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The impact of thermal treatment on the mechanical properties and thermal insulation of building materials enhanced with two types of volcanic scoria additives

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ABSTRACT

The need to substitute cement with eco-friendly building materials has increased in recent years, and attempts to enhance the mechanical and thermal insulation properties of these materials are ongoing. Therefore, the present study aims to use two different types of scoria as substitutes for cement in building materials and investigate the impact of thermal treatment on improving mechanical characteristics and thermal insulation. Black and red volcanic scoria, both before and after thermal treatment at different temperatures (600, 700, 800, and 900 °C), were utilized as cement substitutes in concrete specimens. Concrete specimens with different proportions (0–30 % wt.%) of black and red scoria were cured for different durations (14, 21, 28, and 91 days), and then tested for compressive strength. The compressive strength of specimens increased with increasing curing time, but decreased when scoria content exceeded wt.10 %. Furthermore, thermal treatment positively impacted the compressive strength of concrete specimens with red scoria, but negatively affected those with black scoria, owing to the increase in crystalline phases with increasing temperature. The specimen containing 10 % red scoria thermally treated at 900 °C and cured for 91 days yielded the highest compressive strength (60 ± 1.22 MPa). Further, the thermal insulation analysis of the concrete specimens with each type of thermally treated scoria was performed on day 28 of curing. The thermal insulation increased as the proportions of black and red scoria increased, which involved increasing the thermal treatment temperature of both scoria from room temperature to 900 °C on day 28 of curing. Additionally, the thermal insulation of concrete specimens treated with red scoria was more optimized than that of concrete treated with black scoria, particularly at high thermal treatment temperatures, and more than seven times as much as that of ordinary concrete. The lowest thermal conductivity value of the specimen was 0.157 ± 0.01 W m^{-1} K^{-1}. Based on the findings, concrete with thermally treated red scoria is a suitable eco-friendly building material with high compressive strength and efficient thermal insulation properties.

1. Introduction

Environmental pollution has been exacerbated by increased CO_2 levels in the air, particularly from the manufacture of building materials such as cement, thus contributing to climate change and global warming [1–4]. Moreover, the growing demand for building insulation to save energy consumption has necessitated the identification of environment friendly and cost-effective substitutes for

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Table 1
The average thermal conductivity of the different natural and waste building materials.

Nutural materials	Average of thermal conductivity (W/Km)	References
fly ash	0.938–0.405	[5]
Rice	0.0464–0.566	[6]
Cotton (stalks)	0.0585–0.0815	[6]
Date palm	0.072–0.085	[6]
Reeds	0.045–0.056	[6]
Oil palm	0.055–0.091	[6]

cement. Studies on the use of eco-friendly natural resources and waste materials including kenaf wood fibers, fly ash, coconut shells, and volcanic material, for thermal and acoustic insulation and as substitutes for cement and other construction materials (such as insulator panels) have recently been conducted [5–10]. The thermal conductivities (κ) of several natural and waste building materials vary significantly; they range from 0.035 W/(m k) to 3.50 W/(m k) as shown in Table 1 [5,6]. Thermal conductivity is the primary parameter in determining the thermal insulation properties of building materials; it is influenced by various factors, such as the type, density, porosity, length, and cross-sectional area of material, and the temperature difference between the two ends of the material. This has necessitated research on green building materials aimed at improving environment friendly thermal insulation materials. In particular, volcanic productions like scoria and pumice, which are abundant, are promising substitutes for cement in the fabrication of concrete [7–10]. Most scoria have pozzolanic activity, which can potentially be utilized as cement replacement in the manufacture of strong concrete [11,12]. Scoria concrete exhibits superior thermal resistivity, as well as thermal insulation that is several times more optimized than that of ordinary concrete or concrete made with silica sand [9,13]. Moreover, scoria concrete exhibits more optimized thermal insulation than fly ash concrete ($\kappa = 0.938$ to 0.405 W m^{-1} K^{-1}) [5]. Nevertheless, studies on the potential of scoria for thermal insulation in building materials considering their mechanical and structural characteristics are limited [7,9,10,14]. Moreover, previous study findings on the mechanical properties of scoria have been inconsistent owing to variations in the chemical composition, structural phases, and portions of the additive scoria in the concrete matrix. The effects of volcanic materials on the mechanical and structural characteristics of mortar and concrete have been studied extensively [15–18]. Previous studies have reported the important technical advantages of partially substituting Portland cement with scoria. The compressive strength of mortar containing 20 % volcanic ash (69.6 MPa) was observed to improve owing to the high fineness of volcanic ash compared to that of the control samples (68.1 MPa), particularly at 91 days of curing [4]. Nevertheless, the partial replacement of cement with volcanic material lowered the early age strength of the treated specimen compared to that of control specimens. This result is consistent with a study that found comparable compressive strength between control specimens and those using powdered volcanic material with a 45 mm thickness and a 10 % wt [15]. It was reported that all volcanic materials from the Harrat Rahat (a volcanic lava field in the western region of Saudi Arabia) displayed pozzolanic behavior and were consistent with the Italian conditions [7]. In contrast, another research found that replacing 15 % of cement with fine powdered volcanic material resulted in the building material exhibiting lower compressive strength than that of the control samples at each age [17]. Volcanic ash replacements of up to 30 % of Portland cement resulted in improved vascularity and porosity of the cementitious matrix [19]. It was recorded that a 10 % replacement of volcanic ash in the cement produced a small decrease in strength. Nevertheless, 20 % and 30 % replacement produced a significant decrease in strength [20]. Some researches have reported that volcanic materials have low reactivity, which effects to delays in the improvement of strength and other durability properties. The inconsistencies in study findings are attributed to variations in the physical properties of scoria such as the amount of amorphous phase, mineralogy, specific surface area, and chemical composition which refer to the origin of the magma and eruption conditions. This necessitates the advancement of volcanic ash to increase its reactivity, ultimately reinforcing it and improving its durability. According to earlier researches [21–25], mechanical, chemical, and thermal methods might be applied to enhance the characteristics of natural pozzolan.

This study aimed to determine the effect of thermal treatment on the mechanical characteristics and thermal insulation of two different types of volcanic scoria as a partial cement substitution. Two different types of volcanic scoria were used to create durable, high-performance concrete as well as a natural insulation construction material that is a part of eco-friendly, energy-efficient building materials. The two different volcanic scoriae were subjected to different elevated temperatures (600, 700, 800, and 900 °C) in a furnace to determine the effect of thermal treatment on the pozzolanic characteristics of volcanic scoria. Chemical components and the thermal characteristic of scoria were studied by X -ray fluorescence spectrometry (XRF) analysis and differential scanning calorimetry (DSC) analysis, respectively. The mineral phases were analyzed on both ground volcanic scoria and thermal–treated volcanic scoria specimens using X-ray diffraction analysis (XRD) and Raman analysis. The specimens of concrete were fabricated as a partial replacement for cement with proportions 0 %, 10 %, 20 % and 30 % wt.% volcanic scoria before and after thermal treatment. Then, the compressive strength and thermal conductivity were studied for these specimens.

2. materials and methods

2.1. Materials

The Portland cement was utilized as a major building material. Also, was used raw specimens of different scoria that get from the western region of Saudi Arabia [26]. These specimens were milled using a crusher in two stages and then ground to a very fine powder

Table 2
Mix proportions of cement concrete samples with different red and black scoria percentages.

Specimens no#		Scoria content	Cement (Kg)	Water(Kg)	Red/Black Scoria (Kg)	Coarse aggregate(Kg)	Fine aggregate(Kg)
Black scoria	Red scoria	(%)					
BS1	RS1	0	476	207	0	888	711.4
BS2	RS2	10	428.4	207	47.6	888	711.4
BS3	RS3	20	380.8	207	95.2	888	711.4
BS4	RS4	30	333.2	207	142.8	888	711.4

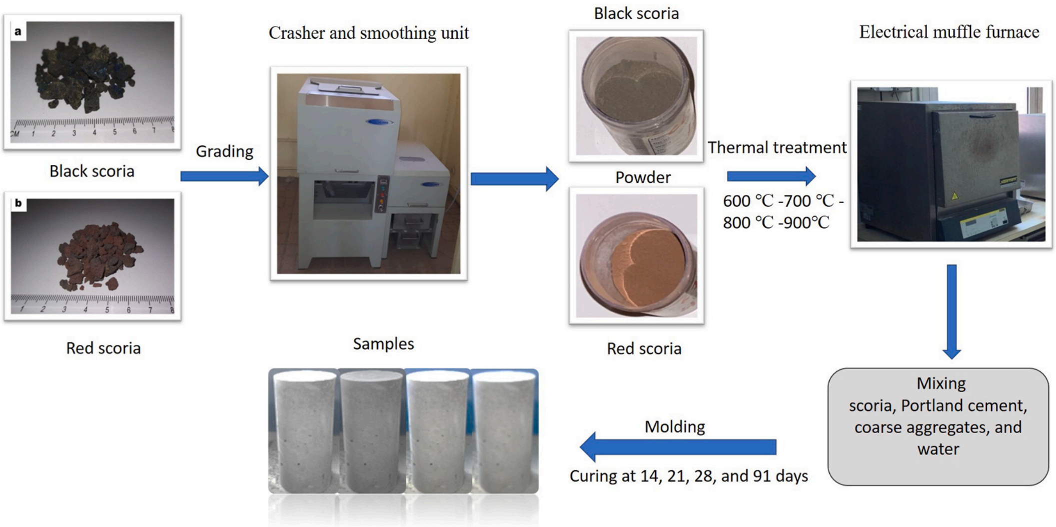

Fig. 1. Schematic of the preparation process of concrete specimens with different proportions of black and red scoria.

using a smoothing machine and sieved to get a particle size 25 μm that passed through sieve no.500 mesh. X-ray fluorescence with SPECTRO - EXPOS (AMETEK Inc., USA) was used to analyze the specimen's chemical composition. The bulk density of the specimens was assessed using an Ultra pycnometer 1000. Differential scanning calorimetry was carried out by using DSC (STA 449 F3 Jupiter; NETZSCH, Germany) in static air at a heating rate of 5 °C/min. The volcanic scoria was heated at various temperatures to investigate the effect of thermal treatment on the mechanical characteristics and thermal insulator. An electric muffle furnace was employed to heat scoria at temperatures of 600, 700, 800, and 900 °C for 2 h. Then, it was allowed to air-cool abruptly. The mineralogical composition of each scoria was studied by XRD (Bruker, USA) using Cu Kα Ni-filtered radiation (λ = 1.54 Å and 2θ = 5–90°) to determine how thermal treatment affects the crystal and phases of the scoria specimens. Raman analysis of the scoria specimens were studied using a DXR Micro Raman microscope (Thermo Fisher Scientific, USA) equipped with a diode-pumped solid-state (DPSS) laser at 532 nm for specimen excitation.

2.2. *Preparation of concrete specimens*

Concrete specimens were fabricated from a mixture of Portland cement, coarse aggregates, fine aggregates, water, and scoria, with Portland cement being substituted in different proportions (0 %, 10 %, 20 %, and 30 % wt.%) using a Hobart mixer. Concrete mix design specimens are presented in Table 2. The water/cement ratio was 0.43. The specimens were casted into molds, and demolded after 24 h. Then, the specimens were cured in a saturated lime water solution until the testing age. Fig. 1 shows the process of preparing concrete specimens. The specimens were fabricated in slab form for thermal conductivity tests and in cylindrical form for compressive strength tests. The thermal conductivity of the specimens in slab form was tested using a NETZSCH heat flow meter model after curing for 28 days. Compressive strength of the cylindrical specimens was tested after 14, 21, 28, and 91 days using a universal testing machine. Three specimens from each mixture were examined for each measurement, then the average test values of thermal conductivity and the average compressive strength were determined to produce the final result. Concrete specimens with red scoria proportions of 0 %, 10 %, 20 %, and 30 % wt.% were designated as RS1, RS2, RS3, RS4, respectively. BS1, BS2, BS3, and BS4 specimens had 0 %, 10 %, 20 %, and 30 % wt.% proportions of black scoria, respectively.

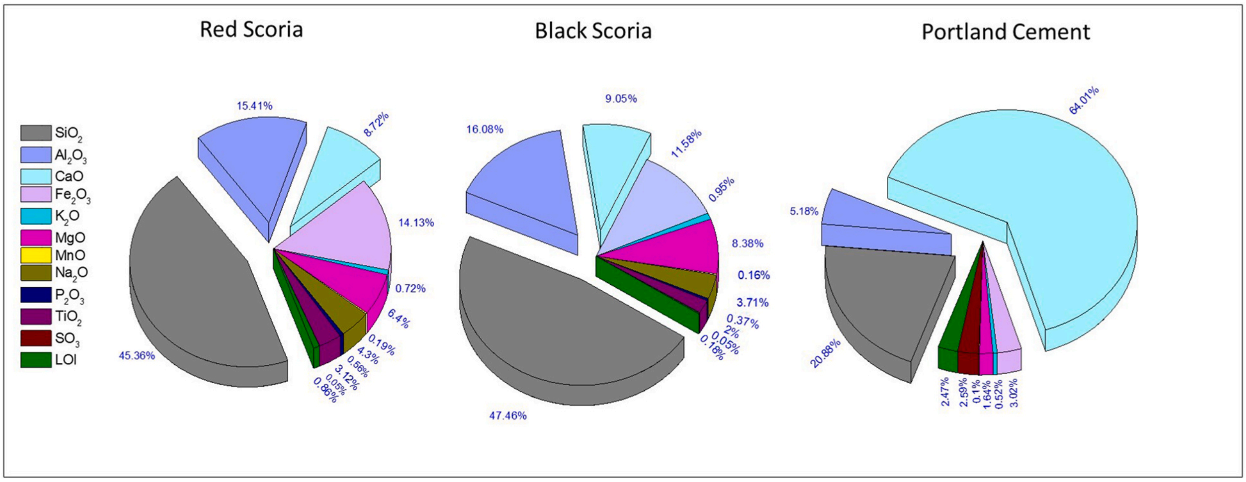

Fig. 2. Chemical analyses of black and red scoria and Portland Cement by XRF (wt. %).

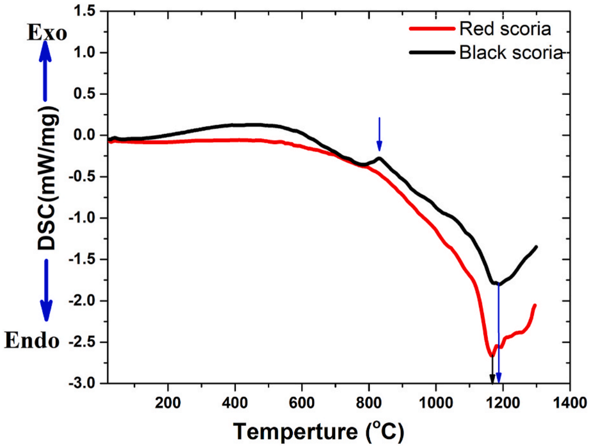

Fig. 3. DSC curves of red and black scoria

3. Results and discussions

3.1. Chemical compositions and thermal characteristics

The chemical compounds of the two scoria and Portland cement were determined by using XRF, as shown in Fig. 2. To quantify the oxides elements (wt%), a chemical analysis of the samples was performed via XRF using SPECTRO XEPOS. Lithium borate salts are necessary for XRF analysis because they effectively dissolve most oxides. First, 1 g scoria powder and 8 g lithium borate were added to the platinum crucible, and the material was thoroughly blended before being placed in the fusion system for 20 min to form a glass disk [27].

The black and red scoria contain major oxides such as Silica (SiO_2), Alumina (Al_2O_3), Iron oxide (Fe_2O_3), Calcium oxide (CaO), and Magnesia (MgO). The other elements in trace contained in black and red scoria were Sodium oxide (Na_2O), Potassium oxide (K_2O), Titanium Dioxide (TiO_2), Phosphorus pentoxide (P_2O_5), Manganese monoxide (MnO), and Sulfate (SO_3). The chemical compositions of the two scoriae were found to be in close proportion. While the main contents present in Portland cement are CaO, SiO_2, and Al_2O_3, while the minor constituents are Fe_2O_3, MgO, K_2O, and Na_2O. Additionally, the bulk densities of black and red scoria were calculated to be 3.13 and 3.30 g/cc, respectively, using the Ultrapycnometer.

The black and red scoria powders were exposed to heat in static air with a rate of 5 °C/min from RT up to 1300 °C to study their thermal properties. Thermal treatment is a significant factor that results in many structural transformations like decomposition, oxidation, surface reconstruction, and formation of distinct phases [28–31]. The DSC analysis of the two scoriae is presented in Fig. 3. The curve of the black scoria displayed an exothermic peak at 830 °C, indicating the oxidization of the materials [32]. Additionally, the endothermic peak was determined to be 1187 °C, this corresponds to the same melting temperature of black scoria. In contrast, the DSC curve of red scoria only showed a strong endothermal peak at 1170 °C. The DSC analysis results confirmed that the black and red scoria

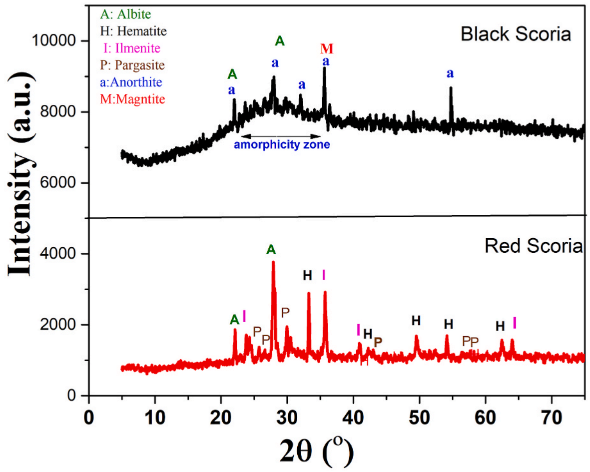

Fig. 4. XRD patterns of red and black scoria before thermal treatment

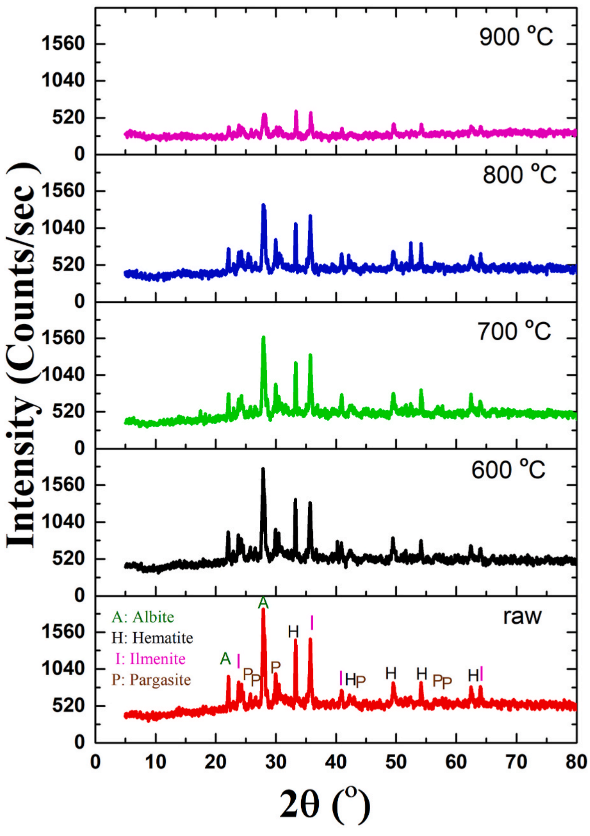

Fig. 5. XRD patterns of red scoria before and after thermal treatment of specimens at 600, 700, 800, and 900 °C.

have excellent thermal stability at high temperatures that can be used in many applications. A similar observation was found in the previous research [26].

3.2. Structural characteristics of the black and red scoria

The minerals and phases of the two scoriae were studied by XRD, as shown in Fig. 4. The XRD spectra of red scoria indicate a high degree of crystallinity and show distinct peaks that are characteristic of four mineral phases: albite ($NaAlSi_3O_8$), pargasite

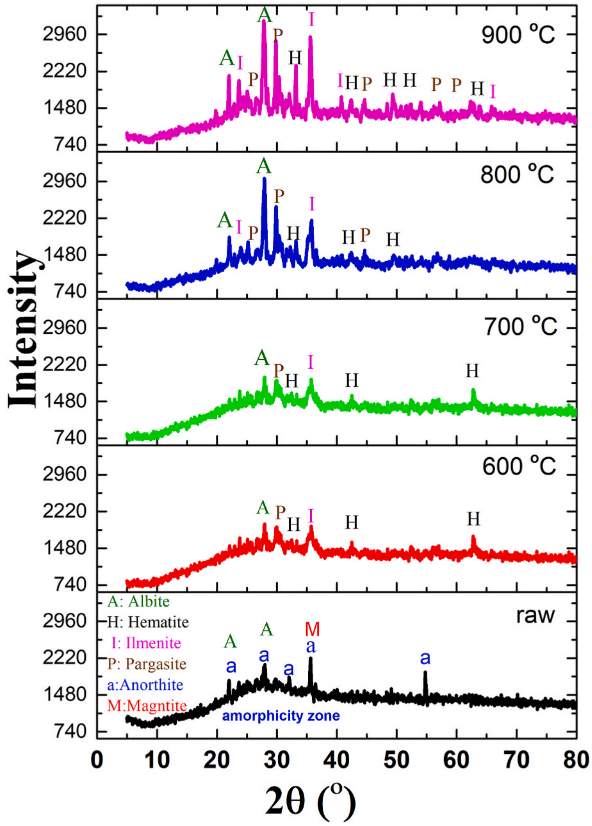

Fig. 6. XRD patterns of black scoria before and after thermal treatment of specimens at 600, 700, 800, and 900 °C.

($NaCa_2Mg_4Al_3Si_6O_{22}(OH)_2$), hematite ($\alpha$-$Fe_2O_3$), and ilmenite ($FeTiO_3$), which was consistent with previous study [26].

The XRD analysis of the raw black volcanic scoria showed a considerable quantity of an amorphous glass phase. This was determined from the wide pozzolanity hump within the range of ($2\theta = 21°–38°$) with some characteristic peaks of crystalline phases [14, 33]. Crystal phase peaks constituted the iron oxide phases such as magnetite (Fe_3O_4), plagioclase ($CaAl_2Si_2O_8$), albite ($NaAlSi_3O_8$) and/or anorthite [14,33,34,35]. XRD results revealed differences between the phases and minerals of the red and black scoria. The black scoria has magnetite and anorthite that are not present in red scoria. Moreover, the black scoria has an amorphous content, which is not present in red scoria. The difference between the structures of the two scoria can affect other properties and lead to variations in mechanical and thermal properties when used as a substitute in building materials. Also, the mechanical and thermal properties of the two scoria are expected to vary based on the thermal treatment at varying temperatures.

3.3. Influence of thermal -treatment on structural properties of the black and red scoria

Figs. 5 and 6 show the XRD spectra of red and black scoria specimens before and after thermal treatment, respectively. The XRD spectra of the thermally treated raw red scoria specimens were found to have similarities. After thermal treatment, the XRD spectra for the red scoria specimens showed a marked reduction in the intensities of all observed XRD peaks. Moreover, no change was observed in the peak positions and crystalline phases following an increase in the thermal treatment temperature. The reduction in the XRD spectra likely resulted from breakdown of the crystalline structure and subsequent dissolution of the phases owing to high temperature.

The mineral and crystal structure of black scoria specimens after thermal treatment at 600, 700, 800, and 900 °C were studied using XRD, as shown in Fig. 6. The XRD spectra of the black scoria specimen heated at different temperatures showed that the intensity of diffraction peaks present enhanced and were sharper than those of the raw specimen. In addition, new peaks associated with the formation of hematite (α-Fe_2O_3), ilmenite ($FeTiO_3$) and pargasite ($NaCa_2Mg_4Al_3Si_6O_{22}(OH)_2$), which changed from black to red at 800 and 900 °C, were observed. These changes are due to the recrystallization of the minerals, oxidation of magnetite or other iron oxides, and conversion to hematite. As the thermal treatment temperature increased, the intensity of the XRD peaks increased and became sharper. This indicated an enhancement in the crystallization of the hematite and other mineral phases.

The XRD analysis results of red and black scoria after thermal treatment showed differences between the crystal structure phases and minerals of the two scoriae. As the thermal treatment temperature increased, the intensity of the peaks in red scoria decreased, whereas the peaks in black scoria presented new phases of minerals and a decrease in the amount of amorphous phase (hump), possibly causing the degradation of mechanical properties [4]. Nevertheless, owing to the complexity of the chemical compositions of volcanic

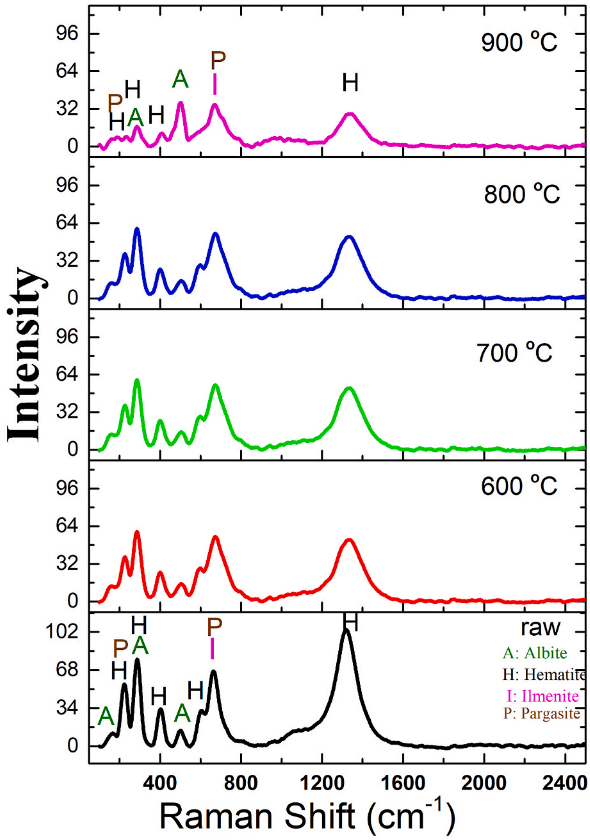

Fig. 7. Raman spectra of red scoria specimens before and after thermal treatment at 600, 700, 800, and 900 °C.

scoria, the spectra of likely minerals expanded with thermal treatment. Therefore, the XRD analysis results need to be validated using other techniques. Moreover, interference between mineral phase peaks tends to complicate the interpretation. Thus, the Raman method, which is an effective method to determine the mineralogy of composite materials, has been used to emphasize the XRD findings.

Fig. 7 shows the result of Raman analysis results of red scoria specimens before and after thermal treatment. The spectra of Raman exhibit different peaks. The hematite metal phase peaks at 1321 cm^{-1} [24,25], while ilmenite and pargasite metal phases peak at 672 cm^{-1} [25,26]. The shoulder peak at 602 cm^{-1} is attributed to as the hematite phase [24,25]. The albite and hematite metal phases are represented by peaks ranging from 540 to 460 cm^{-1} and 402 cm^{-1}, respectively [24,25,28,29]. The peaks located at 288 and 223 cm^{-1} are referred to hematite/albite [24,25,29] and hematite/pargasite metal phases [25], respectively. the peak located at 161 cm^{-1} is attributed to as the albite mineral phase [28,29]. As shown in Fig. 7, all specimens measured show the same peaks without considerable shift after thermal treatment. Nevertheless, the intensity of Raman peaks decreases with increasing thermal temperature treatment. This is consistent with the XRD results. Notably, the peaks belonging to either hematite or ilmenite decrease more compared to those belonging to either albite or pargasite.

Fig. 8 shows the Raman spectra of black volcanic scoria specimens before and after thermal treatment. The Raman spectra of the raw specimen illustrated certain broad peaks, which are attributed to the high amorphous quantity present in volcanic scoria. These peaks are assumed to be a mixture of different mineral phases, including ilmenite, pargasite, and albite.

As can be shown in Fig. 8, the Raman spectra of thermally treated specimens are differ from the raw specimen spectra. It found additional peaks, and the present broad peaks get sharper with a substantial increase in intensity as the thermal treatment temperature increases. At 800 °C, the distinctive peaks of hematite and albite emerged and intensify. Additionally, as the thermal treatment temperature rises to 900 °C the mineral intensity increases, which may be due to the recrystallization of the metal, oxidization of magnetite or other iron oxides, and conversion to hematite. The peaks observed at around 1333, 602, 404, 288, and 223 cm^{-1} were referred to the hematite phase [14,18,19]. The characteristic peaks of albite have appeared at 540–460, 288, and 162 cm^{-1} [14,36,37]. The peak at 672 cm^{-1} is attributed to ilmenite [14,18,20], and the peaks at 672 cm^{-1} and 223 cm^{-1} are attributed to pargasite [14,18,20]. The findings of the Raman analysis agree with those found by XRD [35].

As a result, it can be summarized that the differences were observed using the XRD and Raman spectra between the two scoria specimens before and after thermal treatment. The spectra of red scoria decreased with increasing thermal temperature treatment, while those of black scoria increased with increasing thermal treatment temperature and presented new phases referring to the

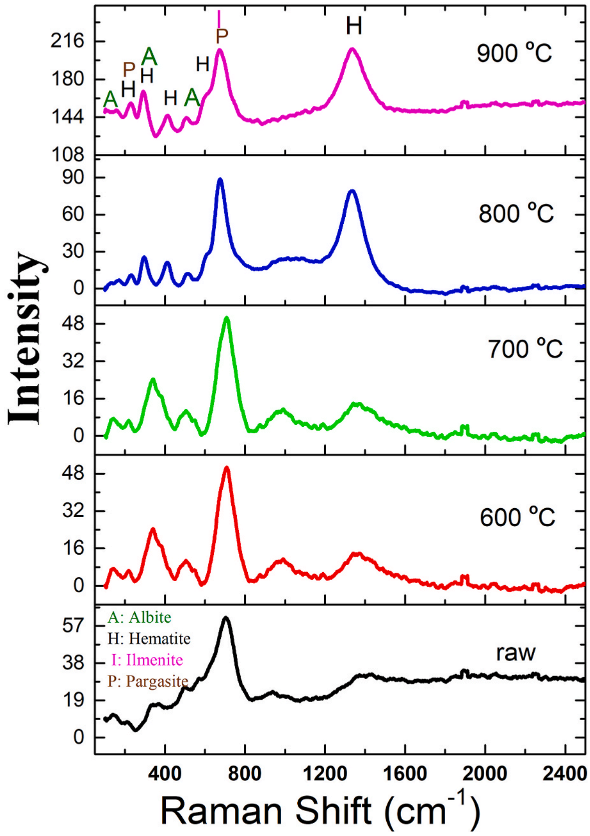

Fig. 8. Raman spectra of black scoria specimens before and after thermal treatment at 600, 700, 800, and 900 °C.

hematite mineral. The impact of thermal treatment on the characteristics of volcanic scoria differs with the crystalline phase and chemical component of volcanic scoria, indicating the suitability of those kinds of volcanic scoria for many applications such as thermal insulation applications.

3.4. Influence of thermal treatment on the mechanical characteristic of concrete specimens

The mechanical properties of concrete are associated with the pozzolanic activity of scoria, which depends on its crystalline to amorphous phase ratio and chemical properties such as elemental oxides [4]. Therefore, cylindrical concrete specimens (d = 15 cm and h = 30 cm) were fabricated with 0 %, 10 %, 20 %, and 30 % of black and red volcanic scoria as cement substitutes before and after thermal treatment. After 14, 21, 28, and 91 days of curing, the compressive strengths of these specimens were evaluated. The compressive strengths of specimens with different amounts of black scoria (0 %, 10 %, 20 %, and 30 %) before and after thermal treatment of the specimens at 700, 800, and 900 °C on various curing days are shown in Fig. 9 (a, b, c, and d). It was noticed an improvement in the compressive strength of specimens with increasing curing time which was attributed to the pozzolanic activity of scoria. The curing time of scoria concretes plays an important role in improving the mechanical properties similar to most pozzolanic materials. In addition, it was found that the compressive strength reduced as the black scoria content increased before and after thermal treatment at 700, 800, and 900 °C. These findings may be owing to a small quantity of cement in the specimen and low pozzolanic reactivity. Black scoria's pozzolanic reactivity was negatively impacted by thermal treatment as a result of the development of crystalline phases at high temperatures [4]. The specimens containing 10 % black after 91 days of curing for black scoria without thermal treatment yielded the highest compressive strength, compared to Portland cement, for which the compressive strength was 54 ± 1.22 MPa. The increased compressive strength for black scoria with increasing curing duration is associated with is linked to the delayed pozzolanic action of scoria. Similar outcomes have been noted by previous studies which found that the use of 20 % volcanic ash or 20 % waste glass sludge as a substitute for cement decreased the compressive strength of the material in the early days of curing [12,38]. Nevertheless, similar to the outcomes of the prior study, a similar strength to that of the control mortar specimens was reported in these studies at later ages (91 days). Other than the positive impact of increased curing days, thermal treatment was observed to adversely impact the compressive strength of all specimens containing black scoria. For example, the compressive strength of specimens with thermally treated scoria decreased slightly similar to that of untreated scoria at all ages, as shown in Fig. 10. This was attributed to the conversion of amorphous structure of the black scoria to a crystalline one. These findings are consistent with those of the previous study [4], which observed that thermal treatment adversely affected the compressive strength of all mortar mixes owing

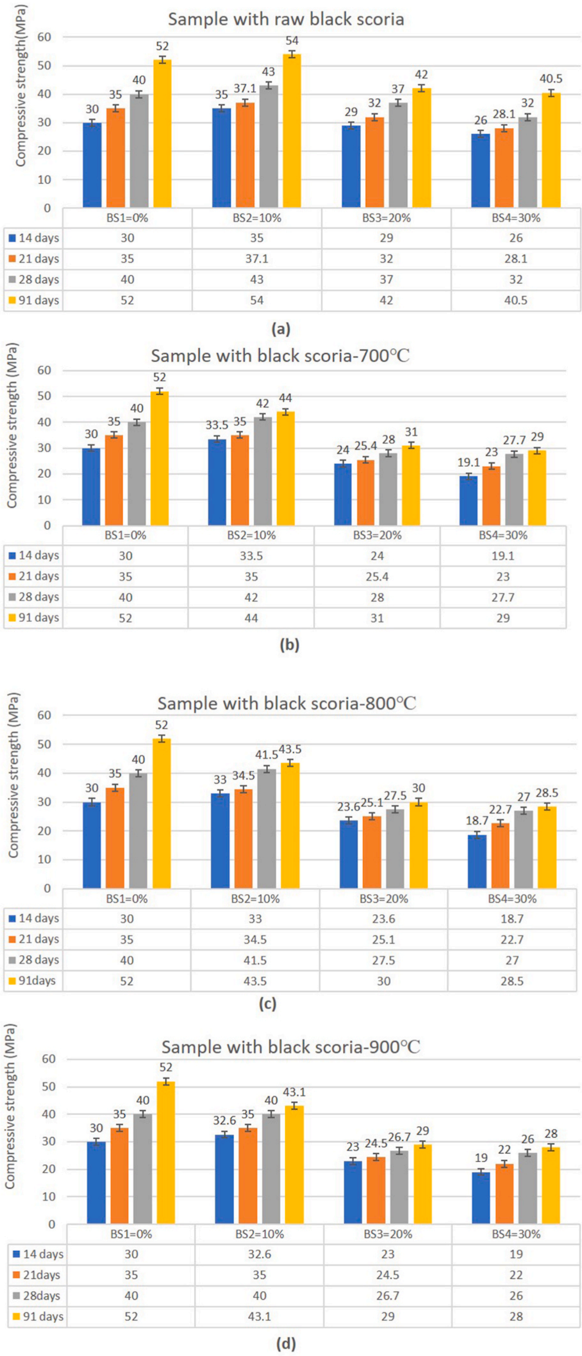

Fig. 9. The compressive strengths of black scoria concrete specimens at different curing days before and after thermal treatment.

to the transformation of the amorphous structure of volcanic ash to a crystalline one. similarity in the compressive strength of all specimens with treated black scoria showed the insignificant impact of raising thermal treatment temperatures. Fig. 11 (a, b, c, and d) and Fig. 12(a, b, and c) present the compressive strength values of specimens with varying proportions of red (0 %, 10 %, 20 %, and 30 %) before and after thermal treatment of specimens at 700, 800, and 900 °C at different curing days. This indicates that the compressive strength of the specimens increased with increasing curing time and decreased with the increasing content of red scoria content before and after thermal treatment at 700, 800, and 900 °C. These results are similar to those for black scoria. However, thermal treatment was found to positively affect the compressive strength for all specimens containing red scoria, particularly at older ages. This increase in compressive strength of the specimen with the thermally treated red scoria is owing to the reduction in the crystallinity of red scoria. This is inconsistent with the findings of the previous study that found thermal treatment to adversely affect

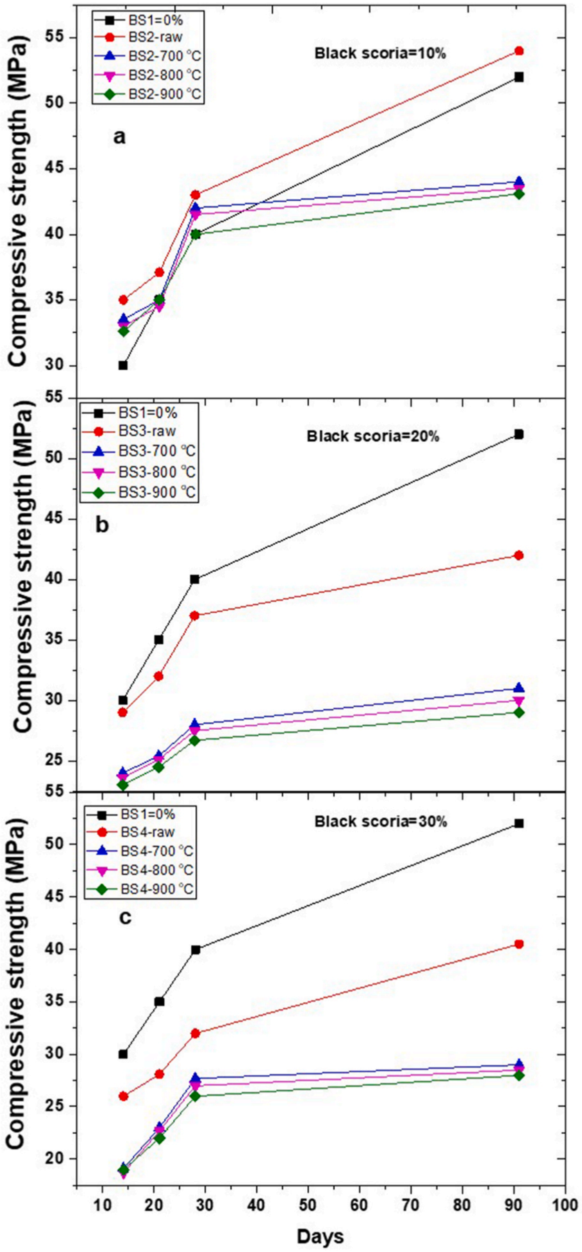

Fig. 10. The compressive strengths of concrete specimens before and after thermal treatment different percentages of black scoria.

compressive strength [4]. This variation in the effect of thermal treatment was attributed to variations in the phases and minerals of scoria. The specimen containing 10 % red scoria, cured for 91 days, and treated at 900 °C, yielded the highest compressive strength value (60 ± 1.22 MPa), exceeding that of Portland cement, as shown in Fig. 12. Therefore, these results suggest that thermally treated red scoria facilitates achievement of the maximum strength potential of the material but thermally treated black scoria is not sufficient to improve the compressive strength of the material. This variation in the effect of thermal treatment on the two types of scoria was attributed to variations in the phases and minerals of different thermal properties that were verified using XRD and DSC analyses.

3.5. Influence of thermal treatment on thermal insulation characteristics of concrete specimens

Scoria exhibited excellent thermal stability at high temperatures and can therefore be used in numerous insulation applications. Therefore, the thermal conductivity of slab concrete specimens (3 cm × 3 cm × 6 cm) with thermally treated black and red scoria was investigated using a NETZSCH heat flow meter model with a mean specimen temperature range of 10–90 °C. Each measurement was performed on 3 of the specimens after 28 days of curing, and the average thermal conductivity was determined. The thermal gradient

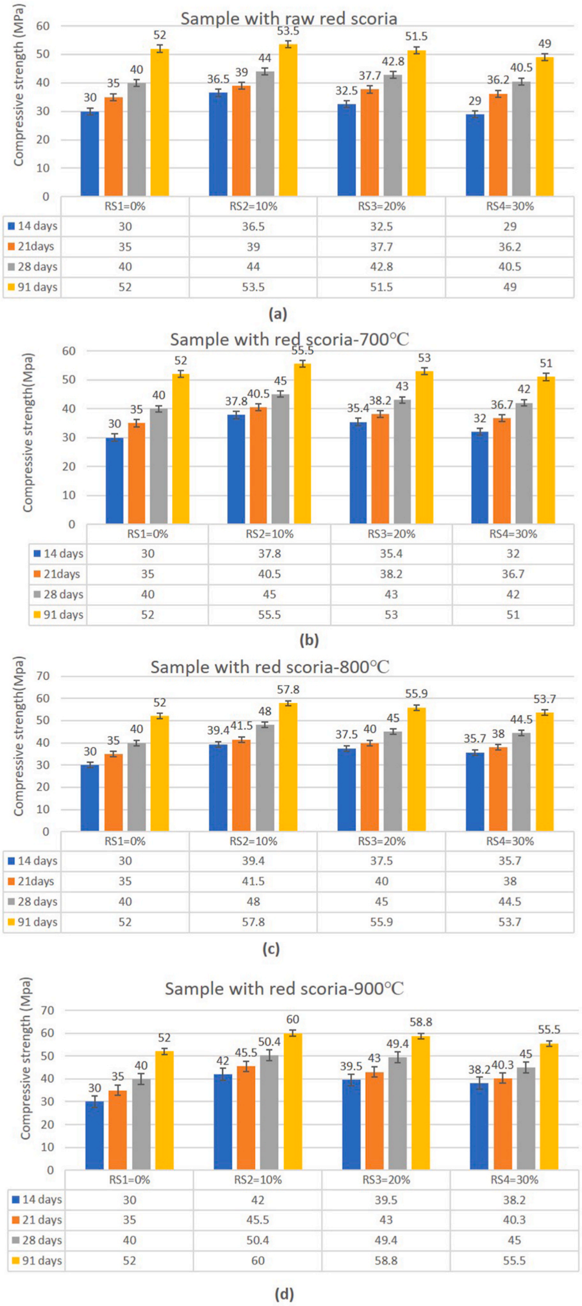

Fig. 11. The compressive strengths of red scoria concrete specimens at different curing days before and after thermal treatment.

was found to increase with increasing scoria content and the thermal treatment temperature. As shown in Fig. 13 and Table 3, the average thermal conductivity of the specimens reduced with increasing in the proportions of black and red scoria and the thermal treatment temperature in the concrete specimen with increasing the temperature of the thermal treatment of black scoria from RT to 900 °C were 0.463 ± 0.01–0.31 ± 0.01, 0.343 ± 0.01–0.288 ± 0.01, and 0.193 ± 0.01–0.168 ± 0.01 W/m K for BS2, BS3 and BS4, respectively. Similarly, the average thermal conductivity values of the specimens given increased thermal treatment temperature of red scoria from RT to 900 °C were of 0.4 ± 0.01–0.298 ± 0.01, 0.311 ± 0.01–0.262 ± 0.01, and 0.187 ± 0.01–0.157 ± 0.01 W m^{-1} K^{-1} for RS2, RS3, and RS4, respectively. Notably, the thermal insulating characteristics of the concrete specimens with thermally treated red scoria were more optimized than those of the concrete specimens with thermally treated black scoria. The lowest thermal conductivity value of specimens with thermally treated red scoria at 900 °C was 0.157 ± 0.01 W m^{-1} K^{-1}. These findings confirmed that the thermal treatment of scoria content in concrete specimens can result in thermal insulation that is numerous times more

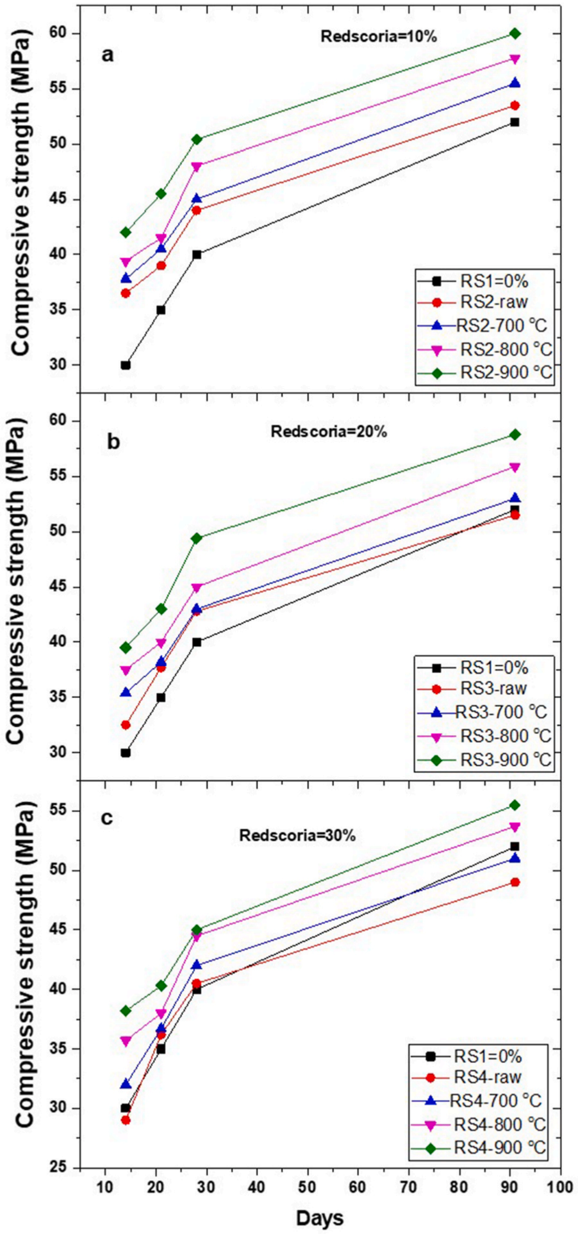

Fig. 12. The compressive strengths of concrete specimens with different red scoria percentages.

optimized than that of ordinary concrete. The thermal conductivity obtained in this investigation is consistent with the results in previous studies [9,39,40]. It was reported that scoria and pumice concrete can insulate heat approximately five to seven times more than that of ordinary concrete and concrete fabricated with silica sand [9,13,39,40]. In addition, scoria concrete has higher thermal insulation capacity than fly ash concrete [5], which was reported to have thermal conductivity values ranging from 0.938 to 0.405 W/m K. The low thermal conductivity of treated scoria concrete makes it highly resistant to heat flow. Therefore, it would be more appropriate to utilize them than ordinary concrete and concrete fabricated with other waste materials as thermal insulation building materials for structures that need to conserve energy. Scoria is an abundant natural resource used in the fabrication of structural concrete and production of masonry blocks, and as thermal insulation material, making it a valuable economic resource.

4. Conclusions

This work estimated the effect of thermal treatment on the performance of black and red scoria utilized as cement substitutes in the manufacture of high-performance building materials with efficient thermal insulation properties. The effect of thermal treatment of

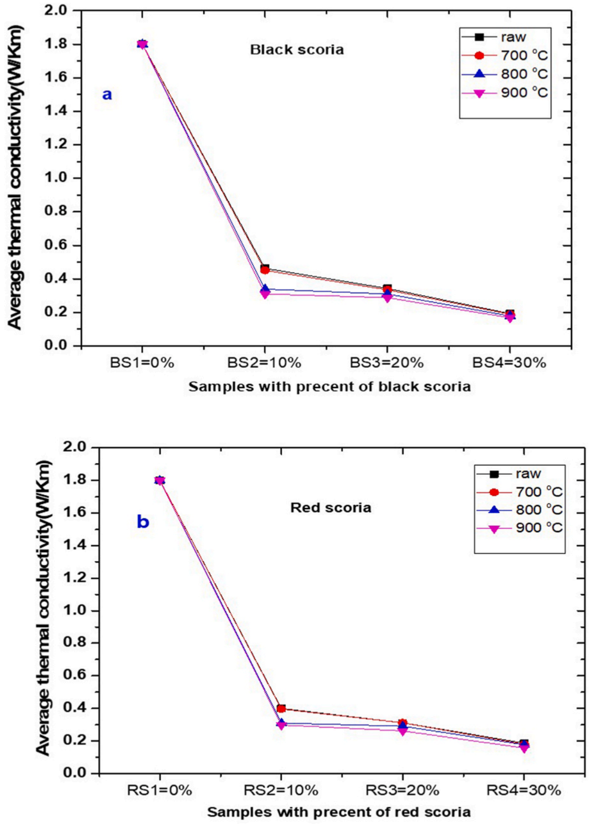

Fig. 13. The average thermal conductivity of the concrete specimens with different red and black scoria percentages

Table 3
The average thermal conductivity of concrete samples with different red and black scoria percentages.

Temperature of thermal treatment	Average of thermal conductivity (W/Km) of samples curing at 28 days							
	BS1 = 0 %	BS2 = 10 %	BS3 = 20 %	BS4 = 30 %	RS1 = 0 %	RS2 = 10 %	RS3 = 20 %	RS4 = 30 %
RT	1.8 ± 0.01	0.463 ± 0.01	0.343 ± 0.01	0.193 ± 0.01	1.8 ± 0.01	0.4 ± 0.01	0.311 ± 0.01	0.187 ± 0.01
700 °C	–	0.451 ± 0.01	0.335 ± 0.01	0.189 ± 0.01	–	0.396 ± 0.01	0.312 ± 0.01	0.18 ± 0.01
800 °C	–	0.339 ± 0.01	0.31 ± 0.01	0.179 ± 0.01	–	0.31 ± 0.01	0.291 ± 0.01	0.177 ± 0.01
900 °C	–	0.31 ± 0.01	0.288 ± 0.01	0.168 ± 0.01	–	0.298 ± 0.01	0.262 ± 0.01	0.157 ± 0.01

black and red scoria at different temperatures (600, 700, 800, and 900 °C) on the compressive strengths and thermal conductivity of building materials (concrete specimens) was studied.

The following conclusions of the current work can be drawn.

i. The effect of thermal treatment on the structural characteristics of black and red scoria differs with their crystal structure and chemical component of volcanic scoria.
ii. The compressive strength of the concrete specimens containing black and red scoria improved as curing days increased. In contrast, compressive strength decreased with increasing scoria content owing to the low quantity of cement in the specimen and low pozzolanic reactivity at early curing ages.
iii. Thermal treatment negatively affected the compressive strength of concrete specimen with black scoria content because the heat changed the amorphous structure of the scoria to a crystalline one. In contrast, thermal treatment improved the compressive strength of all specimens containing red scoria due to the crystallinity reduction under increasing temperature. This enhancement effect is due to the pozzolanic activity associated with the proportion of amorphous phase.

iv. The concrete specimen with 10 % wt red scoria and cured for 91 days at 900 °C had the highest compressive strength (60 ± 1.22 MPa), exceeding the compressive strength of Portland cement.
v. The average thermal conductivity of the concrete specimens reduced with thermal treatment temperature and black and red scoria content in specimens.
vi. The average thermal conductivity values of the concrete specimens with the black scoria content were 0.463–0.31, 0.343–0.288, and 0.193–0.168 W m^{-1} K^{-1} for BS2, BS3, and BS4, respectively. While the average thermal conductivity values of the concrete specimens with thermally treated red scoria reduced with increasing temperature: 0.4–0.298, 0.311–0.262, and 0.187–0.157 W m^{-1} K^{-1} for RS2, RS3, and RS4, respectively, from RT to 900 °C.
vii. The thermal insulation of specimens with red scoria was more optimized than that of concrete specimens with black scoria. In addition, the thermal insulation of concrete containing thermally treated scoria was several times more optimized than that of ordinary concrete.
viii. Eco-friendly structures built with concrete containing thermally treated red scoria, which has high-compressive strength and effective thermal insulation properties, will be more optimized than structures built with ordinary concrete.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] L. Contrafatto, C.L. Danzuso, S. Gazzo, L. Greco, Physical, mechanical and thermal properties of lightweight insulating mortar with recycled Etna volcanic aggregates, Construct. Build. Mater. 240 (2020), 117917. .
[2] W. Mahmood, A.U.R. Khan, T. Ayub, Carbonation resistance in ordinary Portland cement concrete with and without recycled coarse aggregate in natural and simulated environment, Sustainability 14 (1) (2021) 437.
[3] A. Hasanbeigi, L. Price, E. Lin, Emerging energy-efficiency and CO_2 emission-reduction technologies for cement and concrete production: a technical review, Renew. Sustain. Energy Rev. 16 (8) (2012) 6220–6238.
[4] K. Khan, M.N. Amin, M. Usman, M. Imran, M.A. Al-Faiad, F.I. Shalabi, Effect of fineness and heat treatment on the pozzolanic activity of natural volcanic ash for its utilization as supplementary cementitious materials, Crystals 12 (2) (2022) 302.
[5] X.D. Zhang, Y. Han, Thermal insulation properties of fly ash and waste polystyrene mixed block building materials, Chemical Engineering Transactions 55 (2016) 253–258. .
[6] F. Asdrubali, F. D'Alessandro, S. Schiavoni, A review of unconventional sustainable building insulation materials, Sustainable Materials and Technologies 4 (2015) 1–17. .
[7] A.A. Sabtan, W.M. Shehata, Evaluation of engineering properties of scoria in central Harrat Rahat, Saudi Arabia, Bull. Eng. Geol. Environ. 59 (3) (2000) 219–225. .
[8] L. Boukhattem, M. Boumhaout, H. Hamdi, B. Benhamou, F.A. Nouh, Moisture content influence on the thermal conductivity of insulating building materials made from date palm fibers mesh, Construct. Build. Mater. 148 (2017) 811–823. .
[9] M.R. Moufti, A.A. Sabtan, O.R. El-Mahdy, W.M. Shehata, Assessment of the industrial utilization of scoria materials in central Harrat Rahat, Saudi Arabia, Eng. Geol. 57 (3–4) (2000) 155–162.
[10] M.R. Moufti, K. Németh, Harrat Rahat: the geoheritage value of the youngest long-lived volcanic field in the kingdom of Saudi Arabia, in: Geoheritage of Volcanic Harrats in Saudi Arabia, Springer, 2016, pp. 33–120.
[11] K. Khan, M.N. Amin, M.U. Saleem, H.J. Qureshi, M.A. Al-Faiad, M.G. Qadir, Effect of fineness of basaltic volcanic ash on pozzolanic reactivity, ASR expansion and drying shrinkage of blended cement mortars, Materials 12 (2019) 2603.
[12] K. Khan, M.N. Amin, Influence of fineness of volcanic ash and its blends with quarry dust and slag on compressive strength of mortar under different curing temperatures, Construct. Build. Mater. 154 (2017) 514–528.
[13] F.I. de la Precontrainte, FIP Manual of Lightweight Aggregate Concrete, Surrey University Press, 1983, p. .
[14] S. Alraddadi, Effects of calcination on structural properties and surface morphology of black volcanic ash, Journal of Physics Communications 4 (10) (2020), 105002.
[15] M.R. Moufti, A.A. Sabtan, O.R. El-Mahdy, W.M. Shehata, Assessment of the industrial utilization of scoria materials in central Harrat Rahat, Kingdom of Saudi Arabia, Eng. Geol. 57 (2000) 155–162.
[16] A.A. Sabtan, W.M. Shehata, Evaluation of engineering properties of scoria in central Harrat Rahat, kingdom of Saudi Arabia, Bull. Eng. Geol. Environ. 59 (2000) 219–225.
[17] M.I. Khan, A.M. Alhozaimy, Properties of natural pozzolan and its potential utilization in environmental friendly concrete, Can. J. Civ. Eng. 38 (2011) 71–78.
[18] V. Letelier, J.M. Ortega, R.M. Tremiño, B.I. Henriquéz-Jara, I. Fustos, T. Real-Herraiz, G. Moriconi, M.Á. Climent, I. Sánchez, The use of volcanic powder as a cement replacement for the development of sustainable mortars, Appl. Sci. 10 (2020) 1460 [CrossRef].
[19] K. Kupwade-Patil, A.F. Al-Aibani, M.F. Abdulsalam, C. Mao, A. Bumajdad, S.D. Palkovic, O. Buyukozturk, Microstructure of cement paste with natural pozzolanic volcanic ash and Portland cement at different stages of curing, Construct. Build. Mater. 113 (2016) 423–441.
[20] J.S. Al-Fadala, S. Chakkamalayath, A. Al-Bahar, Al-Aibani, S. Ahmed, Significance of performance-based specifications in the qualification and characterization of blended cement using volcanic ash, Construct. Build. Mater. 144 (2017) 532–540.
[21] S. Saamiya, D.F. Raissa, C.G.J. Maria, Calcining natural zeolites to improve their effect on cementitious mixture workability, Cement Concr. Res. 85 (2016) 102–110.
[22] H. Moussa, K. Larbi, C. Martin, C. Pierre, Evaluation and improvement of pozzolanic activity of andesite for its use in eco-efficient cement, Construct. Build. Mater. 47 (2013) 1268–1277.
[23] E. Kucukyıldırım, B. Uzal, Characteristics of calcined natural zeolites for use in high-performance pozzolan blended cements, Construct. Build. Mater. 73 (2014) 229–234.

[24] K. Alaettin, S. Zeynep, Effect of heat treatment on pozzolanic activity of volcanic pumice used as cementitious material, Cem. Concr. Compos. 57 (2015) 128–132.
[25] L.E. Burris, M.C.G. Juenger, Milling as a pretreatment method for increasing the reactivity of natural zeolites for use as supplementary cementitious materials, Cem. Concr. Compos. 65 (2016) 163–170.
[26] S. Alraddadi, H. Assaedi, Physical properties of mesoporous scoria and pumice volcanic rocks, 2021, Journal of Physics Communications 11 (5) (2021), 115018.
[27] S. Alraddadi, H. Assaedi, Characterization and potential applications of different powder volcanic ash, J. King Saud Univ. Sci. 32 (7) (2020) 2969–2975. .
[28] M. Erdemoğlu, M. Birinci, T. Uysal, E. Porgalı Tüzer, T.S. Barry, Mechanical activation of pyrophyllite ore for aluminum extraction by acidic leaching, J. Mater. Sci. 53 (2018), 13801, 12.
[29] W. Zhu, S. Nakashima, E. Marin, H. Gu, G. Pezzotti, Microscopic mapping of dopant content and its link to the structural andthermal stability of yttria-stabilized zirconia polycrystals, J. Mater. Sci. 55 (2020) 524–534.
[30] V.K. Soni, T. Roy, S. Dhara, G. Choudhary, P.R. Sharma, R.K. Sharma, On the investigation of acid and surfactant modification of natural clay for photocatalytic water remediation, J. Mater. Sci. 53 (2018) 10095–10110.
[31] A. Bloise, Thermal behaviour of actinolite asbestos, J. Mater. Sci. (2019).
[32] S. Alraddadi, Effects of Black Scoria on mechanical properties and thermal insulation properties of building materials Mater, Sci. Forum 1047 (2021) 151–157.
[33] G. Fares, A. Alhozaimy, O.A. Alawad, A. Al-Negheimish, Evaluation of powdered scoria rocks from various volcanic lava fields as cementitious material, J. Mater. Civ. Eng. 28 (3) (2016), 04015139.
[34] P. Zhang, J. Huang, Z. Shen, X. Wang, F. Luo, P. Zhang, J. Wang, S. Miao, Fired hollow clay bricks manufactured from black cotton soils and natural pozzolans in Kenya, Construct. Build. Mater. 141 (2017) 435–441.
[35] S. Alraddadi, Surface and thermal properties of fine black and white volcanic ash, Mater. Today: Proc. 26 (2020) 1964–1966. .
[36] A. Charkhi, H. Kazemian, M. Kazemeini, Optimized experimental design for natural clinoptilolite zeolite ball milling to produce nano powders, Powder Technol. 203 (2010) 389–396.
[37] M. Usman, J. Zhu, K. Chuiyang, M.T. Arslan, A. Khan, A. Galadima, O. Muraza, Propene adsorption-chemisorption behaviors on H-SAPO-34 zeolite catalysts at different temperatures, Catalysts 9 (2019) 919.
[38] T. Luamkanchanaphan, S. Chotikaprakhan, S. Jarusombati, A study of physical, mechanical and thermal properties for thermal insulation from narrow-leaved cattail fibers, APCBEE Procedia 1 (2012) 46.
[39] R.L. Bates, Geology of the Industrial Rocks and Minerals, 1960, p. .
[40] S.J. Lefond, Industrial Rocks and Minerals, 1975, p. .

Nomenclature

DSC: differential scanning calorimetry analysis
XRD:: X-ray diffraction analysis
XRF: X -ray fluorescence spectrometry
Θ: the diffraction angle, 2θ, is defined between the incident beam and the detector (°)
RT: room temperature (°C)
κ: the thermal conductivities (W m^{-1} K^{-1})
d: diameter(cm)
h: high (cm)
λ: wavelengths of the incident X-radiation λ = 1.54 (Å)