Chemical Composition and Heat Absorption Potential of Andesite for Thermoelectric Generator Absorbers

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Abstract - ***The performance of thermoelectric generators is highly influenced by heat absorption capability and thermal management at the hot side, as these factors determine the magnitude of the temperature gradient and the resulting electrical energy output. Conventional ceramic materials commonly used as thermal media generally involve high production costs and significant environmental impacts, thereby encouraging the development of alternative materials that are natural, economical, and sustainable. In this study, andesite stone was investigated as a potential natural heat-absorbing material for thermoelectric generator applications through chemical composition analysis using the X-ray fluorescence (XRF) method. The XRF results revealed that the andesite sample is predominantly composed of silica (SiO_2) at 54.15 wt.% and alumina (Al_2O_3) at 20.27 wt.%, forming a stable aluminosilicate structure. In addition, iron oxide (Fe_2O_3) of 8.33 wt.%, calcium oxide (CaO) of 8.52 wt.%, and magnesium oxide (MgO) of 2.12 wt.% were identified. The presence of iron oxide may contribute to enhanced heat absorption through increased emissivity, while calcium oxide and magnesium oxide are associated with improved structural stability and resistance to thermal shock. Furthermore, the very low loss on ignition value (0.02 wt.%) indicates minimal volatile content, suggesting good thermal and chemical stability at elevated temperatures. Based on its oxide composition, the investigated andesite is predicted to exhibit favorable characteristics for thermal energy applications; however, direct measurements of thermal conductivity, heat capacity, and emissivity are required to confirm these properties. Overall, the results indicate that andesite stone has considerable potential as a natural heat-absorbing or coating material in thermoelectric generator systems and may provide a more economical and environmentally friendly alternative to conventional synthetic ceramic materials.***

Keywords — Andesite stone; Chemical composition; Heat absorption; Thermoelectric generator; Natural absorber material

I. Introduction

Thermoelectric generators (TEG) have developed and gained wide attention as solid-state devices capable of directly converting thermal energy into electrical energy. This technology offers various advantages, including high reliability, noise-free operation, and relatively minimal maintenance requirements [1], [2]. The increasing need for waste heat utilization and renewable energy has also driven the intensification of research regarding thermoelectric generator systems for various applications, ranging from industrial processes to independent power generation in remote areas [3], [4]. Nevertheless, the relatively low energy conversion efficiency of thermoelectric generators, which typically ranges from 5–8% under practical operating conditions depending on the thermoelectric material figure of merit (ZT), remains a major constraint, which is highly influenced by thermal management at the heat source and the interface materials used [2], [5].

Effective heat absorption and heat transfer at the hot-side interface are crucial for maintaining the stability of the temperature gradient (ΔT), as this parameter directly determines the magnitude of the electrical output produced by the thermoelectric device [6], [7]. In conventional TEG systems, synthetic ceramic materials such as alumina (Al_2O_3) and zirconia (ZrO_2) are widely used as substrates or thermal coatings due to their high melting points and good mechanical resistance [8]. However, although synthetic ceramic materials generally exhibit good thermal conductivity, particularly alumina, their heat absorption and surface emissivity characteristics may be relatively limited for certain thermal harvesting applications, while they also have high production costs and significant environmental impacts due to fabrication processes that require large amounts of energy [9], [10].

In line with this, research attention has begun to shift toward the utilization of natural mineral-based materials as alternative heat absorbers and coating materials, which are expected to enhance thermal energy utilization while reducing costs and environmental burdens [11], [12]. Natural rocks, especially volcanic rocks, possess complex mineralogical structures and chemical compositions, thereby potentially providing good thermal buffering characteristics and thermal energy absorption capabilities [13], [14]. Among these materials, andesite stone, which is an intermediate volcanic igneous rock, is abundantly available in various regions and shows promising potential for thermal energy applications [15], [16].

Generally, andesite stone is composed of silicate minerals, especially plagioclase feldspar and ferromagnesian phases, which are known to influence thermal conductivity, heat capacity, and structural stability at high temperatures [17], [18]. The thermophysical properties of igneous rocks like andesite are highly determined by their mineral composition and crystal texture, considering that the ratio between plagioclase minerals and mafic minerals plays a role in controlling the thermal conductivity and diffusivity values of the rock [17]. Furthermore, variations in grain size and porosity levels in volcanic rocks also affect the volumetric heat capacity and the rock's response to changes in temperature gradients [17].

Experimental research results show that the presence of ferromagnesian minerals, such as pyroxene and amphibole, tends to increase the rock's ability to absorb and retain heat, which is related to their high density and more compact crystal structure [16]. Under high-temperature conditions, the structural stability of andesite stone is also influenced by the thermal expansion characteristics of its constituent minerals, which can cause microstructural changes without directly decreasing mechanical strength up to a certain temperature limit. The interaction between mineral composition, crystalline texture, and these internal physical properties makes andesite stone one of the prospective natural materials for applications requiring good thermal resistance and heat storage capacity [16].

The thermal behavior of volcanic rocks is reported to be determined not only by mass density but also by elemental composition, mineral bond strength, and microstructural heterogeneities such as grain boundaries and micro-scale porosity [14], [19]. These intrinsic characteristics distinguish natural rocks from homogeneous synthetic ceramics and potentially provide advantages in heat energy absorption and storage [20].

A number of studies indicate that volcanic rocks such as basalt and andesite have moderate thermal conductivity combined with a relatively high specific heat capacity, making them suitable for use as solar energy absorbing materials and thermal energy storage media [21]. However, most previous studies have focused more on measuring thermal properties macroscopically, without directly linking them to the quantitative chemical composition of the material [22]. Therefore, the fundamental relationship between elemental composition and heat absorption potential in andesite stone has not been widely studied, particularly in the context of thermoelectric generator applications [23].

X-ray fluorescence (XRF) spectroscopy is a non-destructive analytical method that has been widely used to determine the composition of major and trace elements in geological materials with a high level of accuracy and reproducibility [24], [25]. The oxide composition from XRF analysis can be used to interpret mineralogical phases, lattice structure stiffness, and phonon transport mechanisms that directly affect thermal conductivity and the heat absorption behavior of the material [26], [27]. Major oxides such as SiO_2, Al_2O_3, Fe_2O_3, CaO, and MgO are known to play an important role in determining heat transfer characteristics, emissivity, and thermal stability in ceramic and mineral-based materials [28], [29].

In this study, the chemical composition of andesite stone was experimentally characterized using XRF analysis conducted at the Center for Geological Survey Laboratory, Indonesia. The XRF characterization confirmed that the studied andesite stone exhibits the typical oxide composition of intermediate volcanic rocks, indicating its potential to provide a balanced combination of structural stiffness, heat absorption capability, and mechanical stability [30]. The distribution of these oxides is also consistent with the geochemical characteristics of intermediate volcanic rocks, where silica content is generally in the range of 52–63% by weight and correlates with the dominance of plagioclase minerals [16].

The relatively high Al2O3 and CaO content indicates the dominance of calcic to intermediate plagioclase, which plays an important role in controlling the mechanical strength and thermal stability of andesite stone [16]. Additionally, the presence of Fe2O3 and MgO shows the contribution of ferromagnesian minerals such as pyroxene and amphibole, which are known to influence density, thermal conductivity, and heat storage capacity due to their dense crystal structure and higher specific gravity [16]. From a petrophysical perspective, variations in major oxide composition significantly affect thermal diffusivity and volumetric heat capacity, where silica-rich structures tend to have lower thermal conductivity compared to phases enriched with mafic minerals [17].

Relatively high silica content contributes to the stability of the lattice structure at high temperatures, while Al2O3 enhances mechanical strength and resistance to thermal deformation [28],. The presence of iron oxide has an important role because iron-containing phases are known to be able to increase radiation heat absorption and emissivity values, which are desired properties for heat-absorbing materials [27], [28]. Furthermore, calcium and magnesium oxides contribute to strengthening the crystal lattice structure and increasing resistance to thermal shock during repeated heating and cooling cycles [29], [26].

The very low loss on ignition (LOI) value of 0.02% indicates minimal volatile content in the andesite stone sample, thus suggesting good thermal stability and a low risk of structural degradation under high-temperature operating conditions. This characteristic is very important for materials designed for long-term use in thermoelectric generator systems and thermal energy conversion [6], [29]. Therefore, the chemical composition obtained from XRF analysis provides a strong basis that andesite stone has the potential to function effectively as a natural heat-absorbing material or as a coating material in thermoelectric generator applications [11], [18].

In line with this, this study aims to provide a chemical composition-based scientific justification for the utilization of andesite stone as a heat-absorbing material, through the analysis of elements from XRF results and a discussion of their relationship with heat absorption behavior and integration into thermoelectric generator systems. Unlike previous studies that mainly focused on the macroscopic measurement of thermal properties of volcanic rocks, this study specifically establishes a composition-property relationship by systematically correlating the oxide composition of natural andesite with its potential thermal functions in thermoelectric generator applications. This approach provides a new perspective for preliminary screening and selection of natural heat-absorbing materials based on geochemical characteristics prior to detailed thermophysical testing. The results of this study are expected to contribute to the development of sustainable, low-cost, and local resource-based thermal energy conversion materials [11], [20].

II. Research Method

A. Material Description and Sample Preparation

The material used in this study is natural andesite stone, classified as an intermediate volcanic igneous rock and widely distributed across Indonesia. Andesite stone is commonly utilized as a construction material due to its good mechanical strength and high thermal stability [31]. The selection of andesite stone in this study is based on its reported potential as a heat-absorbing material, which is related to the dominance of silicate minerals and its favorable thermal properties [3]. The andesite stone samples were obtained from a local mining site and specifically prepared for chemical composition analysis according to standard geological laboratory procedures [5].

Prior to analysis, the andesite stone samples were mechanically cleaned to remove surface contaminants and weathered layers, ensuring that the measurements represent the overall composition of the rock mass[6]. The cleaned samples were then crushed and ground into a fine powder using an agate mortar to minimize potential contamination and elemental bias during the preparation stage [7]. The powder homogenization process was conducted to achieve a uniform particle size distribution, which is a critical factor in generating reliable and reproducible XRF analysis data [8].

To evaluate data reproducibility and minimize the influence of rock heterogeneity, XRF measurements were performed in triplicate on independently prepared pressed pellets. The reported oxide composition values represent the average of three measurements, while the relative standard deviation (RSD) for major oxides was maintained below 5%, indicating good analytical precision and reproducibility.

The homogeneous rock powder was subsequently prepared using the pressed pellet method, which is commonly used in geochemical XRF analysis due to its simple procedure, high level of reproducibility, and suitability for determining major and trace elements [9], [10]. This preparation method minimizes matrix effects and allows for accurate quantification of oxide composition in silicate-based materials [11]. All sample preparation procedures in this study followed the laboratory standard method GL-MU-2.2, as established by the Center for Geological Survey Laboratory, Indonesia.

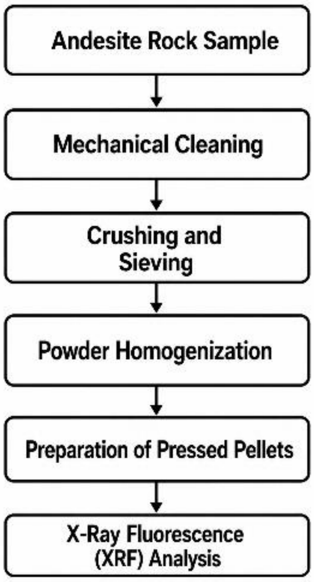

Figure 1. Flowchart of andesite stone sample preparation for X-Ray Fluorescence (XRF) analysis.

B. XRF (X-Ray Fluorescence) Analysis Method

The chemical composition of the andesite stone in this study was determined using the X-ray fluorescence (XRF) spectroscopy method, which is a non-destructive analytical technique widely used for quantitative elemental analysis of geological and ceramic materials. The XRF method is highly suitable for determining major oxides and trace elements in silicate rocks because of its high level of accuracy, relatively short measurement time, and minimal sample preparation requirements. The XRF testing was conducted at the Center for Geological Survey Laboratory, Bandung, Indonesia, which is an accredited national laboratory with competence in the characterization of geological materials.

The analysis was performed using a wavelength-dispersive XRF (WDXRF) system that had been calibrated and operated under controlled laboratory conditions, following standard procedures for quantifying oxide composition in igneous rocks. Instrument calibration was performed using certified reference materials to ensure measurement accuracy and consistency of analytical results across the range of major and trace elements. The analytical method used allows for the determination of major oxide, minor oxide, and specific trace element content, each expressed in units of weight percent (wt.%) and parts per million (ppm) [19].

Additionally, the loss on ignition (LOI) parameter was measured as part of the XRF analysis procedure to evaluate the volatile content in the sample and assess its thermal stability under high-temperature conditions [20]. A low LOI value generally indicates minimal volatile phase content, suggesting the suitability of the material for high-temperature thermal applications [21]. LOI measurements were carried out in accordance with standard geological testing procedures, and the results were used in the final normalization process of the oxide composition.

C. Chemical Composition Interpretation Framework

The XRF analysis results were interpreted based on oxide composition, which provides an overview of the mineralogical phases and thermal behavior of the andesite stone [22], [23]. Major oxides such as SiO2, Al2O3, Fe2O3, CaO, and MgO were specifically analyzed because they have a dominant influence on the lattice structure, phonon transport mechanisms, and thermal conductivity in silicate-based materials. Furthermore, the presence of alkali oxides such as Na2O and K2O was also considered, given their role in affecting ionic mobility and the thermal response of the material, especially in humid environments or under high-temperature conditions.

The iron oxide (Fe2O3) content was evaluated in more depth as it is known to play a role in increasing radiation heat absorption capability and the emissivity value of the material, which are important parameters for heat-absorbing materials. Meanwhile, calcium oxide (CaO) and magnesium oxide (MgO) were analyzed in relation to thermal shock resistance and mechanical stability, as both aspects are very important for materials experiencing repeated heating and cooling cycles in thermoelectric generator systems.

The obtained oxide composition data were then compared with the chemical compositions of volcanic rocks reported in previous studies that have been applied in the thermal and energy fields. This comparison was conducted to assess the level of material suitability and the consistency of the characteristics of the studied andesite stone compared to similar materials that have been used in thermal energy applications [3], [27].

D. Relevance of Andesite Stone to Thermoelectric Generator Applications

The chemical characterization methodology applied in this study was designed to support the evaluation of andesite stone as a heat-absorbing material or coating material in thermoelectric generator applications. Chemical composition analysis provides a fundamental basis for understanding the heat absorption capability, thermal stability, and level of compatibility of the andesite material with commonly used thermoelectric materials, such as bismuth telluride (Bi2Te3) based modules [29].

By linking the oxide composition from XRF analysis results with the thermal behavior of the material, this approach allows for the identification of material characteristics relevant to the operational requirements of thermoelectric generators, particularly on the hot side. This chemical composition-based framework provides a scientific basis in the material selection process, so that further, more complex testing, such as measurement of thermal performance and electrical characteristics, can be carried out in a more targeted and efficient manner [17].

III. Results and Discusion

A. Oxide Composition of Andesite Stone Based on XRF Analysis

The results of X-ray fluorescence (XRF) analysis show that the studied andesite stone is dominated by silicate and aluminosilicate oxides, which are common characteristics of intermediate volcanic rocks [31]. The oxide composition obtained from XRF measurements is presented in Table 1, which provides a comprehensive overview of the content of major oxides, minor oxides, and trace oxides in the analyzed sample.

The reported oxide concentrations are expressed in units of weight percent (wt.%) for major oxides and minor oxides, and in units of parts per million (ppm) for trace oxides, in accordance with geochemical data reporting standards commonly used in material and rock research. The presentation of data in this form allows accurate quantitative evaluation of the chemical composition of andesite stone and serves as a basis for further analysis related to its relationship with thermal properties and its potential application in thermoelectric generator systems.

To validate the geochemical characteristics of the analyzed sample, the major oxide composition obtained in this study was quantitatively compared with several reference datasets of andesite rocks reported in the literature. The comparison, presented in Table 2, demonstrates that the chemical composition of the investigated sample falls within the typical compositional range of intermediate volcanic rocks, particularly in terms of SiO2, Al2O3, Fe2O3, and alkali oxide contents.

Table 1. Results of Oxide Composition Analysis of Andesite Stone Using the XRF Method

Oxide	Content
SiO_2 (wt.%)	54.15
Al_2O_3 (wt.%)	20.27
Fe_2O_3 (wt.%)	8.33
CaO (wt.%)	8.52
MgO (wt.%)	2.12
Na_2O (wt.%)	3.47
K_2O (wt.%)	1.70
TiO_2 (wt.%)	0.661
MnO (wt.%)	0.179
P_2O_5 (wt.%)	0.301
Cl (wt.%)	0.102
SO_3 (wt.%)	0.109
SrO (wt.%)	0.057
CuO (ppm)	84.43
ZnO (ppm)	92.00
LOI (%)	0.02

The analysis results show that SiO2 (54.15 wt.%) and Al2O3 (20.27 wt.%) are the dominant oxides forming the main aluminosilicate framework in andesite stone. The dominance of these two oxides is a common characteristic of intermediate volcanic rocks and plays an important role in determining structural stability and the thermal properties of the material.

The presence of Fe_2O_3 (8.33 wt.%) and CaO (8.52 wt.%) indicates a significant contribution to the total composition of the rock, reflecting the presence of ferromagnesian mineral phases and plagioclase minerals. Iron oxide plays a role in increasing heat absorption capability through radiation, while calcium oxide is related to mineral structural stability and the mechanical strength of the rock.

In addition, minor oxides such as MgO, Na_2O, and K_2O were also detected in smaller amounts. The presence of these oxides indicates the existence of magnesium-containing silicate minerals and alkali feldspar, which are commonly found in andesite rocks. Although their content is relatively low, these minor oxides still influence the thermal response and overall physical properties of the rock.

B. Loss on Ignition and Volatile Content

The loss on ignition (LOI) value obtained from XRF analysis is 0.02%, which indicates that the volatile content in the analyzed andesite stone sample is at a very low level. A low LOI value is generally associated with minimal bound water, carbonate minerals, or organic material content, thus indicating good thermal stability when the material is exposed to high temperatures.

This result confirms that the studied andesite stone is relatively free from volatile phases that have the potential to cause structural degradation or changes in thermal behavior during repeated heating and cooling processes (thermal cycling). Therefore, this low LOI characteristic supports the potential of andesite stone as a heat-absorbing material or a stable coating material for thermoelectric generator applications, especially under high-temperature operating conditions.

C. Comparison with General Andesite Stone Composition

The oxide composition obtained in this study falls within the range of chemical composition of andesite stone that has been widely reported and used for thermal and structural applications. Previous studies reported that the SiO_2 content in andesite stone generally ranges from 52–63 wt.%, while the Al_2O_3 content usually ranges from 15–23 wt.%, showing good agreement with the values obtained in this study.

The Fe_2O_3 and CaO contents measured in the andesite stone sample are also comparable to values reported in previous studies that examined the utilization of andesite stone and similar volcanic rocks for thermal energy storage applications and heat-absorbing materials in solar thermal systems. This similarity in composition indicates that the chemical characteristics of the analyzed andesite stone do not deviate from the general representation of andesite stone used in heat energy-related applications.

The consistency of the oxide composition indicates that the studied andesite stone sample is representative of andesite stone in general, so it can be used as a reference material in evaluating the relationship between chemical composition and thermal properties in further analysis. In addition, the repeatability and agreement of the obtained oxide composition results also support the reliability of the sample preparation method and XRF measurement applied in this study.

D. Summary of Main Experimental Findings

Overall, the XRF analysis results confirm that the studied andesite stone has a silicate-rich composition with significant contributions from alumina, iron oxide, and calcium oxide, which are known to play an important role in influencing heat transfer mechanisms and the thermal energy absorption behavior of the material. The combination of these major oxides reflects the typical chemical characteristics of intermediate volcanic rocks and is relevant for high-temperature thermal applications.

In addition, the very low volatile content and relatively balanced oxide distribution indicate that andesite stone has good chemical stability under high-temperature heating. This characteristic is an important requirement for materials used as heat absorbers or coating materials in thermal energy conversion systems. Therefore, the experimental findings obtained in this study provide a strong scientific basis for further discussion regarding the feasibility of andesite stone as a heat-absorbing material or coating material in thermoelectric generator applications.

E. Discussion

1. Relationship between Oxide Composition and Heat Absorption Characteristics

The XRF analysis results show that the studied andesite stone is dominated by SiO_2 and Al_2O_3, which together form a rigid aluminosilicate framework and play an important role in providing thermal stability and controlling the heat transfer mechanism of the material. High silica content has been widely reported to increase lattice structural stability and resistance to thermal degradation at high temperatures, which is very important for materials exposed to continuous heat flux. Meanwhile, the presence of alumina contributes to improving mechanical strength and resistance to thermal deformation, thereby reducing the potential for cracking due to repeated heating and cooling cycles.

The presence of Fe_2O_3 in a significant amount (8.33 wt.%) provides a direct contribution to increasing heat absorption capability through radiation. Iron-containing oxides are known to have higher emissivity values compared to phases dominated by pure silica. Materials with high emissivity are more effective in absorbing incoming thermal radiation, thereby increasing the amount of heat energy available for conversion in energy harvesting systems. Thus, the iron-rich composition of the analyzed andesite stone supports its potential to act as an effective heat-absorbing layer.

In addition, the presence of calcium oxide (CaO) and magnesium oxide (MgO) also influences the thermal response of the material through their roles in stabilizing mineral phases and increasing resistance to thermal shock under cyclic heating conditions. These two oxides strengthen interatomic bonds in the crystal lattice structure, thereby suppressing the propagation of microcracks due to temperature fluctuations. Overall, the combination of major oxide compositions in andesite stone forms a balanced system between heat absorption capability and long-term thermal stability, which is an important characteristic for materials applied in thermoelectric generator systems.
The oxide composition obtained in this study reveals several distinctive characteristics compared with typical andesitic rocks reported in previous studies. The measured Al_2O_3 content (20.27 wt.%) is relatively high and indicates the dominance of aluminosilicate phases, which may provide improved structural stability during prolonged thermal exposure. Furthermore, the Fe_2O_3 content (8.33 wt.%) is located in the upper range commonly reported for intermediate volcanic rocks, suggesting a greater contribution of iron-bearing minerals to heat absorption through enhanced emissivity. This combination of relatively high Al_2O_3 and Fe_2O_3 contents distinguishes the investigated sample from many conventional volcanic rocks and suggests that the studied andesite may possess advantageous characteristics for thermal energy applications.

2. Correlation of Oxide Composition with the Thermal Function of Andesite Stone

To clearly relate chemical composition with the thermal function of the material, Table 2 summarizes the roles of the main oxides identified through XRF analysis and their relevance to heat absorption mechanisms and their application in thermoelectric generator systems.

Table 2. Correlation between Oxide Composition and Thermal Function of Andesite Stone

Main Oxide	**Content (%)**	**Thermal Function**	**Implication for Thermoelectric Generator Application**
SiO_2	54.15	Stability of the lattice structure and control of thermal conductivity	Maintains ΔT stability on the hot side
Al_2O_3	20.27	Enhances mechanical strength and resistance to thermal deformation	Reduces the risk of cracking due to thermal cycling
Fe_2O_3	8.33	Increases emissivity and heat absorption	Improves heat absorption for energy conversion
CaO	8.52	Stabilizes mineral phases and improves thermal shock resistance	Supports long-term operation
MgO	2.12	Strengthens lattice bonding and thermal stability	Suppresses microcracking caused by temperature fluctuations
$Na_2O + K_2O$	-	Modifies ionic and thermal response	Has a minor influence in high-temperature environments

The data presented in Table 2 show that each major oxide contributes to complementary thermal functions, thereby supporting the suitability of andesite stone to be applied as a heat-absorbing material, not merely as a heat-conducting material. The synergy of these oxide compositions produces balanced thermal characteristics, namely the ability to absorb heat energy while maintaining structural stability during the heat transfer process.
This characteristic is highly beneficial for thermoelectric generator systems, which require a stable and continuous heat supply on the hot side, rather than excessively rapid heat dissipation. Thus, the relationship between oxide composition and thermal function shown by andesite stone strengthens its potential as a heat-absorbing material or coating material in supporting the performance and reliability of thermoelectric generator systems.

3. Thermal-Buffering Effect and Its Implications for Thermoelectric Generator Performance

In thermoelectric generator (TEG) systems, electrical power output is determined by the temperature gradient (ΔT) formed along the thermoelectric element. The magnitude of this ΔT is strongly influenced by heat absorption capability and the thermal buffering effect at the hot-side interface. Materials with excessively high thermal conductivity tend to accelerate temperature equalization between the hot side and the cold side, thereby reducing ΔT and limiting power generation capability. In contrast, materials with moderate thermal conductivity and relatively high heat capacity are able to store heat energy and release it gradually, thereby helping to maintain ΔT stability during operation.

Based on its composition dominated by aluminosilicates and its very low volatile content (LOI = 0.02%), the studied andesite stone is estimated to have moderate thermal conductivity combined with good heat storage capability. This characteristic indicates the presence of a thermal buffering effect, which plays an important role in stabilizing heat flow toward the thermoelectric module. This effect becomes highly beneficial under fluctuating heat source conditions, such as non-constant solar radiation or intermittent waste heat.
To illustrate this conceptual role, Figure 2 presents a schematic comparison between a conventional ceramic interface and an andesite stone-based heat-absorbing layer in a thermoelectric generator system. This illustration shows that the use of andesite stone as a heat-absorbing layer has the potential to produce a more stable heat supply to the thermoelectric element, thereby supporting improved performance stability and overall reliability of the TEG system.

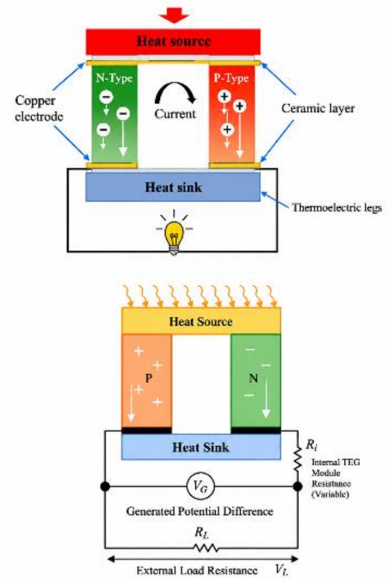

Figure 2. Conceptual illustration of the proposed role of andesite stone as a heat-absorbing material and thermal buffer at the hot-side interface of a thermoelectric generator (conceptual model without experimental validation).

It should be noted that Figure 2 represents only a conceptual illustration of the proposed role of andesite stone as a heat-absorbing material and thermal buffer in a thermoelectric generator system. The present study did not experimentally investigate the integration of andesite stone into an actual thermoelectric generator module. Therefore, the proposed thermal-buffering mechanism and its possible influence on thermoelectric generator performance remain hypothetical and are inferred from the measured oxide composition together with previous literature findings. Further studies involving direct measurements of thermal properties and prototype-scale thermoelectric testing are necessary to experimentally validate the proposed application.

4. Comparison of Andesite Stone with Conventional Thermal Ceramic Materials

When compared with conventional ceramic materials such as alumina (Al2O3) or zirconia (ZrO2), andesite stone offers a unique combination of heat absorption capability, thermal buffering effect, and material sustainability. Synthetic ceramics generally require sintering processes at high temperatures, which result in increased production costs and environmental footprint due to high energy consumption. In contrast, andesite stone can be processed with relatively lower energy requirements while still maintaining adequate thermal and mechanical performance for high-temperature applications.
Although direct comparative experiments with conventional ceramic materials were not conducted in the present study, quantitative data reported in the literature indicate that synthetic ceramics such as alumina and zirconia generally require high-temperature sintering processes and involve higher production costs. In contrast, the investigated andesite can be utilized with minimal processing while exhibiting a chemical composition rich in aluminosilicate and iron-bearing phases. The relatively high Fe_2O_3 content identified in this study may provide additional advantages in terms of heat absorption capability compared with silica-dominated ceramic materials. Nevertheless, direct measurements of thermal conductivity, heat capacity, and emissivity, as well as comparative thermal performance tests against alumina and zirconia, are required in future studies to quantitatively validate these potential advantages.
In addition, the natural microstructural heterogeneity of volcanic rocks, including andesite stone, plays a role in increasing phonon scattering within the material. This mechanism enables better control of heat transfer compared to excessively rapid heat transfer as found in highly homogeneous materials. This characteristic is highly advantageous for thermoelectric applications, where maintaining the temperature gradient (ΔT) in thermoelectric elements is more crucial than merely maximizing thermal conductivity.
By considering aspects of thermal performance, structural stability, and process and material sustainability, andesite stone can be viewed as a promising natural alternative to synthetic thermal ceramic materials in thermoelectric generator systems.

IV. Conslusion

The conclusions from the research results are explained as follows:

1. The X-ray fluorescence (XRF) analysis revealed that the investigated andesite stone is predominantly composed of SiO_2 and Al_2O_3, indicating the presence of a strong aluminosilicate framework that is characteristic of intermediate volcanic rocks.

2. The chemical composition also shows significant contents of Fe_2O_3, CaO, and MgO, suggesting the presence of iron-bearing and ferromagnesian mineral phases that may influence the thermal and structural behavior of the material.
3. The relatively high Al_2O_3 content and the presence of CaO and MgO indicate that the investigated andesite possesses a mineralogical composition potentially associated with structural stability and resistance to thermal degradation.
4. The very low loss on ignition (LOI) value indicates minimal volatile content, suggesting good chemical stability of the material under elevated-temperature conditions.
5. Based on its oxide composition and supporting literature, andesite stone is considered a promising candidate for further investigation as a passive thermal management material, particularly as a heat absorber or thermal buffer layer in thermoelectric generator systems. However, experimental validation in an actual thermoelectric generator system is required to confirm this proposed application.
6. Compared with conventional synthetic ceramic materials, andesite stone offers advantages in terms of natural abundance, simple processing, and potential environmental sustainability, which may support its utilization in cost-effective thermal energy applications.
7. Further studies are required to experimentally determine thermal conductivity, thermal diffusivity, specific heat capacity, emissivity, and direct thermoelectric generator performance in order to validate the suitability of andesite stone for thermoelectric applications.

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