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Heat Transfer Performance of Aluminum as a Conductor Material with Mixtures

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ABSTRACT

With the growing global population, meeting increasing energy demands has become progressively challenging, highlighting the importance of sustainable and eco-friendly energy sources. Energy-related infrastructures—such as thermal piles, buried power cables, and solid or nuclear waste disposal sites—are zones of high-temperature generation. Consequently, there is a critical need for alternative buffer materials capable of mitigating or rapidly dissipating this heat. In this study, a novel buffer material was developed by incorporating aluminum powder, known for its high thermal conductivity, into zeolite-bentonite mixtures at weight ratios of 1%, 2%, and 3%. The experimental results demonstrated that thermal conductivity increased in alignment with literature as the aluminum content rose. For instance, while the thermal conductivity of the pure 95% zeolite - 5% bentonite mixture was 0.749 W/mK, the addition of 3% aluminum increased this value to 0.795 W/mK, representing an enhancement of approximately 6%.

İletken Bir Malzeme Olarak Alüminyumun Karışımlarla Birlikte Isı İletim Performansı

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Sorumlu Yazar

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Anahtar Kelimeler

Termal iletkenlik
Alüminyum tozu
Tampon malzeme

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ÖZ

Artan dünya nüfusu ve bu nüfusun enerji ihtiyacının karşılanmasının giderek zorlaşmaktadır. Enerji kaynaklarının sürdürülebilir ve çevre dostu olması önem kazanmıştır. Enerji yapılarının en temelleri olarak değerlendirilebilecek termal kazıklar, gömülü güç kabloları, katı atık ve nükleer atık depolama alanları yüksek sıcaklıkların oluştuğu alanlar olup, bu nedenle ısının etkisini azaltabilen veya hızla ortadan kaldırabilen alternatif tampon malzemelere ihtiyaç duyulmaktadır. Bu çalışmada, yüksek ısıl iletkenliği ile bilinen alüminyum tozu, zeolit-bentonit karışımlarına ağırlıkça %1, %2 ve %3 oranlarında eklenerek yeni bir tampon malzeme geliştirilmiştir. Deneysel sonuçlar, alüminyum katkısının artmasıyla ısıl iletkenliğin literatürle paralel şekilde arttığını göstermiştir. Örneğin, saf 95zeolit-5bentonit karışımının ısıl iletkenlik değeri 0.749 W/mK iken, %3 alüminyum ilavesi ile bu değer 0.795 W/mK seviyesine yükselerek yaklaşık %6 oranında bir artış sergilemiştir.

1. INTRODUCTION

Thermal conductivity is one of the most important properties of materials. Thermal conductivity is related to the ability of a material to conduct heat. There is a different thermal conductivity coefficient for each material, and it is known that some materials and mixtures have higher thermal conductivity. Aluminum is one of the conductive materials with high thermal conductivity. Aluminum is a light, low-density metal found in the Earth's crust that has high electrical and thermal conductivity. It tends to bond with other elements. Aluminum has many different areas of use, and is used in electronic applications by combining it with fillers such as carbon nanotubes [1,2], graphite [3], Al_2O_3 [4], SiC [5-8] etc. for high thermal conductivity values with light weight. Thus, stronger composite structures can be produced. The thermal conductivity value of the materials formed depends on the microstructure of the components it contains, the bond strength between the materials, and the thermal properties, distribution, and geometry of the additive [6-9]. In addition to aluminum being a very common heat dissipation material, it is also aimed to increase its use for cooling purposes. For this purpose, it has been seen in studies that additive materials such as graphene are added to aluminum. Graphene plays a major role in thermal improvement in mixtures in terms of its thermal properties.

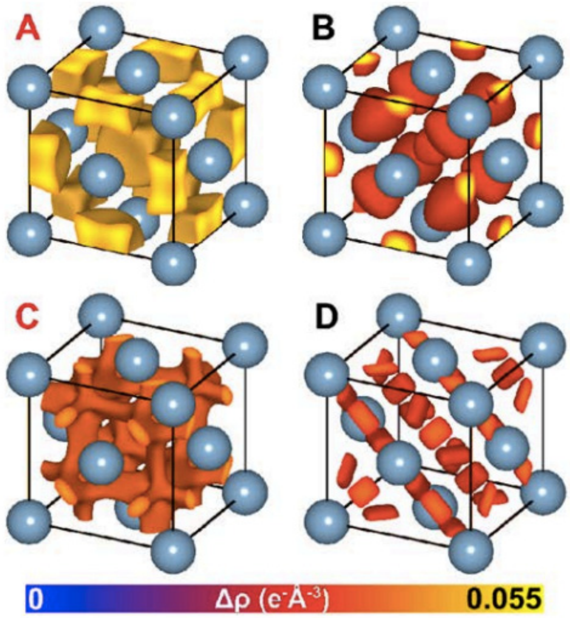

Figure 1. Three-dimensional example representations of bond electron density in aluminum from literature [10-13]

Figure 1 shows information about the nature of the ideal free electron metallic bond. The shapes in A and C were created by XRD analysis, and the shapes in B and D were created as a result of theoretical studies. The hexagonal striped region indicates a very strong tetrahedral bond, while the cross-striped region indicates octahedral bonds [14].

Materials with high heat transfer capability are needed in many different areas. There is a great demand for materials with high thermal conductivity in this research field, defined as energy geotechnics, which deals with the contact of energy geostructures with soils and how high temperature values occurring in the environment affect the engineering properties of soils. The high temperature and temperature cycles may affect the hydraulic conductivity behavior of soils. Many studies have been conducted on the variation of hydraulic conductivity of soils with temperature. In general, the results have been shown that the hydraulic conductivity increases as the temperature increases [15-17]. Also, it is predicted that the amount of energy that soils have when exposed to high temperatures will increase; accordingly, the energy of soil grains will increase. Molecules with increased energy will become more active, further weakening existing bonds. As a result, the amount of compression in the soil will increase [18,19]. In terms of shear strength, it was determined that the cohesion value increased due to the increase in the hardness of the soil with the effect of heating [20].

In the design of high-temperature engineering infrastructures, such as nuclear waste repositories and underground high-voltage power cables, the selection of an appropriate buffer material is of paramount importance. These materials serve a dual purpose: providing a hydraulic barrier to prevent contaminant migration and acting as a thermal conductor to dissipate the intense heat generated by the source. While traditional clay-based materials like bentonite and zeolite are favored for their low permeability, their inherently low thermal conductivity can lead to excessive heat accumulation, potentially compromising the integrity of the entire system. Therefore, enhancing the thermal efficiency of these buffer materials through high-conductivity additives, such as aluminum powder, has emerged as a critical research focus to ensure the safety and longevity of energy-related burial systems.

In areas where high temperatures occur, such as nuclear waste storage areas, the aim is to rapidly transfer the heat away from the heat source (canister) and to conduct it towards the main rock. Similarly, in areas where the natural heat of the ground is used, such as heat piles, it is desired that the thermal conductivity is high. For this purpose, it is essential that the mixture or material planned to be used in these areas has a very high heat conduction capacity. Bentonite and zeolite are of critical importance due to their capacity to serve as thermal and hydraulic barriers in nuclear waste management and underground energy transmission lines. Although the hydraulic properties of these materials have been extensively documented in the literature, their ability to dissipate heat from the surrounding environment is inherently limited. This study aims to optimize the 'thermal efficiency' of these barriers by utilizing aluminum powder. In this study, aluminum added zeolite-bentonite mixtures were formed and thermal conductivity measurements were carried out. The heat carrying capacity of mixtures without additives and aluminum added were evaluated.

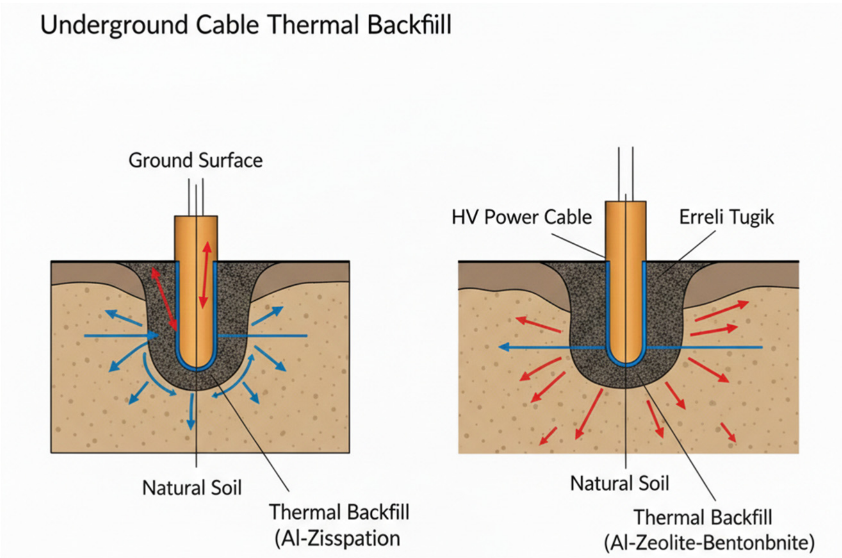

Figure 2. Conceptual design of the field implementation of the aluminum-enhanced mixture as a thermal buffer material for underground power transmission lines

This conceptual design illustrates the practical integration of the developed mixture within energy infrastructure. By replacing conventional backfill with this aluminum-enhanced buffer, a high-efficiency thermal discharge zone is created around the power lines. This arrangement not only prevents overheating but also optimizes the long-term operational safety and energy transmission capacity of the system, demonstrating the material's readiness for real-world geotechnical applications (Figure 2).

2. MATERIALS AND METHODS

2.1. Materials

Zeolite and bentonite were provided from local suppliers (Figure 3). The bentonite used is sodium bentonite. Aluminum used in dried form was added to zeolite-bentonite mixtures. When naming the mixtures, "Z" was chosen as zeolite, "B" as bentonite and "Al" as aluminum. Table 1 shows the physico-chemical properties of the materials used in the present study. The size of the aluminum powder used in the experiments is 120 microns and has a purity of 98.85%.

Figure 3. Dry mixture

Some of its main areas of use include; as a metallic pigment; decorative use in the coating, paint, ink and textile sectors; chemical use in the chemical production of polyphyllin, synthetic alcohol and aluminum-based chemicals for controlled reaction values of aluminum powder; use in the plastics and cosmetics sector; use as rocket fuel; use as an electrical conductor in the production of solar cells. In addition to these; it is used in the metallurgical sector as a reducer, heat source and alloying additive. Due to the exothermic properties of aluminum powder, it is frequently used in aluminothermic applications and exothermic sources. It is used as a refractory in the steel industry; as adhesives, fillers and coatings in space and military applications; and as an explosive in the mining, fireworks and military defense sectors.

Figure 4. Wet mixture

Table 1. Experimentally determined physical properties of the materials used in the study

Property	Zeolite	Bentonite
Specific gravity	2.50	2.40
Liquid limit (%)	50.0	476.0
Plastic limit (%)	N.P.	70.1
pH	7.6	9.5

2.2. Methods

Within the scope of a study, standard proctor tests were performed on zeolite-bentonite mixtures with aluminum additives. Samples with and without additives were created using the compaction parameters obtained according to the test results. The samples were compressed in thermal conductivity measurement molds for thermal conductivity measurements (Figure 5). During the compaction process in the mixtures, care was taken to ensure that the energy to be applied was applied equally depending on the number of impacts. The necessary probe was used for thermal conductivity measurement (Figure 5). The measurement results were determined at least 3 times for each sample and the final value was reached by discarding the insignificant results and taking the average among the significant results. The thermal conductivity of the zeolite-bentonite-aluminum mixtures was measured using the Transient Hot-Wire method, which is preferred in geotechnical research for its ability to provide rapid and accurate results without causing significant moisture migration within the soil sample.

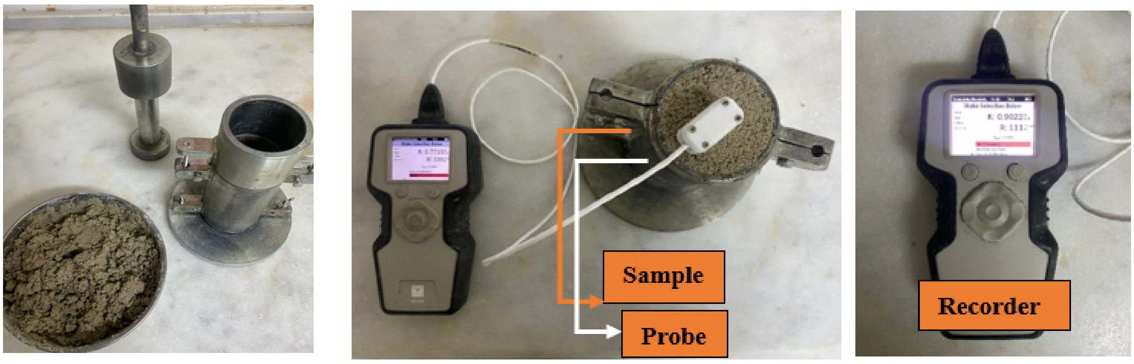

Figure 5. Sample compression apparatus and equipment of thermal conductivity measurement

Thermal properties of soils can vary depending on many factors. Mineralogical structure, particle diameter and grain distribution, dry unit weight, porosity, water content, temperature, pore size, soil skeleton and texture are some of these factors [21-23]. Studies have shown that there are three different factors affecting thermal conductivity: compositional factors, environmental factors and other factors. Examples of compositional factors include mineral composition, gradation, and physical contact area between particles; environmental factors include water content, temperature, and unit volume weight. Other factors include salts, ions, and additives [24]. Different methods have been applied by researchers for thermal conductivity measurements. These methods represent steady state, unsteady state and transition state. Methods such as needle measurement, hot ball method [25], disk-shaped probe measurement [26] have been tried and there are also measurement methods under development. The mathematical model of effective thermal conductivities is given in Equations 1 and 2:

$$k = k_w^{\perp} = [\sum \frac{\emptyset_\alpha}{k_\alpha}]^{-1} \text{ (Series)} \quad (1)$$

$$k = k_w^{U} = \sum \emptyset_\alpha k_\alpha \text{ (Series)} \quad (2)$$

ϕ_α : volume fraction, **k_α :** thermal conductivity, $k_w^{\perp}$ k_w^{U} and are the lower and upper Wiener bounds [27].

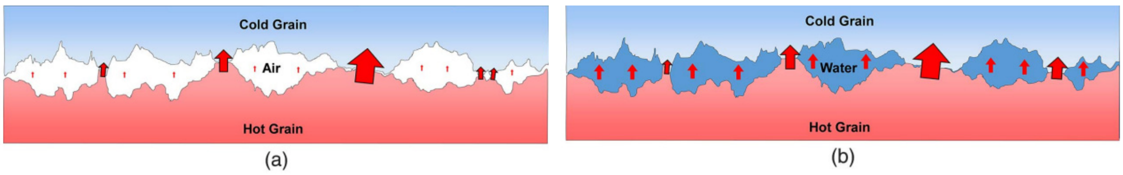

Figure 6. Illustration of heat conduction paths for (a) dry and (b) saturated conditions

Figure 6 shows that the contact resistance and thermal conductivity vary depending on the grain size [28,29]. The contact area and the distances between these surfaces depend on the forces between the grains, the properties of these grains such as strength and hardness, and the roughness of the surfaces [30].

3. RESULTS

3.1. Standard Proctor Test Results

In this study, compaction tests of zeolite-bentonite mixtures were carried out. The experimental results showed that as the amount of zeolite in the mixtures decreased or the amount of bentonite increased, the dry unit weight decreased and the water content increased. Since the ratio of aluminum additive used in the mixtures to the total weight of the mixture is quite low, samples were prepared based on mixtures without additives in the compaction tests. While the fact that the specific gravity of zeolite is slightly higher than the specific gravity of bentonite is shown as one of the reasons for the increase in dry unit weight, it was also observed that the water content increased due to the increase in the bentonite ratio in the mixtures, since bentonite is a material with a very high water absorption capacity [31]. Compaction parameters of the mixtures are given in Table 2.

The compaction characteristics of the zeolite-bentonite mixtures with varying aluminum (Al) content are illustrated in Figure 7. It is observed that the addition of aluminum powder leads to an increase in the Maximum Dry Density (MDD) while causing a slight decrease in the Optimum Moisture Content (OMC). This shift is attributed to the high specific gravity of aluminum particles compared to the clay matrix, which fills the void spaces and creates a more densely packed structure. From a geotechnical standpoint, achieving higher density at lower moisture levels is beneficial for the stability of thermal backfill materials. Since thermal conductivity is significantly enhanced by particle-to-particle contact, all subsequent thermal tests were conducted at these identified OMC points to ensure the samples represented their most stable and thermally efficient state.

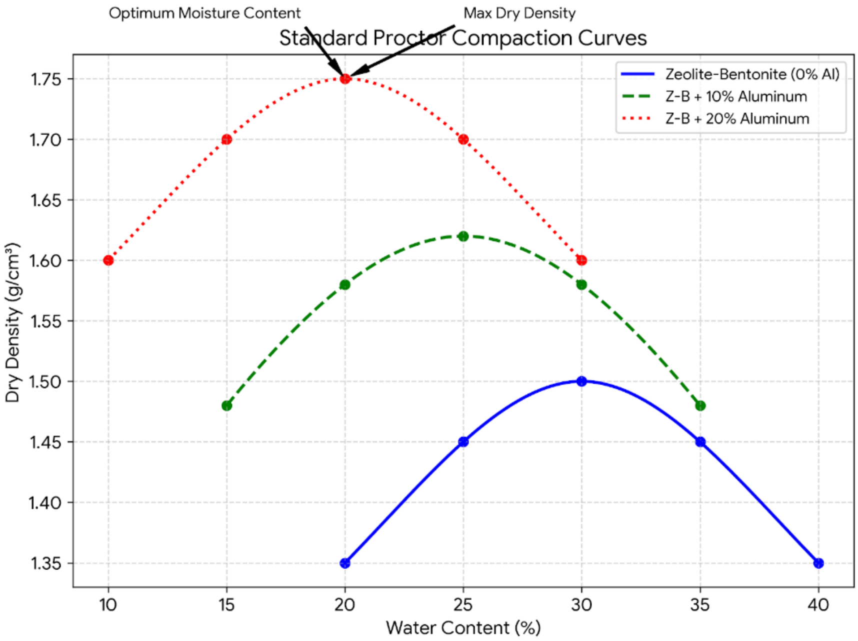

Figure 7. Standard proctor compaction curves for zeolite-bentonite mixtures with varying aluminum powder content, indicating the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) points

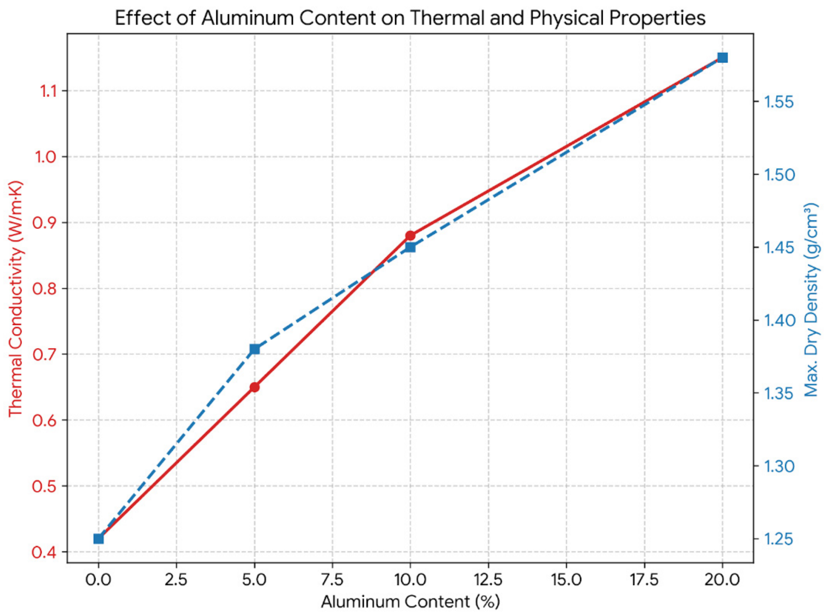

Figure 8. The correlation between aluminum additive percentage and the resulting thermal conductivity and dry density of the mixtures

The relationship between aluminum additive percentage, dry density, and thermal conductivity is presented in Figure 8. The results demonstrate a linear-to-exponential improvement in thermal conductivity as the aluminum content increases from 0% to 20%. Specifically, the inclusion of Al particles creates 'thermal bridges' within the relatively insulating zeolite-bentonite matrix, drastically reducing thermal resistance. Regarding the concerns about soil strength, the observed increase in dry density (as shown in the dual-axis plot) suggests a potential improvement in the compressive strength of the mixture due to reduced porosity. However, while the thermal performance is optimized, the mechanical behavior (such as shear strength and cohesion) may vary depending on the metallic-to-clay particle ratio. This enhancement in thermal conductivity without compromising density confirms that these mixtures are suitable candidates for high-voltage cable insulation and energy pile applications where heat dissipation is critical.

Table 2. Compaction parameters of the mixtur

Mixture	$\gamma_{dry,max}$ (kN/m^3)	w_{opt} (%)
95Z-5B	12.0	24
90Z-10B	11.5	27
85Z-15B	11.1	30

3.2. Thermal Conductivity Measurements

In this study, thermal conductivity values of zeolite-bentonite mixtures with and without additives were determined at room temperature. The measurement results showed that thermal conductivity values decreased with increasing bentonite amount in the mixtures without additives (Table 3). As the proportion of bentonite in the mixture increases, it is seen in Table 1 that the dry unit weight decreases. As the dry unit weight decreases, the thermal conductivity value also decreases due to the grains being able to contact less. The contact surface/area and water play an important role in thermal conductivity measurements [32]. While the contact surfaces of the grains control the thermal conductivity behavior at low water content values, as the amount of water increases, water takes over the control and after a certain level, its effect becomes negligible.

Table 3. Coefficient of thermal conductivity (λ)

Mixture	λ (W/mK)
95Z-5B	0.749
90Z-10B	0.723
85Z-15B	0.702

The findings obtained from this study are intended for field applications, particularly as backfill materials around thermal piles (energy piles). The increase in density observed with higher aluminum content (Table 2) may exert a positive indirect effect on the geotechnical bearing capacity by improving the material's compactability. However, advanced triaxial compression tests are required to optimize the balance between thermal enhancement and mechanical stability.

Figure 9 shows the thermal conductivity changes when aluminum was added to zeolite-bentonite mixtures at 1, 2 and 3% percentages. Mixtures 1, 2 and 3 represent 95Z-5B, 90Z-10B and 85Z-15B mixtures, respectively. The fact that the contribution rates are quite low and very close to each other explains the closeness of the thermal conductivity measurement results. It was also observed that the thermal conductivity value of the 95Z-5B mixture without additive was 0.749 W/mK, while it increased to 0.771 W/mK with 1% aluminum additive and to 0.786 and 0.795 W/mK with 2% and 3% aluminum additives, respectively. Although the increasing amount of bentonite in the pure mixtures has a decreasing effect on conductivity, each pure mixture has become more conductive thermally with the aluminum additives. When it is necessary to interpret the situation with a simple example, while the value of the 90Z-10B-1Al mixture is 0.764 W/mK, the conductivity value of the 85Z-15B-1Al mixture is determined as 0.792 W/mK. This situation can be explained by the decrease in unit volume weight and contact area of increasing bentonite.

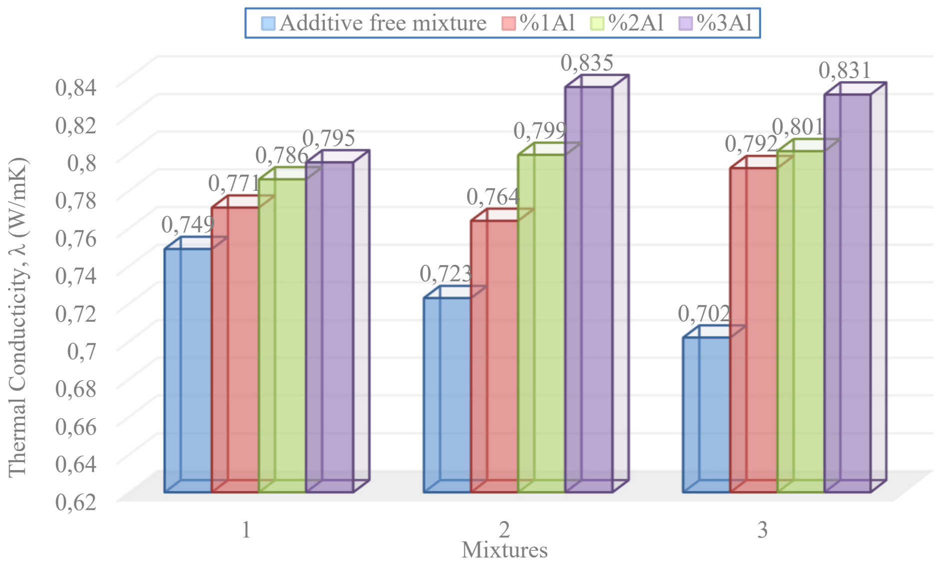

Figure 9. Effect of aluminum addition on thermal conductivity behavior of zeolite-bentonite mixtures

4. CONCLUSIONS

Within the scope of a study, standard proctor tests were performed on zeolite-bentonite mixtures with aluminum additives and thermal conductivity values of zeolite-bentonite mixtures with and without additives were determined at room temperature. It is known that thermal conductivity is among the most important ground parameters and can vary depending on the structure of the ground. Therefore, the minerals in the ground structure, ground texture and bonding methods can directly change the thermal properties. Parameters such as the degree of saturation of the ground, temperature, void ratio are also among the affecting factors. In this study, apart from these factors, the conductivity of new mixtures formed by using aluminum additives was evaluated. The results revealed that thermal conductivity increased as the amount of aluminum increased. On the other hand, it was noted that conductivity decreased as the amount of bentonite increased. This study is primarily limited to the thermal performance of the mixtures at their optimum moisture content (OMC). Since the thermal behavior of soils can vary significantly under different saturation levels, future research is recommended to investigate these mixtures under fully saturated and bone-dry conditions to provide a comprehensive thermal characteristic profile for diverse environmental scenarios. The use of aluminum-added zeolite-bentonite mixtures in targeted areas can be evaluated by performing and interpreting complementary experiments determining other engineering properties such as permeability and compressibility in terms of soil.

Within the scope of this study, the effects of aluminum powder utilized to enhance the thermal performance of zeolite-bentonite mixtures were experimentally investigated. The primary findings are presented below:

1. The addition of aluminum powder increased the thermal conductivity coefficient of the mixtures across all specimens in a linear trend. Increasing the aluminum content from 1% to 3% by weight resulted in an average improvement of approximately 18% in thermal conductivity.
2. The highest thermal conductivity value was measured as 0.835 W/mK.
3. The decrease in thermal conductivity values observed with increasing bentonite content was successfully compensated for by aluminum reinforcement. Compared to the pure zeolite-bentonite mixture, the thermal conductivity in specimens containing 3% aluminum rose from 0.749 W/mK to 0.795 W/mK.
4. A positive numerical correlation was identified between the dry density values obtained from Standard Proctor tests and the measured thermal conductivity, indicating that increased compaction directly benefits heat transfer.

In addition to the thermal enhancements, the influence of aluminum reinforcement on the mechanical strength of the mixtures warrants consideration. As demonstrated in the compaction data, the inclusion of aluminum powder led to an increase in the maximum dry density of the specimens. This densification typically results in a more robust particle arrangement and reduced porosity, which are key indicators of improved compressive strength and bearing capacity in geotechnical applications. Furthermore, the metallic particles may act as micro-inclusions that reinforce the zeolite-bentonite matrix, potentially increasing the overall stability of the buffer material. However, it should be noted that while higher density suggests a positive trend in strength, the potential impact of metallic additives on the cohesion and internal friction angle of the clay-based matrix should be further validated through comprehensive shear strength and triaxial compression testing to ensure long-term structural integrity under field loading conditions.

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