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Analyzing thermal insulation of concrete polymer by adding mineral wool

Hamid M. Mahan[1*], Ali Katawy[2], Omran A. Shabeeb[3], Ahmed A.A.G. Alrubaiy[2]

[1] Middle Technical University, Technical Institute of Baquba, Diyala, Iraq
[2] University of Diyala, Collage of Engineering, Baquba, Diyala, 32002, Iraq
[3] Middle Technical University, Electrical Engineering Technical College, Baghdad, Iraq
* Corresponding author's e-mail: hamid.m.mahan@mtu.edu.iq

ABSTRACT

Modifying concrete with polymers offers numerous benefits, leading to more efficient, durable, and sustainable building practices, as well as energy savings for heating and cooling purposes. When selecting a polymer or polymer-modified concrete for a specific application, it is crucial to consider the desired properties and performance characteristics to achieve optimal results. In this research, the effect of adding rock wool and sand to a polyester-cement mixture on compressive strength and thermal insulation was studied by creating four different samples. The first sample consisted of 70% cement and 30% polyester. The second sample included 60% cement, 20% polyester, and 20% sand, without rock wool. The third sample comprised 60% cement, 19% polyester, 19% sand, and 2% rock wool. The fourth sample contained 58% cement, 19% polyester, 19% sand, and 4% rock wool. The results indicated that the basic sample (70% cement and 30% polyester) had a compressive strength of 74.233 MPa and the highest thermal conductivity of 0.7079 W/m·K. Among the three modified samples, the second sample (20% sand without rock wool) achieved the highest compressive strength of 89.34 MPa. Conversely, the fourth sample, with 4% rock wool, demonstrated the lowest thermal conductivity values, making it the best sample for thermal insulation. This superior insulation performance is attributed to the inclusion of rock wool, which has excellent thermal insulation properties, helping maintain stable internal temperatures and reduce energy costs in buildings.

Keywords: compressive strength, thermal conductivity, polyester, rock wool, thermal diffusivity.

INTRODUCTION

For many years, concrete has been a widely used material in various types of construction due to its favorable properties, versatility, and ease of production. The advent of synthetic polymers and their composites in the twentieth century has significantly expanded the range of available materials (1). Thermoplastic and thermoset polymers, along with their composites, are increasingly utilized in diverse structures to fulfill multiple functions. The remarkable versatility of polymers is the main driver of this trend, enabling the design and manufacture of a wide range of products to meet diverse application requirements at reasonable costs (2, 3). A comprehensive set of destructive tests, non-destructive methods, and microstructure investigations was conducted to evaluate the potential applications of rubber-treated concrete. The rubberized concrete exhibited decreased workability and increased porosity, resulting in higher air content within the mix. However, it also demonstrated reduced density and cost while improving ductility. A scanning electron microscope was used to examine the interface between aggregates and binding materials (4). The study also investigated the use of waste polypropylene fibers, focusing on mechanical properties and cement protection with fibers. The findings revealed that increasing the polypropylene fiber content reduced slump values while increasing the (VEBE) time of fresh concrete. The VEBE test is performed to measure quantify the ability capacity of the concrete to remold under given listed vibration conditions. It is a measure quantify of low consistency dependability of the fresh concrete mix. The research initially explored the effects of macro-polymeric and hybrid fibers, as well as polypropylene, on the physico-mechanical properties of concrete. It then assessed the impact of nano-silica and silica fume additions to high-quality cement without fibers. By increasing structural integrity and lowering energy loss due to deformation, basalt fibers at low percent between 0.1% and 1.5% by aggregate volume improve mechanical properties, especially flexural and tensile strengths, so indirectly supporting thermal insulation (5, 6).

Utilizing additives is a practical and efficient approach to improving the properties of rubberized cement-based materials (7–9). Fly ash (FA), an industrial by-product, possesses smooth morphological characteristics that create a "ball-bearing effect," enhancing interactions between the slurry and aggregates (10, 11). Studies, including those by Shao et al. (12), have shown that combining FA with crumb rubber significantly improves the flexural properties of ultra-high-performance concrete (UHPC). Other researchers, such as Zhao et al. and Shao et al. (13, 14), have also highlighted FA's contribution to enhancing the ductility of cement-based materials. Research conducted by Xiong et al. (15) explored the use of carbon fiber-reinforced polymer in creating rubber concrete. Their findings revealed modest gains in compressive strength but significant improvements in ductility, flexural toughness, impact resistance, and energy absorption. Similarly, Su et al. (16) investigated basalt-polypropylene fiber-reinforced rubber concrete, noting that the inclusion of these fibers significantly enhanced performance, particularly under high-temperature conditions.

Grynkowicz-Bylina et al. (17) created a technique to examine polymer material homogeneity including SBR rubber granules. This is pertinent to our research since consistent thermal insulation values across all samples depend on uniform distribution of additives such as polyester and rock wool in concrete. Glass fiber (GF), valued for its thermal insulation, tensile strength, heat resistance, and durability, is widely used in construction applications (18, 19). Despite these advantages, studies on rubberized cement-based materials modified with glass fiber remain limited, highlighting the need for further research in this area.

Polymers with various fillers are widely used as building materials due to their excellent binding properties and aggregate adhesion. Investigating the damage tolerance of epoxy-glass composites Masiewicz et al. (20) underlined the need of preserving mechanical strength in line with thermal enhancements. This fits our aim of maximizing concrete mixtures for structural integrity and thermal insulating value. Their long-chain structure facilitates the formation of a long-range network bonding structure, in contrast to the short-range bonding structure provided by cement materials. As a result, polymer materials typically offer superior compressive, tensile, and flexural strength compared to Portland cement concrete (21). Thermal conductivity, a characteristic property of materials, is influenced by factors such as density, moisture content, pore structure, solid particle shape, temperature, material composition, and the type of entrained gas. With increasing awareness of energy conservation and heat transfer control, as well as the implementation of basic performance standards, the use of concrete continues to grow in civil engineering applications, including building construction, roads, dams, mass concrete structures, and storage tanks. To meet future demands for energy efficiency and indoor thermal comfort, good thermal insulation is essential. This is critical for achieving low energy consumption, reduced carbon emissions, and a sustainable way of life (22). To enhance mechanical properties, chopped basalt fibers were added to recycled concrete aggregate at 0.1%, 0.3%, 0.5%, 1%, and 1.5% by the aggregate volume of the mix. The results indicate that while the compressive strength of the mix showed only a minor increase, the flexural and tensile splitting strengths improved significantly (23).

This study aims to develop concrete with enhanced overall performance, including superior mechanical and thermal insulation properties. To achieve this, two additives—rock wool and a mix of sand, cement, and polyester—were incorporated into the concrete. Rock wool boards, made from volcanic rock and other natural minerals, are high-performance insulation materials designed to provide thermal insulation, sound insulation, and fire protection properties. This investigation was designed to evaluate the impact of rock wool and sand addition on the thermal conductivity and compressive strength properties of the concrete-polyester mix. The primary objective is to determine the optimal properties of the developed composites by examining the effects of reclaimed fibers used as the reinforcement matrix, aiming to enhance their performance as insulation barriers in terms of both thermal conductivity and compressive strength.

MATERIALS AND EXPERIMENTAL PROCEDURE

Materials

The main raw materials used to create the specimens in this study were polyester, sand, cement, and rock wool. The physical and chemical properties of the Portland cement (ASTM Type I), with a specific gravity of 3.15, are provided in Table 1. Anti-slip river sand grains with a fine-medium size (0.5 mm) and a specific gravity of 2.66 were manufactured in Jordan by an English company. The thermosetting resin used was an unsaturated polyester with a density of 1.04 g/cm³ and a thermal conductivity of 0.288 W/m·°C. The chemical structure of the unsaturated polyester is depicted in Figure 1.

Material uses

Using an electronic balance (Model: AB135-S, precision: ± 0.001 g), the components for this study were precisely weighed to guarantee consistent sample preparation. This balance guarantees great accuracy and repeatability in the experimental results since its error percentage is less than 0.01%. Polyester was pre-mixed with sand and cement slowly for five minutes, before the last mixing operation to guarantee homogeneous distribution. Using an electronic balance the materials for this study were precisely weighed, in the concrete laboratory, a 0.07 m³ mixer was used to mix the components in line with the required amounts for every sample. Four samples were set up as shown in Table 2. Through first tests the chosen percentages of rock wool were found to maximize thermal insulation while preserving sufficient compressive strength so balancing structural integrity with energy efficiency. Polyester was added to the materials and mixed thoroughly to create a homogeneous mixture, which was then left to rest for 20 minutes at room temperature. Four

Table 1. Chemical oxide analysis and physical properties for cement

Components										
CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	I.R.	L.O.I.	L.S.F.
62.2%	20.1%	5.0%	3.6%	2.3%	1.2%	0.2%	0.5%	1.1%	2.9%	0.9%
Specific surface area (m^2/kg)		Initial setting time (hr.)		Final setting time (hr.)		Soundness (%)				
483		2:50		4:30		0.25				

Note: I.R. – insoluble residue, L.O.I. – loss on ignition, L.S.F. – lime saturation factor.

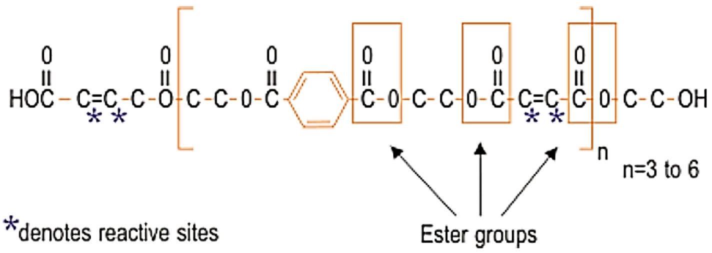

Figure 1. Chemical composition of unsaturated polyesters (24)

Table 2. Mix proportions of various polyester concert

Specimen No.	Cement (%)	Sand (%)	Polyester (%)	Rock wool (%)
Sp.1	70	-----	30	-----
Sp.2	60	20	20	----
Sp.3	60	19	19	2
Sp.4	58	19	19	4

iron cube molds measuring (100 × 100 × 100 mm) received the mixture. This was carried out right after the 20-minute rest period to allow for appropriate hydration and degassing of the mixture so guaranteeing homogeneity and lowering of air voids (25).

After pouring the molds were left undisturbed for 24 hours to allow the hardening process to complete. Once hardened, the molds were removed and the samples were left at room temperature for 21 days to cure and determine their compressive strength. The samples were kept under a regulated temperature of 23 °C ± 2 °C, relative humidity of 50% ± 5%, and low light exposure to stop any possible degradation during this period. Additionally, samples for the thermal conductivity test were prepared using four cubic molds with dimensions of 50 × 50 × 25 mm. Four samples of each mix proportion were tested to ensure data reliability and statistical significance.

Figure 2. Compressive test apparatus

TESTING METHODS

Compressive test

The compressive strength test was conducted in accordance with standard testing procedures, following the guidelines of ASTM C39, to ensure the validity and reliability of the results. Polymer concrete specimens with dimensions of 100 × 100 × 100 mm, as shown in Figure 3, were created and allowed sufficient curing time. The specimens were then carefully placed inside the testing apparatus (SKU: C040N Cyber-Plus Evolution) with a capacity of 1500 KN, as depicted in Figure 2. This apparatus is located in the Civil Engineering Department at the College of Engineering, Diyala University. This testing method not only determines the material's ultimate compressive strength but also provides insights into its behavior under load, including signs of cracking, deformation, or other failure mechanisms (26). Compressive strength is a critical property of polymer concrete, particularly in applications

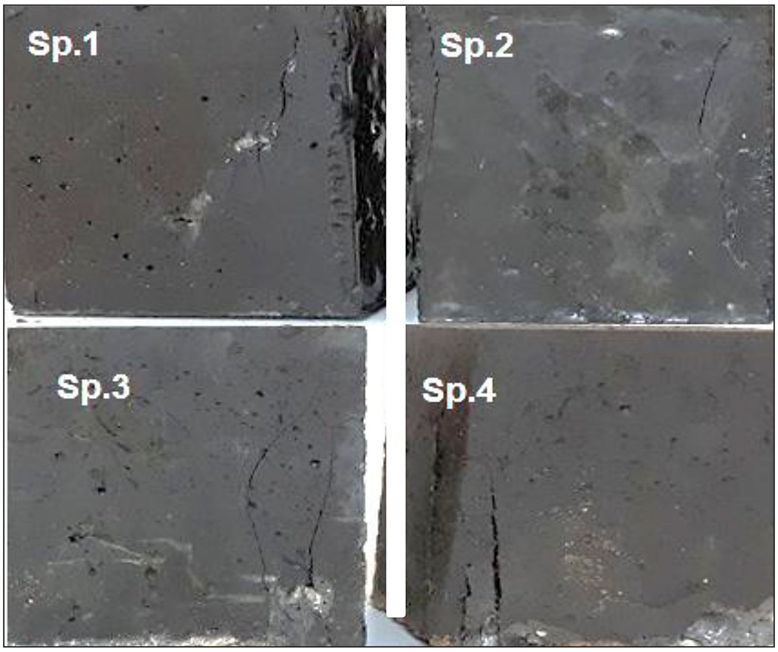

Figure 3. Specimens of compressive test

where materials are subject to dynamic loads. It directly influences the material's suitability for civil engineering and construction projects. A material with high compressive strength can bear heavy loads without failure, making it ideal for various structural applications. This characteristic is essential for ensuring the safety, reliability, and durability of construction materials in demanding environments.

Thermal conductivity test

A photograph of the thermal conductivity testing apparatus, equipped with a planar hot disk sensor, is shown in Figure 4. The apparatus is housed in the Materials Engineering Department at the Technical University of Iraq. Thermal conductivity (in W/m·K) was calculated using thermal diffusivity (in cm²/s, which denotes the rate of heat diffusion through the material), density (in g/cm³), and specific heat (in J/g·K). Thermal diffusivity was measured using the laser streak method, which involved a pulsed laser (Coherent General, MA), Labtech software, and a data acquisition board. The test specimens were disc-shaped, with a diameter of 50 mm and a thickness of 25 mm. As depicted in Figure 5, four specimens of each type were tested. The hot disk sensor was positioned as a sandwich between two identical specimen materials, which were prepared to standard dimensions in compliance with instrument specifications.

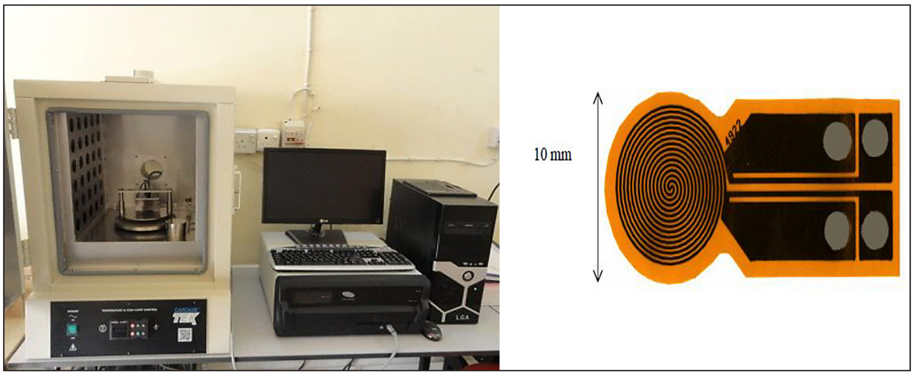

Figure 4. Device for measuring thermal properties and configuration of hot disk sensor

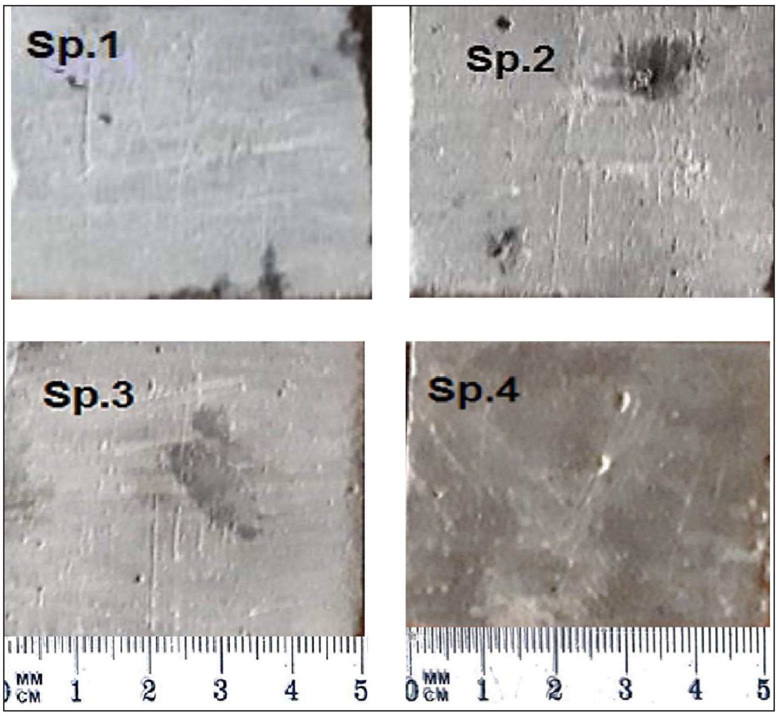

Figure 5. Specimens of thermal conductivity test

The sensor was centered and placed within the samples to ensure accurate thermal conductivity measurements (ASTM D7984). The sensor acted as both a heat source and a temperature sensor. It was briefly heated by passing an electrical current, while simultaneously recording the temperature increase over time. To minimize edge effects, the temperature increase from both the sensor and the surrounding specimen material was measured. From this data, the thermal diffusivity was calculated accurately.

Calculation of thermal properties

Thermal conductivity was calculated using the Equation (1):

$$k = \alpha \cdot \rho \cdot c \tag{1}$$

where: k – thermal conductivity (cm²/s), α – thermal diffusivity (mm²/s), ρ – density (g/cm³), c – specific heat capacity (J/g·K).

The solution relates specific heat, density, and thermal diffusivity to temperature response. Simultaneously computing thermal conductivity, diffusivity, and specific heat this model generates. This approach makes homogeneous and isotropic assumption on material (27).

RESULTS AND DISCUSSION

Compressive strength

Figure 6 illustrates the compressive strength results for all specimens after 21 days. As shown, all specimens exhibited notable compressive strength values. The mix containing 70% cement and 30% polyester achieved a compressive strength of 74.233 MPa. In comparison, the mix with 60% cement, 20% sand, and 20% polyester showed a 15.107% increase, reaching approximately 89.34 MPa. The mix containing 60% cement, 19% sand, 19% polyester, and 2% rock wool exhibited a slight decrease of 3.87% compared to the previous mix, with a compressive strength of about 85.47 MPa. However, the final mix, comprising 58% cement, 19% sand, 19% polyester, and 4% rock wool, recorded the lowest compressive strength at 65.1 MPa, representing a 20.37% decrease compared to the previous sample. The variation in compressive strength is attributed to the addition of 20% sand in the second mixture, which enhances the bonding strength between polyester and cement, thereby improving the overall structural integrity of the mix (15, 16). While this study provides insights into compressive strength, the absence of stress-strain data limits the mechanical behavior analysis. Future work should include stress-strain curves to enhance evaluation of mechanical properties.

Thermal conductivity test results

This study examined the impact of adding rock wool to polymer concrete on the composite samples' thermal conductivity and insulation properties. The effects of incorporating rock wool at 2% and 4% of the total concrete weight are presented in Table 3. The findings indicate that increasing the rock wool content

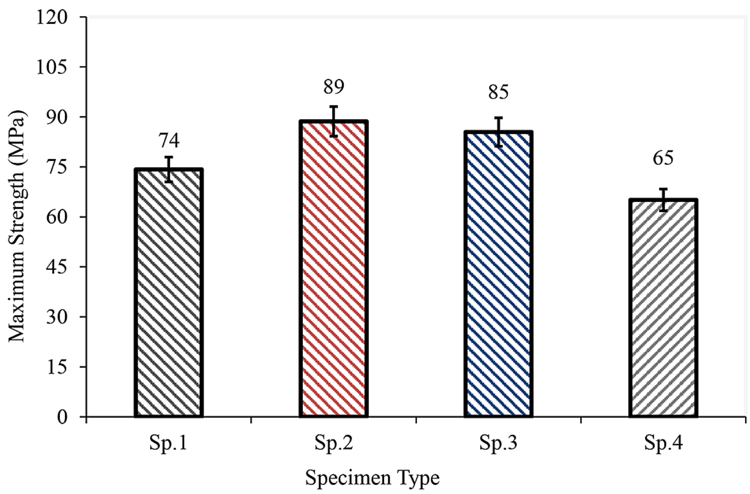

Figure 6. Compressive strength test for all sample

Table 3. Isolation results

Specimen No.	Thermal conductivity (W/mK)	Thermal diffusivity (mm^2/s)	Specific heat (MJ/m^3K)
Sp.1	0.7079	0.4458	1.637
Sp.2	0.6026	0.3681	1.611
Sp.3	0.362	0.216	1.501
Sp.4	0.296	0.201	1.471

decreases thermal conductivity and diffusivity while slightly reducing the concrete's compressive strength, thereby influencing its structural performance. These results highlight the beneficial properties achievable by adjusting the proportion of rock wool (19). When applied as insulation on surfaces or walls, the addition of rock wool significantly enhances the thermal insulation of buildings, effectively reducing the energy required for heating or cooling.

The first sample, which contains no sand or rock wool, exhibits the highest thermal conductivity and diffusion rates due to its high cement (70%) and polyester (30%) content compared to the other samples. In contrast, the thermal conductivity rate decreases in the second sample due to the reduced polyester content (20%) and the addition of sand (20%), which has a high silica content. The third sample shows a more significant reduction in thermal conductivity compared to the second sample, attributed to the further decrease in polyester (19%) and sand (19%), combined with the addition of rock wool (2%). The inclusion of rock wool demonstrates

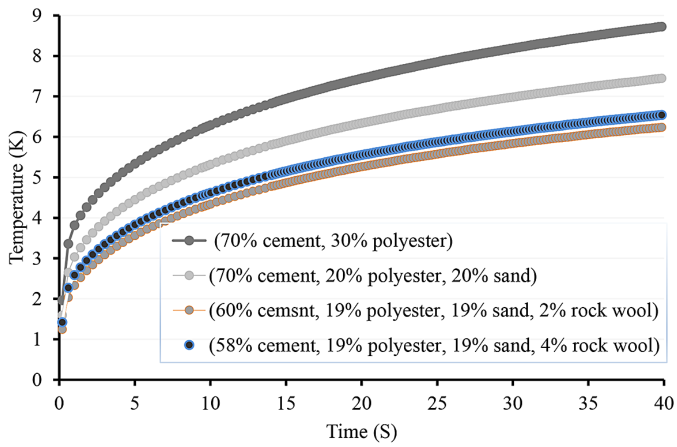

Figure 7. Temperature response of concrete mixtures with varying rock wool content over time

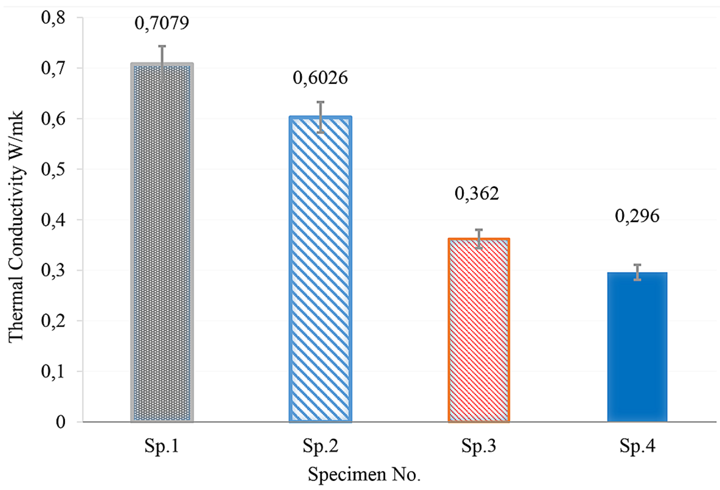

Figure 8. Thermal conductivity for all sample with the different ratio rock wool

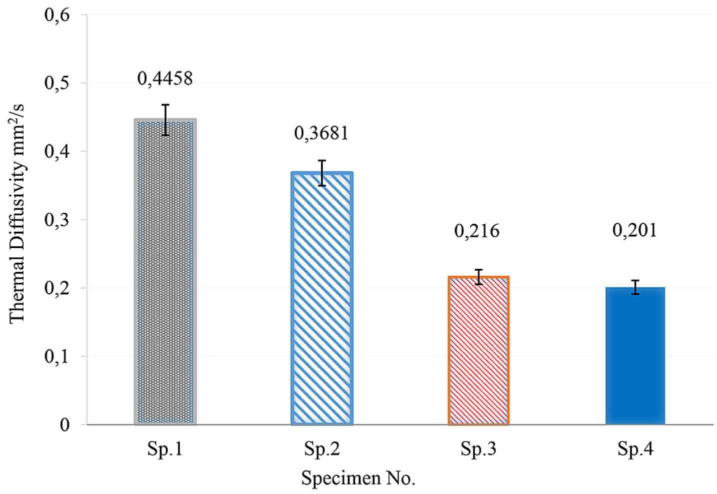

Figure 9. Thermal diffusivity coefficient for all sample with the different ratio rock wool

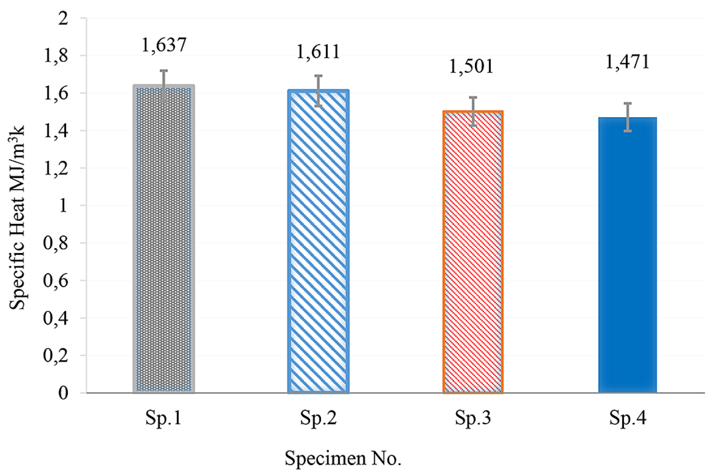

Figure 10. Specific heat coefficient for all sample with the different ratio rock wool

a noticeable thermal insulation effect, which becomes even more pronounced in the fourth sample. This final sample achieves the highest thermal insulation rate, as the rock wool content increases to 4%, while the proportions of other materials remain the same as in the third sample. Considering the thermal conductivity coefficients of polyester (0.33 W/m·K) and cement (52 W/m·K), the fourth sample exhibits excellent thermal insulation. This is due to the chemical reaction with rock wool, which contains a high silica content (derived from basalt stone). Figures 7–10 illustrate this effect. These results align with the influence of sand, which also has a high silica content (15). This analysis underscores how selecting appropriate materials can significantly impact energy efficiency and reduce the energy consumption of cooling and air conditioning systems.

CONCLUSIONS

This paper investigates the effect of varying amounts of rock wool fibers on the compressive strength and thermal conductivity of a composite mixture containing rock wool, sand, cement, and polyester. The main findings are as follows:

1. A porous polymer composite insulation material based on rock wool fibers was successfully prepared at room temperature. In the third sample, which included 2% by weight of rock wool fibers, the material achieved a thermal conductivity of 0.362 W/(m·K), a compressive strength of 85 MPa, and a thermal diffusivity of 0.216 mm²/s. With an increased rock wool content of 4% in the fourth sample, the thermal conductivity decreased to 0.296 W/(m·K), the compressive strength dropped to 65 MPa, and the thermal diffusivity reduced to 0.201 mm²/s.

2. The compressive strength of the concrete is higher when it consists solely of cement compared to samples containing rock wool fibers.
3. An increase in the proportion of rock wool fibers results in a decrease in compressive strength.
4. The incorporation of rock wool fibers, ranging from 2% to 4% by weight, leads to a reduction in thermal conductivity and thermal diffusivity, improving thermal insulation. However, this improvement comes with a decrease in compressive strength, particularly after heat treatment.

In conclusion, the rock wool fiber-reinforced polyester porous thermal insulation material developed in this study demonstrates strong potential for use in the construction industry, offering excellent thermal insulation and energy-saving capabilities. To improve mechanical qualities and thermal insulation even more, future research should investigate alternative additives including nanomaterials or bio-based fibers. Furthermore this ideal concrete mix is used practically in energy-efficient building designs, including insulated walls or roofs to lower heating or cooling costs and increase construction project sustainability.

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