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Optimization of Phase Change Materials as Backfill Materials for Underground Cable

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ABSTRACT

In recent years, the application of phase change materials (PCMs) has gained increasing interest due to their potential for energy conservation and thermal comfort in buildings. However, due to a limitation of study on backfilling PCM, only a few studies have examined the effects of backfill materials on ground heat exchanger characteristics. Hence, this research was conducted to identify if paraffin suitable for use as thermal backfill materials, as well as the qualities and performance as thermal backfill materials. Various percentages of paraffin wax (0%, 2%, 4%, 6%, 8%, and 10%) were mixed with Ordinary Portland Cement (OPC) and 10% fly ash to prepare concrete specimens. These specimens were tested for compressive strength, thermal conductivity, heat storage, and thermal stability. The results showed that specimens with 10% paraffin wax content exhibited a 13.63 J/g heat storage capacity and a reduced thermal conductivity of 0.5769 W/m·K, compared to 4.62 J/g and 0.7812 W/m·K for specimens without paraffin. Compressive strength tests revealed that although the presence of paraffin wax reduced compressive strength by 10%, it still increased over time with curing, achieving 48.94 MPa after 28 days. Additionally, specimens with higher paraffin content demonstrated improved thermal stability, with SEM analysis showing reduced porosity and more homogeneous microstructure. These findings indicate that higher paraffin content significantly enhances heat storage capacity, reduces thermal conductivity, and improves thermal stability, effectively managing the thermal load of underground cables.

This research demonstrates that paraffin wax can extend the lifespan of underground power cables by maintaining lower temperatures, thereby supporting both engineering and environmental goals through improved thermal performance and energy efficiency.

Keywords: Geothermal Energy Systems; Paraffin Wax; Phase Change Material (PCM); Thermal Backfill Material; Thermal Conductivity

INTRODUCTION

Underground cables are integral to power distribution, especially in regions where overhead lines are impractical or hazardous. The inherent resistance in these cables generates heat due to resistive and dielectric losses, causing a rise in temperature [1]. Experimental results indicate that the estimated lifespan of cables ranges from 7 to 30 years when operating at temperatures between 95 and 105 °C [2]. However, excessive temperatures can significantly reduce the lifespan of these cables. Geothermal energy systems offer a solution to this problem by enhancing energy efficiency in power generation and building heating/cooling [3]. A crucial part of these systems is the backfill material used in ground heat exchangers. The type of backfill material can greatly affect the system's performance and sustainability. Traditionally, materials like silica sand have been used [4, 5], but with increasing focus on energy efficiency and environmental sustainability, there is a need to explore better alternatives.

Recent studies have highlighted the limitations of conventional backfill materials in managing the thermal demands of underground cables. Although materials such as silica sand are widely used, they often fail to provide optimal thermal conductivity and energy efficiency [6]. Phase Change Materials (PCMs) present a promising alternative to traditional backfill materials. PCMs can store and release thermal energy during phase transitions, making them effective for managing the heat generated by underground cables. During the thermal cycling process, PCMs can transition from solid to liquid. As they change phases, such as from liquid to solid and vice versa, PCMs can absorb and return heat energy to the atmosphere. PCMs can retain latent heat energy even after tens of millions of phase change cycles [7]. Despite their potential, research on the use of PCMs in this application remains limited and widely used only in construction applications [8]. PCMs are classified into two main types: organic and inorganic [9]. This paper investigates the optimization of paraffin wax, an organic PCM, as a thermal backfill material for underground power cables. The study involves a comprehensive analysis of the physical, mechanical, and thermal properties of paraffin wax when mixed with Ordinary Portland Cement (OPC) and 10% fly ash. Various percentages of paraffin wax (0%, 2%, 4%, 6%, 8%, and 10%) were incorporated into concrete specimens. These specimens underwent a series of tests, including compressive strength, thermal conductivity, heat storage, and thermal stability to assess the potential of paraffin wax to enhance the thermal management and extend the lifespan of underground cables.

The primary aim of this study is to bridge the research gap by evaluating the suitability of paraffin wax as a thermal backfill material. By investigating its physical, mechanical, and thermal properties, the research seeks to determine the efficacy of paraffin wax in enhancing the performance and lifespan of underground power cables. Using PCMs in backfill materials supports both engineering and environmental goals. For engineering, PCMs can improve the thermal performance of underground power cables, reducing overheating and maintenance needs [10]. Environmentally, PCMs help conserve energy and reduce greenhouse gas emissions by improving the efficiency of thermal energy storage systems. This research not only advances the use of PCMs in technology but also supports broader environmental goals, highlighting the importance of sustainable materials in modern infrastructure.

METHODS

Materials

This study selected Ordinary Portland Cement (OPC) as the primary cementitious material, with a density of 1,440 kg/m^3. To enhance workability, durability and reduce the cement content of the concrete mixtures, fly ash was added at 10% of the cement weight. The use of 10% fly ash is based on studies showing that this percentage optimizes compressive strength.

Lustosa and Magalhães [11] noted a 10% replacement provided the highest increase in compressive strength at 28 days. Similarly, Fantu et al. [12] reported that concrete with 10% fly ash achieved a significant increase in compressive strength, identifying 10% as the optimal replacement level.

Paraffin wax, microencapsulated in polymethyl methacrylate (PMMA), was used as the Phase Change Material (PCM), with a melting point of 28°C and a latent heat of 165 kJ/kg, as detailed in Table 1. Tests on cement were conducted in accordance with BS EN 197-1/2011 standards. The inclusion of fly ash aimed to improve the concrete's workability and resilience, while the microencapsulated paraffin wax PCM was specifically chosen for its thermal properties as described in the product specifications.

Table 1: Physical properties of microencapsulated paraffin wax (PCM)

Property	Unit	Value
Melting point	°C	28
Specific gravity		0.84
Density	gm/cm³	0.83-0.84
Particle Size	µM	<10
Latent Size	KJ/Kg	165
Thermal conductivity	W/m.K	0.21
Specific Heat	J/kg.K	2100
Core		Organic paraffin wax
Shell		Poly (methyl methacrylate) (PMMA)
Appearance		White powder

Source: Hangzhou Phase Change Technology Co., ltd.

Mix Design

Six different concrete mixture were included in the experiment with each group comprising six cylinders of identical composition. One set served as a control which contained a reference mix of concrete and 10% fly ash without paraffin, while the other five sets contained paraffin at various proportions: 2%, 4%, 6%, 8%, and 10% by mass of the binders.

To prepare the concrete samples, concrete, fly ash, and paraffin were mixed. Each sample consisted of 45 g of cement, 4.5 g of fly ash, and a water-cement ratio of 0.5, with paraffin added in varying proportions (0%, 2%, 4%, 6%, 8%, and 10%) based on the total weight of the concrete. After mixing, all specimens were allowed to set and then cured in water for 28 days. Figure 1 shows the preparation of concrete samples with different percentages of paraffin.

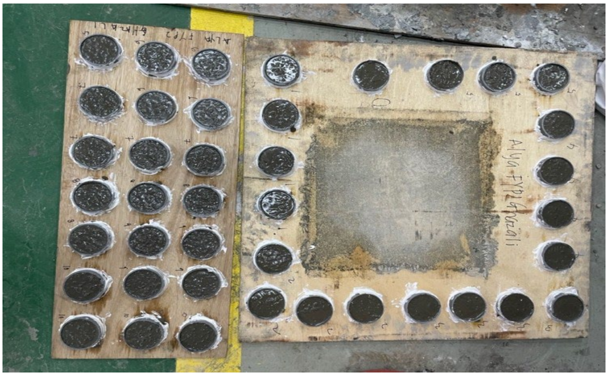

Figure 1: Sample Preparation with Different Percentage of Paraffin

Compressive Strength Test

The experiment involved a total of twelve concrete cubes, divided into two sets: six cubes without paraffin wax and six cubes with 10% paraffin wax. Each set was cured for three different durations: 3, 7, and 28 days. Each cube, made with 2 kg of OPC, 1.2 kg of fly ash (constituting 10% of the total concrete weight), and water, maintained a water-cement ratio of 0.5. All components, including any waste, were precisely measured for each mixture.

The concrete mixture, which included OPC, fly ash, and water, was poured into 100 mm x 100 mm x 100 mm molds and allowed to set. The following day, the concrete cubes were de-molded and cured in water for the specified durations of 3, 7, and 28 days. After each curing period, two cubes were tested for compressive strength. These tests were conducted according to ASTM C109 standards, using a mechanical tester with a constant compression rate of 5 mm/min.

Thermal Conductivity Test

To study thermal conductivity, six specimens were prepared, each shaped into a cylinder with a 50 mm diameter and a 10 mm height, giving a volume of approximately 29.452 x 10^{-6} m^3. The thermal conductivity of each specimen was measured using a thermal conductivity instrument, following ASTM C 177-10 standards. The testing device's heating system included an electric heater to transfer heat to the paraffin within the specimen. Each test lasted up to one hour to ensure accurate measurements. During testing, the specimen was placed between two surfaces with different temperature flows. The upper plate was heated to 38°C, while the lower plate was set to 18°C. These temperatures were applied to the specimen to determine its thermal conductivity.

Heat Storage Test

The thermal heat storage of specimens containing varying amounts of paraffin was evaluated using infrared thermography. Six specimens were chilled at 0°C for 24 hours to ensure a consistent internal temperature. During the test, the samples were placed on a 50°C heating platform, with their bottom surfaces coated in thermally conductive silicone to ensure efficient heat transfer. The surface temperature of the specimens was monitored and recorded in real time using a thermal conductivity instrument and the final temperature was recorded after 40 minutes. The average atmospheric temperature in the experimental setting was 23°C.

Thermal Stability Test

Using SEM, the thermal stability of specimens containing varying amounts of paraffin was evaluated. In this examination, another one set out of five (5) sets was utilized which consist of six (6) specimens comprised of cement, 10% of fly ash (from quantity of cement) and different amount of paraffin (0% 2%, 4%, 6%, 8%, and 10% by mass of binders). The specimens' surface morphology was characterized using JSM-7900F field emission SEM.

RESULTS AND DISCUSSION

Compressive Strength

The compressive strength of twelve concrete cubes was measured after curing periods of 3, 7, and 28 days. Table 2 displays compressive strength results of all twelve (12) specimens relative to the curing time.

Table 2: Compressive Strength

Sample number	Curing time (day)	Compressive Strength (MPa)	Average Compressive Strength (MPa)
CT 1	3	25.03	31.40
CT 2		37.77	
PCM 1		22.53	28.27
PCM 2		34.00	
CT 3	7	38.55	41.51
CT 4		44.48	
PCM 3		34.70	37.37
PCM 4		40.03	
CT 5	28	51.29	54.37
CT 6		57.45	
PCM 5		46.16	48.94
PCM 6		51.71	

The results from Table 2 indicate that the compressive strength of the concrete increases with longer curing times. For control samples (CT), which contain 10% fly ash but no paraffin wax, the average compressive strength increases from 31.40 MPa at 3 days to 54.37 MPa at 28 days. This trend demonstrates the well-known principle that concrete continues to gain strength over time as the hydration process progresses. The inclusion of fly ash enhances this strength development by promoting the formation of calcium-silicate-hydrate (C-S-H) gel, resulting in a denser microstructure with reduced porosity [13]. In contrast, the samples with 10% paraffin wax (PCM) show a reduction in compressive strength compared to the control samples. The average compressive strength for PCM samples is 28.27 MPa at 3 days, increasing to 48.94 MPa at 28 days. The inclusion of PCM in concrete mixes significantly enhances compressive strength, especially with longer curing times [14]. Although the compressive strength still improves with longer curing times, the presence of paraffin wax introduces higher porosity, which negatively impacts the mechanical properties of the concrete.

Comparing both sets of data, the inclusion of paraffin wax in concrete compromises compressive strength. Control samples (CT) without paraffin wax exhibit higher compressive strength, whereas PCM samples with paraffin wax show reduced compressive strength due to the increased porosity. Specifically, the 28-day compressive strength of PCM samples is 48.94 MPa compared to 54.37 MPa for control samples, indicating a reduction of approximately 10%.

Thermal Conductivity and Heat Storage

Thermal conductivity is a crucial thermal property that influences the heat storage/release rate of thermal energy storage composites. Table 3 displays the thermal conductivity results and heat storage of all six (6) specimens containing varying amounts of paraffin.

Table 3: Thermal Conductivity and Heat Storage

Sample Number	Cement Quantity (g)	PCM (%)	Thermal Conductivity (W/m·K)	Temperature (°C)	Heat Storage (J/g)
S1	45	0	0.8912	30.3	4.62
S2	45	2	0.7935	30.4	5.17
S3	45	4	0.7529	31.5	7.82
S4	45	6	0.7194	31.7	9.85
S5	45	8	0.6916	30.0	11.81
S6	45	10	0.6669	29.7	13.63

The control specimen, without any paraffin wax, recorded the highest thermal conductivity at 0.8912 W/m·K. As the paraffin wax content increased, thermal conductivity decreased, with the 10% paraffin wax specimen exhibiting the lowest thermal conductivity of 0.6669 W/m·K. This inverse relationship highlights the insulating properties of paraffin wax, which enhance the material's ability to maintain lower internal temperatures by reducing heat transfer. When the paraffin mass fraction increased from 0% to 2% and 10%, the thermal conductivity of the specimens decreased to 0.7935 W/m·K and 0.6669 W/m·K, respectively. Although the vacuum impregnation technique used in this study effectively removed air from the specimens to increase paraffin adsorption, some pore spaces remained blocked by air, hindering efficient heat transfer from the slag matrix materials to the paraffin [15]. This finding is consistent with previous research, which also observed a decrease in thermal conductivity with increased paraffin content due to improved thermal stability and form-stable properties of the composite material [16]. The trend of thermal conductivity in relative to the percentage of paraffin is illustrated in Figure 2.

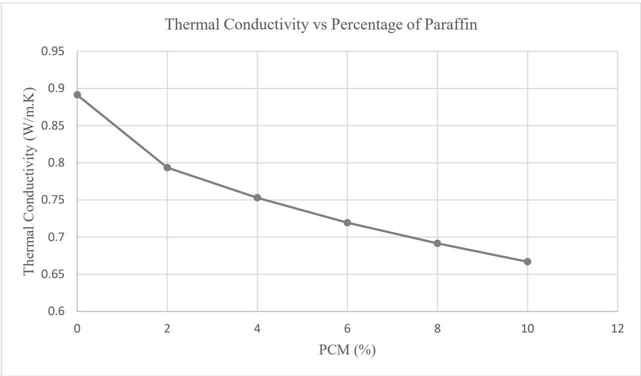

Figure 2: Thermal Conductivity vs Percentage of Paraffin

Figure 2 shows a clear and consistent decline in thermal conductivity as the percentage of paraffin wax increases. The thermal conductivity drops significantly from 0.8912 W/m·K at 0% paraffin wax to 0.6669 W/m·K at 10% paraffin wax. This reduction in thermal conductivity is critical for applications that require effective thermal insulation, as it indicates the material's improved ability to limit heat flow.

The final temperatures of the specimens were recorded after 40 minutes of heating to understand the thermal energy storage capability of the materials. As shown in Table 3, the result indicate that the inclusion of paraffin wax significantly enhances the heat storage capacity of the concrete. The control sample (S1) with 0% paraffin wax exhibited the lowest heat storage capacity of 4.62 J/g. As the percentage of paraffin wax increased, the heat storage capacity also increased significantly. For instance, the specimen with 2% paraffin wax (S2) had a heat storage capacity of 5.17 J/g, and this value continued to rise with higher paraffin contents, reaching 13.63 J/g for the specimen with 10% paraffin wax (S6). Infrared thermography images revealed that the surface temperature of the control sample (S1) increased faster compared to the samples with paraffin wax. The final temperatures recorded after 40 minutes of heating were 30.3°C for S1, 30.4°C for S2, and 29.7°C for S6. This slower temperature rise in samples with paraffin wax indicates their higher heat storage capacity, as they absorbed more heat over the same period.

The surface temperature of S2 and S6 after 32 minutes of heating was 29.0° C and 25.5° C, respectively, while that of S1 reached 32.2° C. In addition, it was observed that the surface temperature of sample S6 after 36 minutes of heating was approximately the same as that of sample S1 after 24 minutes of heating, which was approximately 29oC. Thus, the surface temperature of S6 was 12 minutes later than that of S1. This result demonstrates that the incorporation of paraffin significantly enhanced the thermal energy storage capacity of the specimens. Similarly, the research by Shen et al. [17] found that incorporating phase change materials (PCM) into concrete can result in superior thermal stability and higher energy storage density. Consequently, it can be concluded that the prepared specimens have a high capacity for thermal energy storage and temperature regulation. Figure 3 illustrates the relationship between the percentage of paraffin wax (PCM) in the concrete specimens and their corresponding heat storage capacities.

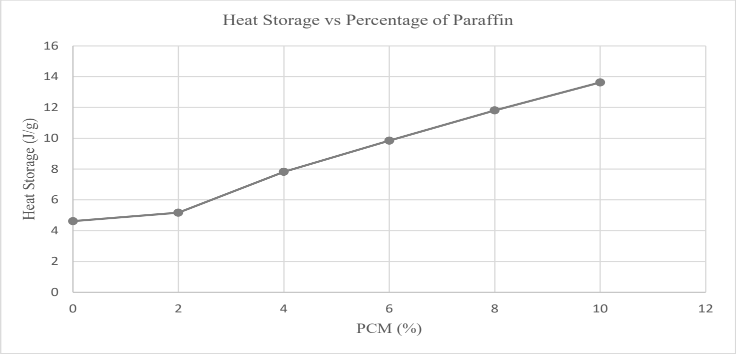

Figure 3: Heat Storage vs Percentage of Paraffin

Thermal Stability Test

As shown in Figure 4, the SEM images display concrete specimens with varying percentages of paraffin wax. These measurements correspond to the various particle sizes of the sacrificial PMMA utilized to prepare the materials. The paraffin wax is effectively encapsulated in the concrete mixture, and the porous structure of the concrete may function as a heterogeneous nucleation site to reduce specimen supercooling.

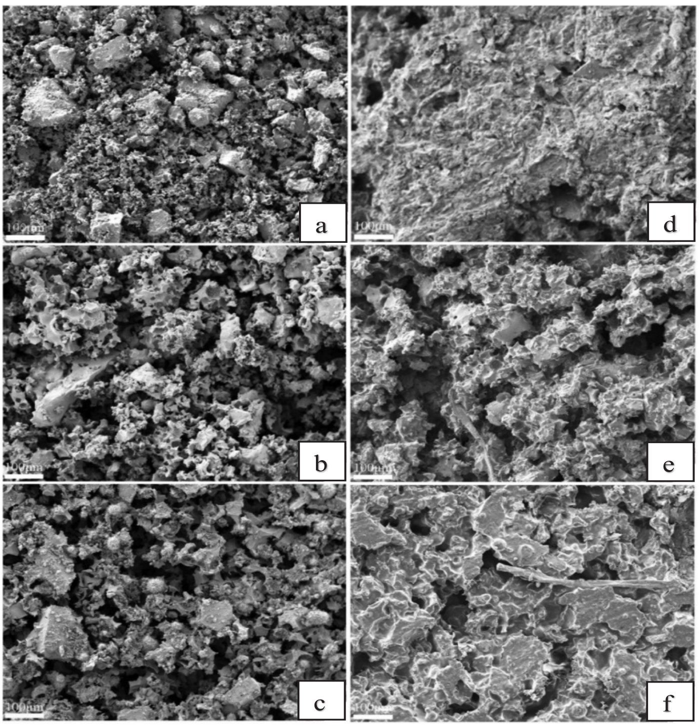

Figure 4: SEM Images of Porous Specimens with Varying Percentages of Paraffin Wax: (a) 0%, (b) 2%, (c) 4%, (d) 6%, (e) 8%, and (f) 10%

Based on Figure 4, SEM images reveal that increasing the percentage of paraffin wax in concrete specimens leads to a significant reduction in the number of pores while increasing the size of the remaining pores. The paraffin wax effectively fills the pores, particularly in specimens with higher percentages, resulting in a smoother surface texture. The specimen in

Figure 4(f) with 10% paraffin wax shows the greatest reduction in porosity and the smoothest surface, indicating the highest impregnation efficiency. Figure 4(a), serves as the control specimen demonstrates that the surface of specimens without any paraffin wax exhibits a less pronounced porous structure. Specimens with lower percentages of paraffin wax (2% and 4%) do not achieve as effective filling as those with higher percentages. This results in fewer nucleation sites and a higher likelihood of supercooling, making the phase change process less reliable and leading to greater temperature fluctuations and reduced thermal stability.

Comparing the specimen impregnation efficiencies of 4% in Figure 4(c) and 10% in Figure 4(f), it is evident that the impregnation efficiency of 10% paraffin is significantly higher than that of 4% paraffin. This is indicated by the greater amount of paraffin surface overglow under tension. This observation suggests that within a certain range of pore sizes, a higher quantity of paraffin can be effectively encapsulated in specimens with larger pores, thus enhancing the overall thermal stability and structural integrity of the concrete. Smoother surfaces with well-encapsulated paraffin wax enhance the material's ability to absorb and release heat during phase transitions. This property is crucial for maintaining stable temperatures, as the wax can effectively buffer against temperature fluctuations. A well-distributed paraffin wax within the concrete matrix provides numerous nucleation sites, thus it can facilitate the phase change process and reducing supercooling. This leads to more predictable and stable thermal behavior.

CONCLUSION

This study investigated the optimization of phase change materials (PCMs), specifically paraffin wax, as backfill materials for underground power cable systems. The research aimed to determine the suitability of paraffin wax by analyzing its physical, mechanical, and thermal properties through a series of rigorous tests. The qualities of paraffin were the subject of this study, which consisted of analyzing such properties in accordance with the findings of several physical tests. During the physical testing, paraffin wax was utilized by mixing it with cement paste along with 10% of fly ash. This created a compound that was used. Because it was demonstrated that 10% of fly ash in the concrete mixture has the best compressive strength compared to any other percentage, this is the amount of fly ash that was added to the concrete mixture (the quantity of cement used was 10%). The primary components of the concrete mixture that was used in this study are fly ash, cement, and various percentages of paraffin wax (0%, 2%, 4%, 6%, 8%, and 10%, respectively).

The results showed that the inclusion of paraffin wax significantly enhanced the thermal properties of the concrete specimens. The heat storage capacity increased from 4.62 J/g for the control sample (0% PCM) to 13.63 J/g for the sample with 10% paraffin wax. This substantial increase highlights the effective thermal energy storage capability of paraffin wax, making it a promising additive for improving the thermal management of underground power cables. Additionally, thermal conductivity decreased from 0.8912 W/m·K for the control sample to 0.6669 W/m·K for the 10% paraffin wax sample, indicating improved insulation properties. However, the inclusion of paraffin wax also resulted in a reduction in compressive strength. Control samples without paraffin wax exhibited higher compressive strength, increasing from 31.40 MPa at 3 days to 54.37 MPa at 28 days. In contrast, samples with 10% paraffin wax showed a compressive strength increase from 28.27 MPa at 3 days to 48.94 MPa at 28 days. This reduction, approximately 10% lower than the control samples, is attributed to the increased porosity introduced by the paraffin wax. Infrared thermography further revealed that the surface temperature of specimens with paraffin wax increased more slowly compared to the control samples, indicating higher heat absorption and storage capacity. For instance, the final temperatures recorded after 40 minutes of heating were 30.3°C for the control sample and 29.7°C for the 10% paraffin wax sample, demonstrating the effectiveness of paraffin wax in thermal energy management.

Specimens with a higher paraffin content are able to store more heat for longer periods of time. This demonstrates that paraffin is the material that performs the best in terms of catering to the heat if it were employed as the backfill material. The paraffin has the ability to absorb and retain heat from the UPCS XPLE cables, and then release it when the cables have cooled down to their normal operating temperature. This phenomenon demonstrates that the efficiency of paraffin as a backfill material could assist UPCS XLPE cables in being utilized for a longer period of time, despite the cables' sensitivity to high heat. On the basis of the data that were obtained, it is possible to demonstrate that there has been a change in the properties of paraffin in terms of its physical, mechanical, and thermal aspects. This is due to the fact that the melting point of paraffin wax was at 28° C. As a result of this, it is possible to draw the conclusion that the paraffin went from being a solid to a liquid when the heat was transferred during the test. Aside from that, the findings demonstrated that the specimens that contained paraffin had a higher level of thermal stability than the specimens that did not contain paraffin.

While carrying out the preparations for this research investigation, it has been discovered that there are certain limits. One of the limitations is that PCM was used extensively as building materials, but there is a lack of study done about the use of paraffin as a backfill material for sand to cater heat from UPCS. Consequently, there is a need for additional findings in this study in order to strengthen the purpose of this investigation. It is possible to draw the conclusion that this study has demonstrated that paraffin is suitable to be used as one of the backfill materials due to the properties and performance that it possesses. This conclusion could be reached at the end of this study. Not only does paraffin have excellent thermal energy storage and thermal conductivity, but it also has excellent thermal stability, which means that it allows heat to flow inside the specimens by being impregnated to pores in the specimen. However, the trade-off between compressive strength and thermal properties must be carefully balanced to optimize both structural integrity and thermal efficiency.

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