductivity testing of cement

Cement's thermal conductivity is tested using a DRP-2 type thermal conductivity tester, as seen in Figure 2(a). The principle is to heat the cement block through the heating plate and then move the heat through the tested block to the copper plate. The upper surface temperature (T1) and lower surface temperature (T2) create a steady temperature differential after the heat transmission is stable. T1 and T2 values were noted. Every 30 seconds, the temperature of the copper plate is recorded while it is left out in the open to cool naturally. Lastly, the analytical program is used to determine the sample's thermal conductivity. All of the temperatures in this study are expressed in ° C, and the thermal conductivity is expressed in W/(m·K). To guarantee accuracy, disc-shaped cement samples with a diameter of 13 cm and a thickness of 1 cm were prepared (Figure 2(b)).

2.2.3 Characterization of physical-chemical properties of cement

(1) *Foundation performance testing*. To characterize the compressive strength of cement, the WDW-600E microcomputer-controlled electronic universal testing equipment was used to record the maximum load. Calculate the mean of each group's three tests. Calculate the cement density by dividing the volume of the blocks by the mass of the demolded blocks. The truncated cone round mold method is used to assess the cement slurry's fluidity. (2) *Polarizing microscope test.* The pore/crack distribution in the cement sample was observed by a polarizing microscope (Model Olympus BX53P, Japan). Then, the statistical analysis was performed by using the Nano Measurer software. (3) *SEM test*. The cut cement sample was pasted on the copper tape. Then the gold spray and vacuum extraction were carried out. The surface characteristics of the cement samples were observed by using SEM (Model JEOL JSM-7610F Plus, Japan). (4) *X-ray diffraction test.* After grinding the test sample into a fine powder, the tablet was made by using a mold, and the X-ray diffraction instrument (Model Bruker D8-ADVANCE, Germany) was used for detection. The 2θ angle range of the test was 5°~70°, and the scanning speed was 10°/min.

3. Results and Discussion

3.1 Thermal Conductivity of ACF Cement

Figure 3 illustrates the addition of ACF significantly increases the thermal conductivity of cement at various temperatures. The thermal conductivity of ACF cement first rose and then fell as the ACF concentration rose from 2.5% to 20%. The best reinforcement effect is seen at 7.5% ACF. At 40°C, 60°C, 80°C, and 100°C, the thermal conductivity of 7.5% ACF-cement rose by 50%, 280%, 96.2%, and 100%, respectively, in comparison to the control group. The cement cost rose as the concentration of ACF grew, but the rise in heat conductivity steadily reduced as

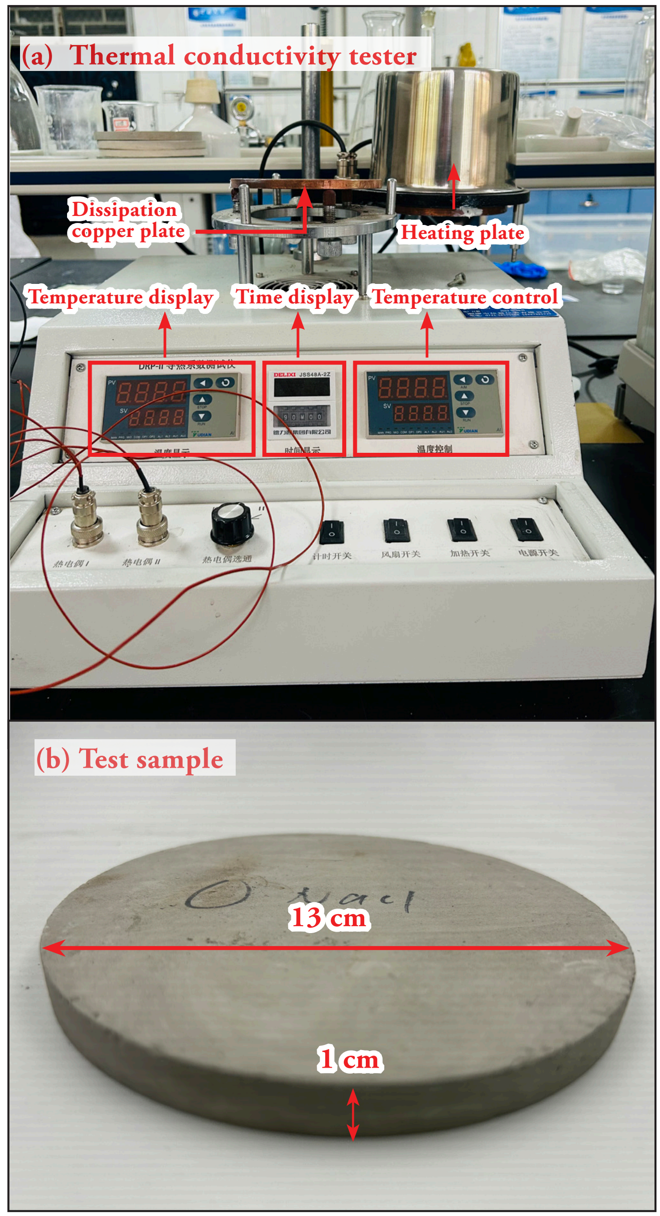

Figure 2. Thermal conductivity tester (a) and test sample (b).

a result of the pore-forming property of ACF. The negative effect of 12.5-20% ACF is more than the positive effect for ACF cement cured at 40° C, which causes the cement's thermal conductivity to rise negatively. In conclusion, 5-10% ACF greatly increased the thermal conductivity of G-cement at T<60 °C, whereas 5-12.5% ACF is advised at T≥60 °C. 7.5% ACF is the best option when taking application cost and heat conductivity into account.

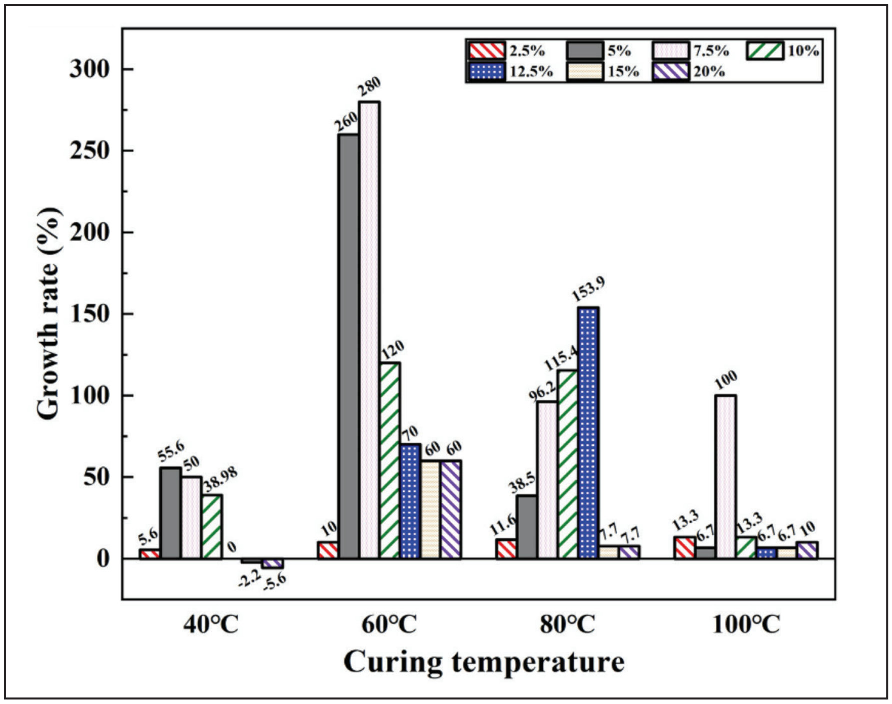

Figure 3. The growth rate of thermal conductivity of 2.5~20% ACF-cement cured at different temperatures.

3.2 ACF' Influence on the Compressive Strength, Density, and Fluidity of Cement

The stability and service life of the geothermal well are determined by the cement's compressive strength. It should not be less than 10.3 MPa. Figure 4(a) illustrates the compressive strength of 2.5-20% ACF cement varies within the range of 10.6-20.1 MPa as the ACF increases, meeting the standard's requirements. Based on the recommended concentration, 7.5% ACF has a compressive strength higher than 11.8 MPa.

Mastering the variation of cement density helps to match the right reservoir pressure. Figure 4(b) shows that ACF decreased the cement's density. After 40-100° C curing, the control group's density varied between 1.462 and 1.689 g/cm³, whereas the 2.5-20% ACF cement's density varied between 1.307 and 1.662 g/cm³. As the ACF increased, the density steadily dropped. Geothermal reservoirs are typically fractured structures with low pressure, making the ACF cement more suitable for low-pressure geothermal fields due to their reduced density.

Fluidity has an impact on cement pumping. ACF's inclusion somewhat decreased the cement's fluidity, as seen in Figure 4(c). Nonetheless, the cement fluidity varied between 17.3-22.5 cm at 40-100 °C, consistently fulfilling cementing standards. In short, the impact of ACF on the basic properties of G cement is acceptable.

3.3 Comparison of ACF and Reported Thermal Conductive Fillers

ACF has been proven to successfully increase cement's thermal conductivity while maintaining its fundamental qualities, as indicated in Table 2. The thermal conductivity rose by 280% after 7.5% ACF was added to the G cement, yet the strength and fluidity still met all API requirements. The cement's thermal conductivity rose by 151% when 6% graphite was added; nevertheless, the fluidity and compressive

Table 2. Comparison of the effects of thermal conductive fillers on cement properties.

Sample	Thermal conductivity	Compressive strength	Fluidity
7.5% ACF	Increased by 280%	Increased by 14%	19.8cm
6% Graphite (Li et al. 2022)	Increased by 151%	Decreased to ~2MPa	<6cm
10% Composite graphite (Yu et al. 2020)	Increased by about 18%	<6MPa	<6cm

strength dropped to about 6 cm and 2 MPa, respectively. Cement's mechanical qualities and fluidity were significantly diminished by graphite powder, making it challenging to pump underground or preserve wellbore stability.

3.4 The Salt Resistance of ACF Cement

Geothermal resources are located in large sedimentary basins, and the majority of formations contain salt rock layers and carbonate rocks. High concentrations of Na^{+}, Cl-, and even hot brine are caused by soluble minerals dissolving in subterranean hot water (Zhang et al. 2024). As shown in Figure 5, tests were performed on G cement and 7.5% ACF cement cured at 80°C with a 2.5%-10% NaCl solution.

Figure 5(a) shows that the thermal conductivity of ACF cement progressively drops as the concentration of salt ions rises. Nonetheless, ACF cement consistently has a higher thermal conductivity than the control group. Compared to the control group, the thermal conductivity of ACF cement increases by 199.7%, 50.1%, 117.3%, and 51.5% in 2.5%, 5%, 7.5%, and 10% NaCl solutions, respectively. In fluids with a high salinity, the thermal conductivity effect of ACF cement is noticeably improved. Figure 5(b) demonstrates that the compressive strength of 7.5% ACF cement varies between 14.09 and 16.47 MPa when the concentration of NaCl rises from 0 to 10%, consistently satisfying the needs of geothermal cementing. The compressive strength decreases by 1.3% at a rate of 7.5% NaCl. The influence of salt solution on the cement compressive strength is relatively small, especially for the ACF cement. In short, ACF cement has good applicability in high salinity geothermal formations.

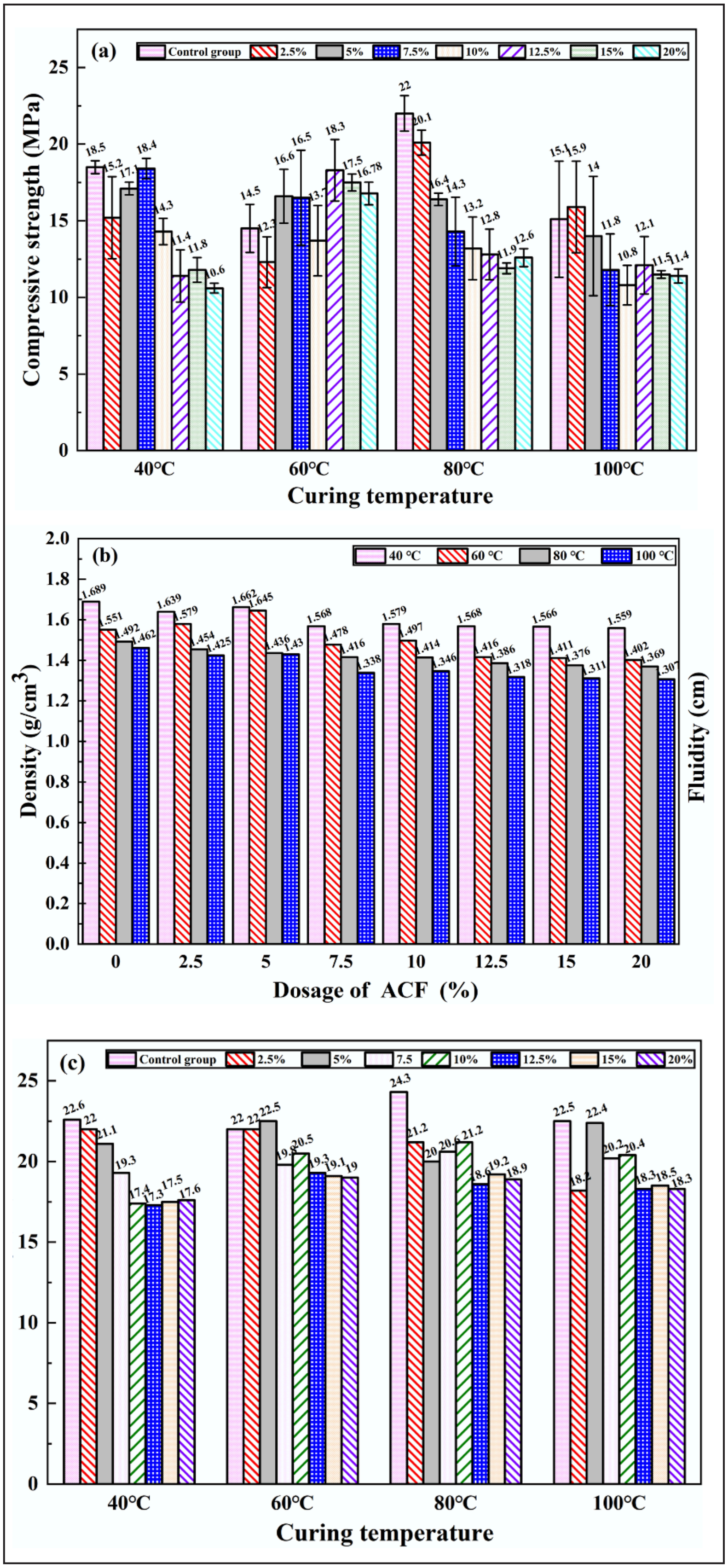

Figure 4. The effect of 0~20% ACF on the performance of cement under different curing temperatures: (a) compressive strength; (b) density; (c) fluidity.

3.5 Mechanism Analysis of Thermal Conductivity Enhancement of the ACF Cement

3.5.1 Observation of scanning electron microscope (SEM)

The G cement has a significant number of micropores, as seen in Figure

6(a). Mi-

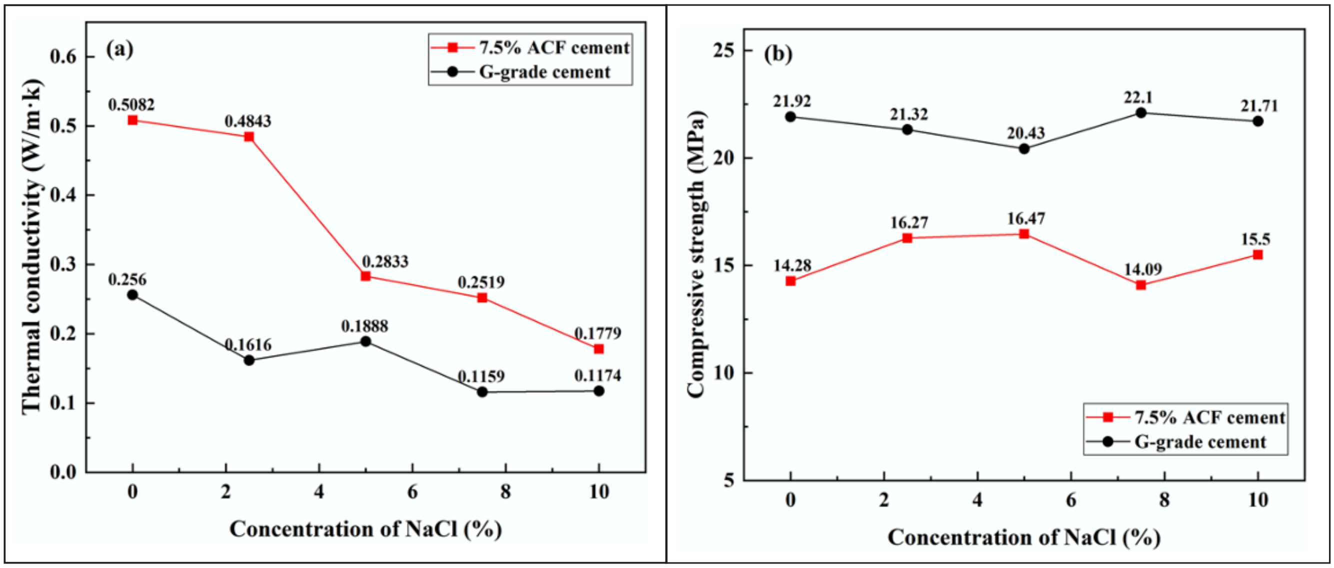

Figure 5. Thermal conductivity of cement cured with 80 salt water: (a) thermal conductivity; (b) compressive strength.

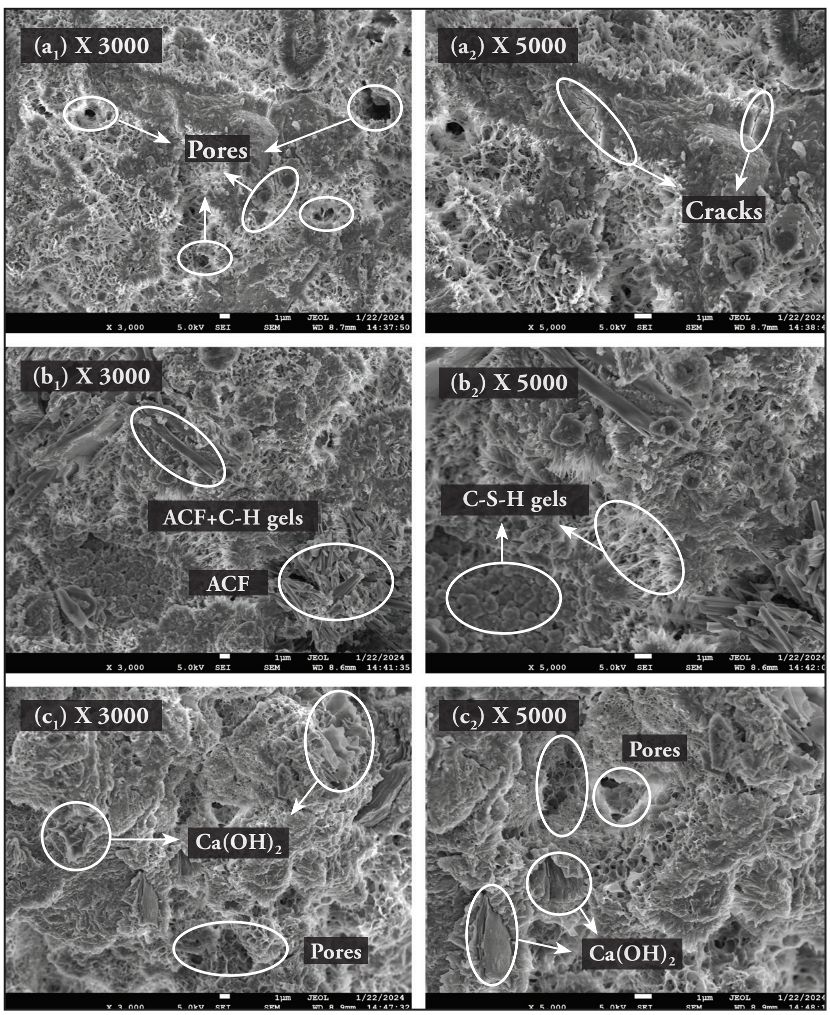

Figure 6. SEM images of cement: (a) G cement; (b) ACF cement; (c) ACF cement +NaCl.

crocracks were also discovered. The control group had a lower thermal conductivity as a result of these loose pore configurations.

Numerous spherical particle structures and fibrous spatial network structures, which are C-S-H gel, can be found in ACF cement (Fig. 6(b)). By efficiently filling in the spaces left by the un-hydrated cement particles, these gel formations create a dense microstructure (Haiyue et al. 2023). ACF particles exist in cement in two forms: well-dispersed ACF can provide a site for the formation of C-S-H gel, which is surrounded by a tightly stacked structure. High-compactness cement composed of high thermal conductivity materials corresponds to a significant increase in thermal conductivity. However, microscopy examinations have indicated that when ACF fibers are not completely dispersed, a grass-like ACF structure may form in cement. This could result in the production of large-diameter pore structures and a reduction in cement strength.

ACF cement cured with NaCl solutions is depicted in Figure 6(c). It shows a lot of irregular plate-like Ca(OH)2 crystals. The decrease in cement's thermal conductivity is caused by a considerable increase in the number of micropores as compared to Figure 6(b).

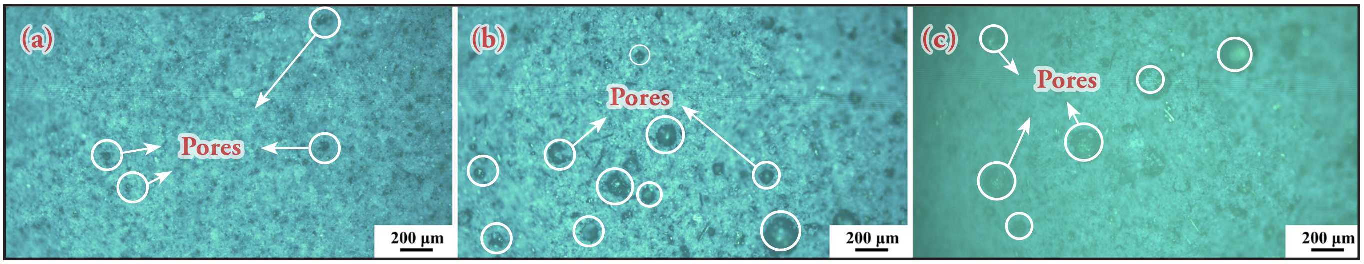

Figure 7. Microscopic images of cement: (a) G cement; (b) ACF cement; (c) ACF cement+NaCl.

3.5.2 Observation of polarizing microscope

The cement's large-diameter pore structure (d > 10 μm) was investigated using a polarizing microscope, as shown in Figure 7. Statistical analysis of about a thousand pores in several microscopic pictures was summarized in Figure 8 and Table 3.

The distribution of pore sizes follows the normal distribution pattern. A Gaussian function is used to fit the pore size distribution curve. The expectation value (μ) of the Gaussian function is consistent with the average diameter, and the variance (σ^2) indicates the distribution's central tendency. The distribution is more concentrated when the variance is less. In the ACF cement, 92.3% of pores are scattered between 10.0 and 70.0 μm, whereas in the G cement, roughly 93.4% of pore diameters are distributed between 12.5 and 32.5 μm. The σ^2 of ACF cement was 98.5% higher than that of G cement. The expectation and average diameter of G cement were 21.88 μm and 23.22 μm. The expectation and the average diameter of ACF cement were 30.38 μm and 40.22 μm. Hence, ACF increased the content of large-diameter pores. The loose structure corresponds to a lower compressive strength, which explains the data in section 3.2.

The average pore diameter of ACF cement cured at 10% NaCl is 50.64 μm. 90.5% of pores are found in 30.0-110.0 μm. Accordingly, the large-diameter pore structure in ACF cement is not significantly impacted by the NaCl solution, and the cement can sustain a steady compressive strength, which is in line with the findings in section 3.4.

3.5.3 Analysis of X-ray diffraction (XRD)

The hydration reaction is the key to the cement stone product obtained from cement hardening. As shown in Figure 9 (a-d), the hydration products of cement were investigated by XRD. The diffraction peaks at 11.6° and 34.4° are the analogous hydrotalcite phase (Ht). The strong peak at 18° was attributed to Ca(OH)2. The peaks of 21.6°, 31.5°, and 47.4° were attributed to C-S-H gel. ACF cement does not produce any new hydration products in comparison to G cement.

Table 4 shows the statistical calculation of the peak intensity in the XRD curve based on the integrated area. It is evident that ACF cement's Ht peak is consistently greater than G cement's. The Ht phase can effectively fill pores, preventing cementitious materials from shrinking and fostering long-term performance improvement (Yonghui et al. 2023). The C-S-H gels in ACF cement also had larger total integration areas than the control group. This suggested that ACF can serve as a good nucleation and growth site for C-S-H gel, thereby increasing the amount of C-S-H gel in hydration products. C-S-H gel fills the micropores, improving compactness and shortening the cement's heat transfer path. The addition of NaCl inhibited the hydration process of cement. The $Ca(OH)_2$ peak value of ACF cement cured with

Table 3. The pore size data of cement.

Sample	Range of pore diameters (μm)	Average diameter (μm)	Expectation (μm)	Variance (σ^2)
G cement	10.36~62.67	23.22	21.88	6.57
ACF cement	11.33~222.06	40.22	30.38	13.04
ACF cement+NaCl	18.14~270.13	50.64	38.99	5.50

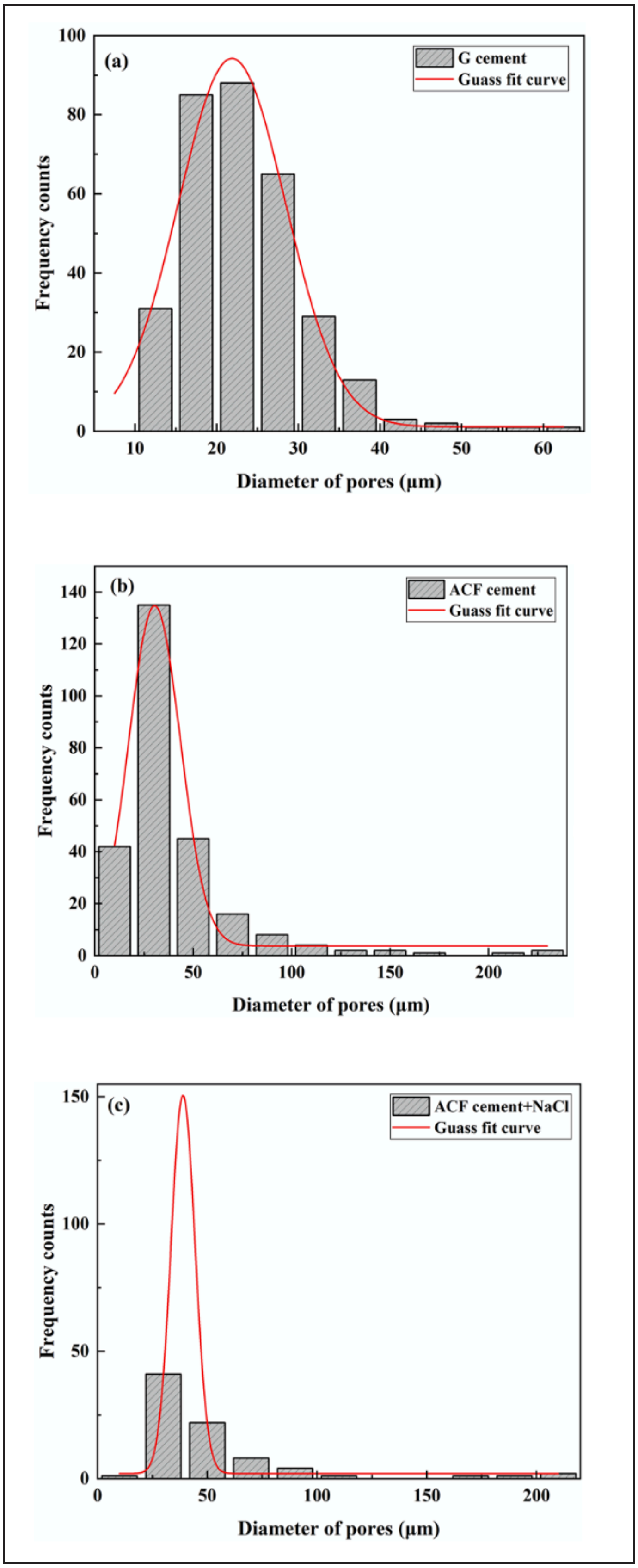

Figure 8. Pore distribution: (a) G cement; (b) ACF cement; (c) ACF cement+NaCl.

10% NaCl was reduced considerably. This suggests that the quantity of C-S-H gels has decreased, and the microstructure is generally loose.

3.5.4 Analysis of thermal conductivity mechanism

The mechanisms can be summed up as follows: As illustrated in Figure 10(a), the fibrous ACF material is susceptible to developing a grass-pile structure as a result of uneven mixing, which raises the cement's large diameter pore count. The cement's density and compressive strength are decreased by these big pores. Srengthening the ACF cement's microstructure and preparation method should resolve this issue.

On the other hand, by offering locations for hydration reactions, ACF accelerated the cement's hydration process and raised the amount of hydration products. C-S-H makes up the cement structure's micropores, minimizes microcracks, and produces a dense microstructure. In inorganic non-metallic materials, phonon conduction is the primary method of heat conduction. ACF greatly reduces the heat transfer path, raises the total heat transfer per unit time, and exhibits good heat transfer performance at the macro level, as seen in Figure 10(b).

3.6 Educational Impact of the Research Study for Engineering Technology Field

The following effects of this study on research-based education in engineering technology were observed:

(1) Student cognition: Despite having finished foundational courses, students' knowledge and comprehension of the subjects, as well as their acceptance of their understanding as they approach professional life, are still limited, according to this study. Course-based undergraduate research experiences (CUREs) are interventions that expose students to graduate-level research into specific engineering phenomena (Kribs 2022). Students will gain a deeper understanding of the cutting-edge theories and foundational information in their field by working independently to complete experiments. Effectively avoiding the problem of students losing interest and enthusiasm for learning quickly due to the content being too profound and tasteless (Zhan et al. 2022; Phillips et al. 2023).

(2) The application of research findings in teaching: Although the mechanical and physicochemical characteristics of concrete are generally introduced in teaching, it is unclear how these relate to engineering. Understanding the materials and techniques

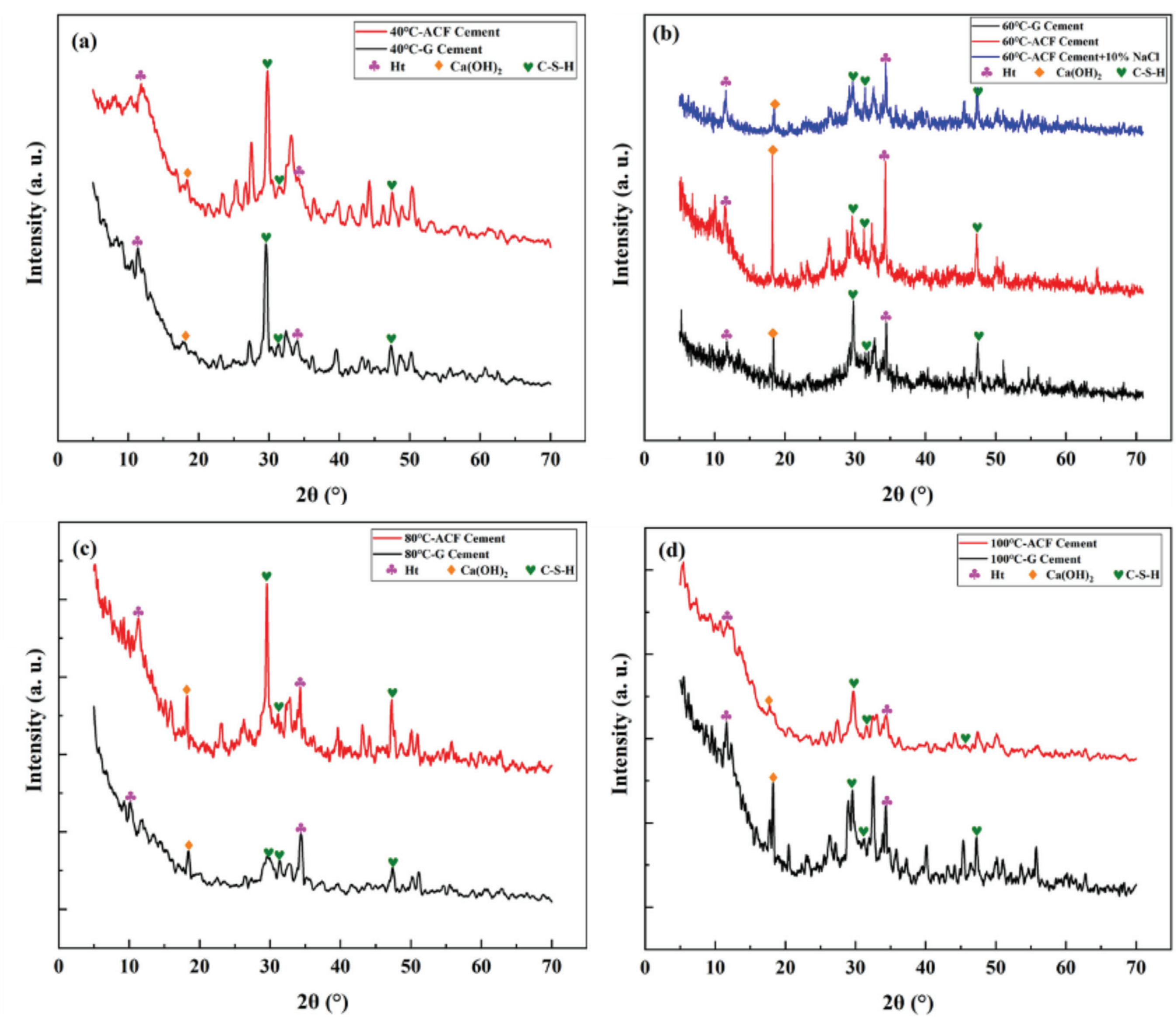

Figure 9. XRD curves of cement samples cured at different temperatures: (a) 40° C; (b) 60° C; (c) 80° C; (d) 100 ° C.

Table 4. Integral area of characteristic peaks in XRD curve.

T (°C)	Sample	Ht		C-S-H gels			
		~11.6°	~34.4°	~29.6°	~31.5°	~47.4°	Total
40	G cement	76.81	35.82	71.67	27.33	29.98	128.98
	ACF cement	167.63	184.72	55.71	48.51	45.24	149.46
60	G cement	22.99	32.83	65.88	15.22	26.55	107.65
	ACF cement	67.86	51.98	69.42	31.79	34.69	135.9
	ACF cement +10% NaCl	27.17	27.89	44.67	24.23	24.81	93.71
80	G cement	37.88	29.56	65.54	27.52	26.03	119.09
	ACF cement	98.96	41.38	106.88	23.18	39.46	169.52
100	G cement	51.84	21.00	26.37	16.58	17.37	60.32
	ACF cement	85.97	23.22	48.01	21.87	25.34	95.23

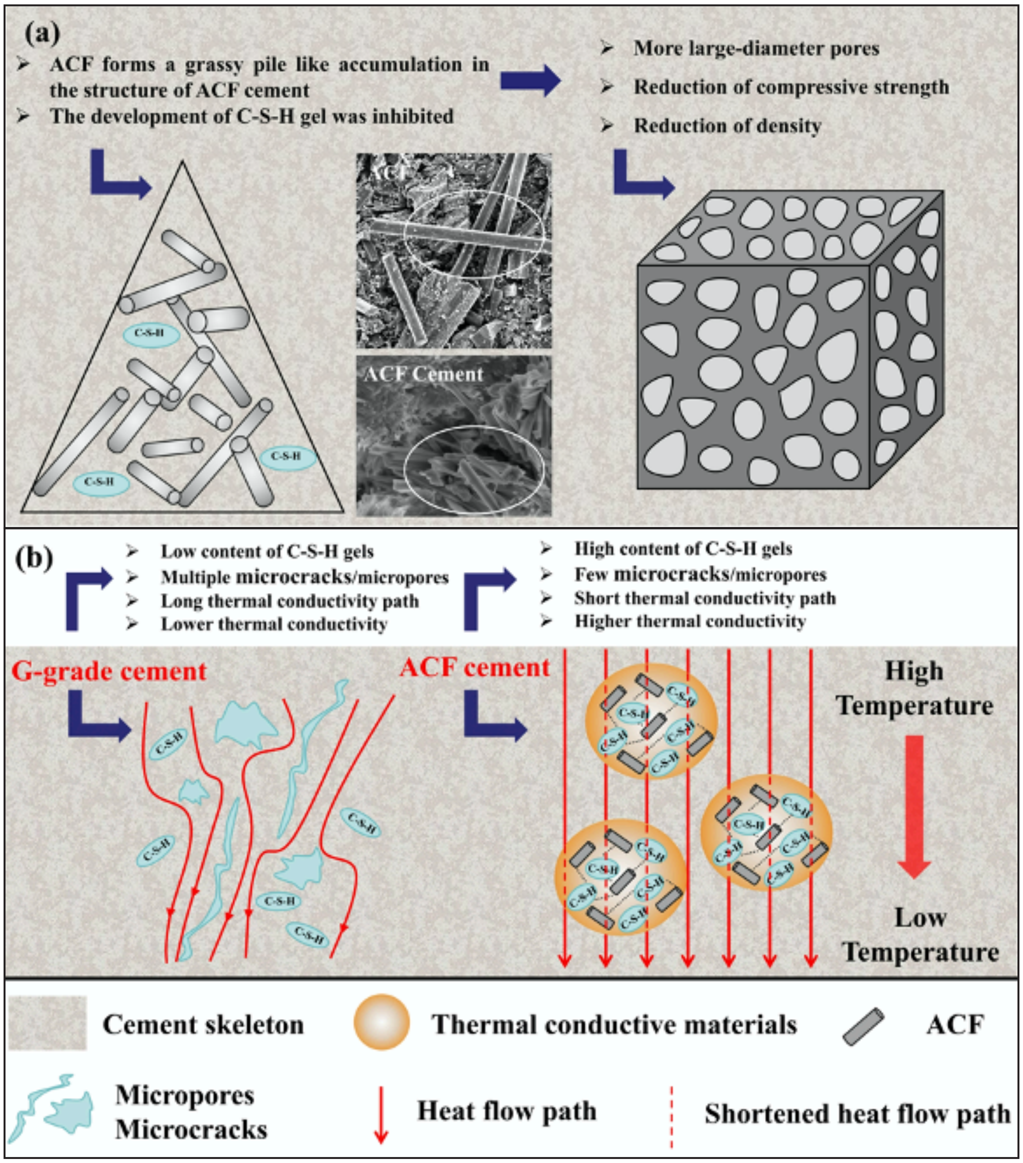

Figure 10. Mechanism analysis of the influence of ACF on the thermal conductivity and strength of G cement: (a) influence on the strength; (b) influence on the thermal conductivity.

that can be utilized to control the attributes and the governing principles is similarly challenging. In future teaching projects, this study can be used as a case to illustrate the data sources and analysis techniques of cement performance changes, and help students develop inquisitive thinking skills.

(3) New educational components: The sandwich education model, which is dominated by multiple factors, has been successfully applied in guiding graduation design, practical course reform, Chinese international education, and other fields (Hailang et al. 2021; Jianling 2014). This project has implemented the effective "1+1+1" educational model, which consists of an undergraduate student, a graduate student, and a professional teacher. They were tasked with developing research directions, directing the use of equipment, and gathering data, respectively. The key to this model is for teachers to help assist students in solving experimental funding. On the other hand, in the "1+1+1" mode, regular group discussions of three people have been proven effective, ensuring that the guiding teacher has a grasp of the progress and direction of the experiment.

(4) Research method: In this investigation, the conventional concrete thermal conductivity sample in the construction field was creatively reduced to a 13 cm diameter disc model by using a portable thermal conductivity tester. Its remarkable reliability was confirmed by experimental results. Promoting this device in undergraduate teaching is beneficial for fully utilizing limited platform resources, expanding the practical scope of college students, and improving experimental efficiency.

3.7 Industrial Impact of the Research Study

According to research, ACF can significantly increase geothermal cement's thermal conductivity, which could have a variety of effects on the manufacturing sector:

(1) This finding contributes to the economic enhancement of geothermal systems' extraction efficiency. This boosts the competitiveness of manufacturing companies that use geothermal energy by reducing energy costs and increasing energy consumption efficiency. Given the growing use of geothermal energy in manufacturing, it is reasonable to assume that more manufacturing businesses will adopt this technology to lessen their reliance on conventional energy sources, cut carbon emissions, and achieve green production.

(2) The application of ACF in construction materials, geothermal energy, and other areas will increase market potential and profit margins for businesses, supporting the manufacturing sector's diversification. Manufacturers will increase research and development, encourage technological advancement, and upgrade the ACF material industry to fulfill the need for high-performance ACF materials in geothermal energy. Simultaneously, manufacturers will focus on environmental protection throughout ACF's production, use, and recycling life cycle and support the green development of manufacturing to support the sustainable development of ACF materials.

4. Conclusion

This work investigates the new thermally conductive filler ACF, which is resistant to high temperatures and salt. While preserving fundamental performance requirements, it shortens the heat transmission path, compensates for the micropores in cement by encouraging the hydration process, and greatly improves the heat transfer properties of geothermal cement. The significance of cementing engineering in the development of geothermal energy has been reinforced by this study, which expands the use of cementing cement. It is anticipated that this research will eventually lead to the low-cost enhanced geothermal energy recovery goal in cementing engineering. Next, an eco-friendly organic solvent will be taken into consideration to optimize the ACF cement preparation process, which is anticipated to decrease the creation of grass pile structures and increase the cement's compressive strength.

Finally, the impact of this study on the geothermal industry, especially the manufacturing industry, has been revealed. The study's effects on undergraduate education and student cognition were examined, and the feasibility of the CURE intervention measure was confirmed. A new "1+1+1" educational component was explored. The application effect of a portable testing instrument in undergraduate teaching trials was also examined.

Acknowledgments

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