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Thermal Properties of Rocks and Environmental Sustainability

Khawar Jalil[1]*, Tariq Feroze[1], Muhammad Saqib Jan,[1] Adnan Khan[2]

[1]Department of Advanced Geomechanical Engineering, Military College of Engineering, National University of Sciences and Technology, Risalpur 23200, Pakistan
[2]Department of Geology, University of Karachi, Pakistan

*Email: khawarjalil4136@gmail.com

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Abstract Sustainable environments and the pursuit of alternative energy supplies are central to modern societies. At the same time the global warming is emerging as a serious issue for all nations. In contrast to the physical and mechanical properties of rocks, the thermal properties of rocks provide information on its potential for alternative thermal energy sources. This study examines the earlier research studies on the evaluation of rocks' thermal properties, with a particular emphasis on geothermal potential, dimension stone thermal comfort, and indirect evaluation utilizing characteristics including porosity, moisture content, p-wave velocity, and mineral composition. The transient approach and steady state technique were used to evaluate thermal characteristics of rocks. Given that Pakistan is among the nations adversely affected by global warming, it is imperative to investigate alternative energy sources and sustainable materials. This study tries to provide directions to enhance the knowledge base for future research to analyze the thermal properties of rocks originating from Pakistan and how strategically these rocks may be utilized to lessen global warming through environment sustainability and zero carbon emissions and to achieve sustainable development goals.

Keywords: Environment sustainability, thermal properties of rocks, dimension stones, thermal comfort.

Introduction

Global warming is a serious threat to all human beings living on planet earth. Carbon dioxide, methane, nitrous oxide, and other gases are examples of greenhouse gases (GHGs), which are thought to be the primary contributors to global climate change(G. Moiceanu & M. N. Dinca, 2021) and eventually causing global warming. According to a report of United Nation Environment Program(G. Moiceanu & M. N. J. S. Dinca, 2021; *UNEP - 2023*)(G. Moiceanu & M. N. J. S. Dinca, 2021; *UNEP - 2023*)(Moiceanu & Dinca, 2021; UNEP, 2023) , emissions can be split into five major economic sectors: energy supply, industry, agriculture and Land Use, Land Use Changes, and Forestry (LULUCF), transport and buildings. During 2022, energy supply was the largest source of emissions at 20.9 $GtCO_2e$ (36% of the total), industry is the second with 14.4 $GtCO_2e$ (25%), followed by agriculture and LULUCF CO_2 (global book keeping approach) (10.3 GtCO2e, 18%), transport (8.1 $GtCO_2e$, 14%) and buildings (3.8 $GtCO_2e$, 6.7%). However, if power sector emissions are re-allocated to final sectors based on their use of electricity and heat (i.e. indirect emissions, which highlight a demand perspective), then the contribution of the industry and building sectors increase significantly to 34% and 16% respectively. The adverse effects of climate change are clearly observed across the globe in the form of melting glaciers, anomalous flooding and snowfall patterns, and famines etc. (Pearce & Parncutt, 2023). United Nations has urged all member countries to take immediate steps for environment sustainability and to explore alternate energy resources to reduce the reliance on conventional energy resources which are polluting the atmosphere. Sustainable buildings, green environment, zero carbon emission, and utilization of natural resources in buildings are the key notions of modern societies (Rinne, Ilgın, & Karjalainen, 2022). Developed nations have started utilizing thermal energy besides hydrothermal and wind energies as an alternate to coal or petroleum fuels-generated energies to reduce carbon emissions. The global demand of marbles and granites has ever increased for their aesthetic appeals and feel of natural environment. Whether oceanic regions or lands, rocks have huge spread on earth. These rocks can be a valuable source of thermal energy while dimension stones (a commercial category of these rocks) may contribute to temperature management in buildings thereby reducing reliance on warming or cooling technologies to eventual reduce carbon emissions. The potential of thermal energy source or temperature management can be analyzed through assessment of thermal properties of these rocks.

Thermodynamics of rocks are crucial in geothermal energy exploration, underground mining, and environmental engineering. Understanding their behavior is essential for designing heat transfer systems, forecasting rock stability, and streamlining energy extraction procedures (Tiskatine et al., 2023). Dimension stone, a commercial category of rocks has gained integral importance in buildings and architectures. These natural stones are used in architecture and construction for passive heating, cooling, insulation, energy efficiency, and fire resistance. However, their high thermal conductivity can lead to excessive energy demand and increased cooling and heating costs (Eljufout & Alhomaidat, 2021). Natural materials play an important role in thermal insulation for roofs because they have low thermal conductivity, which helps lower room temperature by reducing heat transmission (Bintarto, Purnowidodo, Darmadi, & Widodo, 2022). It is also suggested that understanding dimension stone thermal properties is crucial for industrial applications and cultural heritage preservation, as it helps evaluate their geological characteristics (Shin et al., 2024). Laboratory assessment of thermal properties of rocks is critically important and need insightful details and sophisticated measurements for accurate and reliable commercial implications.

Thermal conductivity can be estimated indirectly through incorporating various mineralogical, physical and mechanical properties etc. In order to forecast the thermal conductivity of rocks (Kang, Yu, Wu, Zhang, & Gao, 2021) referred to four input variables: moisture content, porosity, density, and P-wave velocity and while (Ye et al., 2022) utilized mineral composition and porosity for the same purpose.

The comprehensive insight of available literature highlights that isolated researches have been conducted to seek the information about thermal characteristics of rocks. Each research incorporated few rocks or specific categories; most researches utilized only one of many practical methods with specific equipment(s) aiming to identify one or few thermal properties of rock(s) of a specific case study for a specific purpose. For developing countries like Pakistan where the critical importance of thermal properties of rocks is yet a less-known phenomenon, there is a need for an integrated knowledge about all aspects of previous researches as a guideline to conduct well-directed and target-oriented initiatives regarding the “identification” of thermal properties of commercially valuable rocks. Unfortunately, no recent up-to-date research has been carried out in context of rocks occurring in Pakistan in general and commercially available dimension stones of Pakistani origin in specific to gather valuable data on their thermal properties; and vital utilization of this data for environment sustainability and energy production.

This study aims to provide an overview of the most recent studies (2021-2023) carried out on the thermal characteristics of rocks. This study incorporates multiple aspects to collate the previously available information and to comprehend the current state of knowledge regarding various aspects of thermal properties of rocks. The aspects include (a) major categories of rocks investigated in earlier research studies in context of thermal properties (b) the objectives of previous research studies conducted in terms of thermal properties of rocks (c) materials and methods utilized in previous research studies for the assessment of thermal properties of rocks and (d) core conclusions of previous studies in terms of rock’s thermal properties.

Materials and Methods

Extensive literature review was carried out to find out all dimensions of thermal properties of rocks and their association with material energy relationships. The criteria for the selected research papers for literature review were as follows:

1. No research paper, book, or thesis published before 2021 was taken into consideration for this study until or unless those were used to define the thermal properties of rocks or to describe the procedure for measuring those qualities.

2. Research paper lacking a DOI was not considered to be taken into account for this study.

3. Unless the keywords included, for example, "rocks" in general or "any specific rock name," no research paper relating to the "composites" or other materials was considered for this review study.

Among all selected, no paper used a "literature review" as its methodology i.e. original research was considered to better explain.

Results and Discussion

Major categories of rocks in terms of thermal properties

The research papers consulted for this study covered the thermal characteristics of various rocks. This classification is neither on pure geological basis nor commercial basis but only on general purpose of utilization in previous researches. Figure 1 displays the percentage of various rocks from different origin categories. Rocks like shale, sandstone, and granite are typically discussed and identified individually in terms of thermal energy and hence covered under the term “geothermal rocks”. The majority of sedimentary rocks covered in these research publications are limestone, shale, sandstone, carbonate rocks, and evaporates. These are covered under the main term “stones” and sub-term “building materials and building stones”. Other than these rocks, sedimentary rocks are referred to as "other sedimentary rocks". Few research studies cover all three types of rocks—igneous, sedimentary, and metamorphic—in one study (G. Moiceanu & M. N. Dinca, 2021).The rocks are identified as "multiple categories of rocks" in such circumstances. Igneous rocks such as gabbro, diorites, and diabase, are also studied by many researchers in context of thermal energy and hence covered under the term “geothermal rocks”. Few studies examined "composites"—materials made by combining elements from at least one or more rocks with additional material like resins, etc. Because these are addressed in relation to dimension stones and ornamental stones, rocks like marble, granite, slate, and basalt are referred to as "stones". Figure 1 shows the pie chart distribution of these rocks discussed in various research studies from 2021 to 2023.

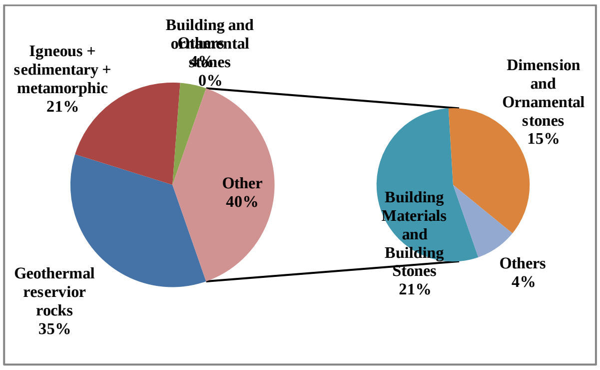

Fig. 1 Pie chart of various rocks discussed in the previous researches for assessment of their thermal properties.

The objectives of previous studies in terms of thermal properties of rocks

During the last decade extensive research has been carried out on in various dimensions of thermal properties of rocks. Previously published research papers can broadly be classified into six main groups which are as follows:

a) Indirect evaluation of thermal properties

Evaluation of the relationship between thermal properties and petrophysical, mechanical, engineering, and mineralogical qualities; connection between these properties and thermal properties; and construction of a model for indirect evaluation of thermal properties via these properties. In these studies, estimates were made for nearly all thermal parameters, including thermal conductivity, thermal diffusivity, and thermal expansion.

b) Geographical diversity

Evaluation of the thermal characteristics of dimension and construction stones from various geographical regions to determine how well they stand up to exposure to weathering, sunshine, and temperature anomalies. These studies estimated thermal parameters such thermal conductivity, thermal diffusivity, and thermal expansion. In this frame, several marbles, granites, gneiss, limestone, and other carbonate rocks were discussed.

c) Application of laboratory equipment or tools

Researches include detailed explanations of the ideas and workings of various lab tools used to estimate the thermal characteristics of various rocks.

d) Mixing Models

Researches take into account several mixing models that are utilized to estimate the thermal characteristics of various rocks.

e) In-situ and laboratory evaluation

In-situ and laboratory evaluation of the thermal conductivities of different rocks, including shale, sandstone, and granite, for geodynamics including geothermal gradient, geothermal mapping, thermal storage, thermal potential, and thermal anisotropy, etc. of these rocks.

f) Simulation of several models

Simulation of several models for estimating the thermal characteristics of various rocks in an indirect manner.

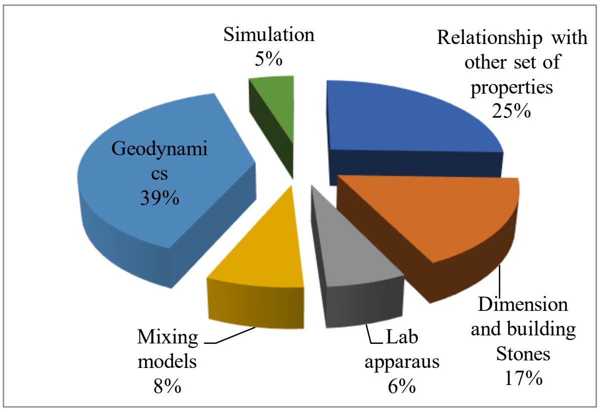

Fig. 2: Pie-chart showing percentage of different research objectives selected by various research groups during earlier studies

The objective of simulation was not generally discussed exclusively instead in continuity of other objectives. Figure 2 shows the pie-chart distribution of these 6 objectives used for the research studies during the period referred in this paper.

From the pie chart, it can be observed that 25% of the papers sought to estimate the thermal properties of rocks and their relationships with other petrophysical, mechanical, and engineering properties for general purposes, such as addition to the body of knowledge or indirect estimation of thermal properties through other properties, while 39% of the papers sought to perform geodynamics-related research on the thermal conductivity of rocks. While 8% of research papers have the goal of estimating mixing models for indirect assessment of the thermal properties of various rocks, and 6% of papers have the goal of showcasing laboratory apparatuses used for estimation of the thermal properties of rocks, 17% of research papers discussed the thermal properties of dimension stones and other building stones, materials, and rocks used for the similar purposes. 5 % of the research works were done in context of simulation of thermal properties of rocks. Table 1 shows the references of various authors and research publications utilizing different sets of objectives. Only selected references (prioritized in the basis of recent years of publication) are mentioned here.

Table 1: Objectives of research on thermal properties of rocks.

S. No.	Objective	Authors (2021-23)
1	Relationship with other Properties in General Context	Lasheen, Rashwan, and Azer (2023); Chae, Park, and Kim (2023); Yang and Zhang (2022); Jiang, Wu, Fang, and Liu (2021); W. Liu, Ma, Sun, Khan, and Technology (2021); Tang et al. (2021); Carson (2021); Yuan et al. (2021); Gegenhuber and Dertnig (2023); Li, Long, Feng, and Zhang (2021)
2	Dimension and Building Stones	Rahmouni et al. (2023); Rashwan, Lasheen, and Azer (2023); Cárdenes, Rubio-Ordóñez, and García-Guinea (2023); Khwayyir, Hachim, Aboodi, and Alwan (2022); Alzahrani, Lasheen, and Rashwan (2022); Özdemir (2022); Z. Zhu et al. (2022); Eljufout and Alhomaidat (2021); Siegesmund, Menningen, and Shushakova (2021); AlQdah (2021);BİÇER (2021); Alsaiari and El Aal (2021); Ahmed, Basharat, Sousa, and Mughal (2021);
3	Lab Apparatus	Heisig, Wulf, and Fieback (2023); Grigorev, Nikulin, Vazhenin, and Vakhnina (2023); Tiskatine et al. (2023); N. Liu, Li, Li, Song, and Wang (2022); A. Sharo, Rabab'ah, Taamneh, Aldeeky, and Al Akhrass (2022); Podugu and Roy (2022); Persson and Biele (2022); Pandey, Kattamuri, and Sastry (2021); Colinart, Pajeot, Vinceslas, De Menibus, and Lecompte (2021); Wu, Morrell, Clark, and Chapman (2021);
4	Mixing Models	Yiming Wang, Chu, Li, Zhao, and Ji (2023); Adrinek, Singh, Janža, Żeruń, and Ryżyński (2022); Carson (2022); Tatar, Mohammadi, Soleymanzadeh, and Kord (2021); Shen et al. (2021); Preux and Malinouskaya (2021); Coletti et al. (2021)
5	Geodynamics	Sugamoto, Ishitsuka, Lin, and Sakai (2023); Redouane, Bellanger, Haissen, Sadki, and Raji (2023); Xie, Zhu, and Tang (2023); Gegenhuber and Dertnig (2023); Li, Xing, Long, and Liu (2023); Sedara, Ray, and Alabi (2022); (Yu et al., 2022); Ye et al. (2022); Y Wang et al. (2021); Curtis Neto, Ribeiro, Kobelnik, and Monticelli (2021); Heap et al. (2022); Gerard, Vincent, and François (2021); Baghban, Arulrajah, Narsilio, and Horpibulsuk (2022); W. Liu et al. (2021); Förster, Fuchs, Förster, and Norden (2021)
6	Simulation of different models for indirect estimation of thermal properties of various rocks.	C. Zhu, Chen, and Jiang (2023); Samaei, Massalow, Abdolhosseinzadeh, Yagiz, and Sabri (2022); Lawal, Kwon, Kim, Aladejare, and Onifade (2022); Kang et al. (2021); Kan, Mao, Wang, and Shi (2021)

Materials and methods used in previous research studies

In reference to the research publications those were shortlisted for this study, 48% used steady state methods to estimate thermal characteristics while 44% used transient state approaches. 4% of the publications examined thermal characteristics of rocks using indirect estimation models. Out of all studies describing steady state techniques for estimating thermal characteristics, 54% explored optical scanning techniques and the remaining 46% covered the divided bar technique. Therefore, optical scanning was used in 26% of the articles that were discussed overall, while divided bars were used in 18% of the overall studies utilized in this research. The pie-chart representation of the percentage distribution of articles describing optical scanning methods, divided bar methods, transient methods, and indirect estimating approaches is shown in Figure 3.

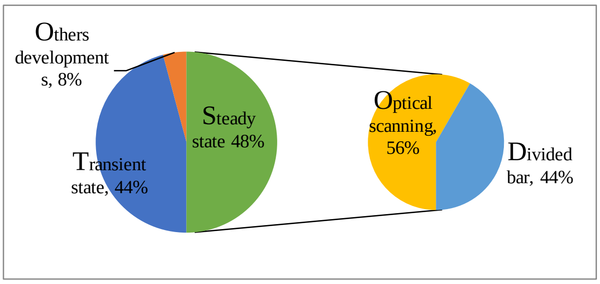

Fig. 3 Pie chart of different methods selected in earlier researches to measure thermal properties of rocks.

Methods utilized by various authors, for research purposes, have been described in Table 2. Please note that few researchers have used more than one technique to measure thermal properties and this is termed as "Multiple techniques" (Table 2) while few other authors used mixing models or other techniques such as Fourier's Law and such cases are termed as "others" in this table. Only selected references, prioritized in the basis of recent years of publication, are mentioned here.

Table 2: Methods used by researchers for measurement of thermal properties of rocks.

S.No	Rock	Authors (2021-2023)
1	Transient state method	Sugamoto et al. (2023); Heisig et al. (2023); Tiskatine et al. (2023); Gegenhuber and Dertnig (2023); Lawal et al. (2022); A. Sharo et al. (2022); Sedara et al. (2022); Adrinek et al. (2022); Yang and Zhang (2022); Y Wang et al. (2021); Shen et al. (2021); Eljufout and Alhomaidat (2021); BİÇER (2021); Shen et al. (2021); W. Liu et al. (2021)
2	Optical scanning method	Rahmouni et al. (2023); Xie et al. (2023); C. Zhu et al. (2023); Chae et al. (2023); Li et al. (2023); Ye et al. (2022); Kang et al. (2021); Heap et al. (2022); Coletti et al. (2021)
3	Divided bar method	Rashwan et al. (2023); Lasheen et al. (2023); Yu et al. (2022)
4	Multiple techniques	Podugu and Roy (2022); Jiang et al. (2021); Tang et al. (2021)
5	Others	Redouane et al. (2023); Yiming Wang et al. (2023); Förster et al. (2021)

When measuring thermal characteristics of rocks, different writers employed various instruments. The material being evaluated and the type of prepared samples were the main determining factors in the choice of these instruments. Researchers (e.g. Eljufout and Alhomaidat (2021); and BİÇER (2021) used ISOMET-2104 when conducting research primarily on construction and dimension stones and other related natural materials, whereas only a small number of other researchers (e.g. Lawal et al. (2022) used ISOMET-2114. To conduct their research on thermal properties of building materials, sandstone, and other sedimentary and igneous rocks, few researchers (e.g. Heisig et al. (2023); A. A. Sharo, Taamneh, and Rabab'ah (2022) etc.) used the TPS-2500S, whereas a smaller number of researchers e.g. A. Sharo et al. (2022) used the TPS-2200.

To test the thermal properties of particular sedimentary, metamorphic, and igneous rocks, researchers e.g. Sedara et al. (2022); Adrinek et al. (2022); Y Wang et al. (2021); and W. Liu et al. (2021)etc.) used the KD2 - Thermal Properties Analyzer. A few researchers e.g. Chae et al. (2023) etc. measured the thermal characteristics of selected igneous rocks using various laser flash apparatus types, including the LFA-457, LFA-427, and LFA-447. Few researchers e.g. Gegenhuber and Dertnig (2023); Podugu and Roy (2022) used TeKa's TK-04 instrument to measure the thermal characteristics of different volcanic rocks.

Conclusions of previous researches

Researchers suggest that the thermal conductivity, thermal diffusivity, and specific heat capacity of the rock samples can be used to understand the thermal properties of the Earth's crust and mantle e.g. Xie et al. (2023). Geothermal gradients, virgin rock temperatures, and the thermal properties of different rocks must all be thoroughly understood in order to plan the ventilation and refrigeration requirements for deep mines (Jones, 2015; Trofimov, Atchley, Shrestha, Desjarlais, & Wang, 2020). A thermal conductivity map might be a helpful place to start for ground-source heat pump projects during the pre-design phase (e.g. Gerard et al. (2021). For the precise design of ground-source heat pump projects, the measured thermal conductivities' fluctuation is too great to be directly used in the design of a ground-coupled heat pump project.

Dimension stones with low linear thermal expansion coefficients are preferred for their uses in construction applications (Rashwan et al., 2023). The moisture content has a significant impact on the thermal inertia parameters of building assembly layers. The influence of hygrothermal properties and thickness of layers on the decrement factor and time lag has a decisive impact on the heat wave evolution (e.g. Eljufout and Alhomaidat (2021). The thermal and optical properties of natural and artificial marble should be taken into account when designing buildings, particularly in relation to energy efficiency and thermal comfort. Different thermal coefficients of different minerals cause formation of cracks and decay and bending strengths of roofing dimension stones (Cárdenes et al., 2023). Marbles high solar reflectivity, which makes it suitable for use in outdoor applications (Khwayyir et al., 2022). Researchers concluded that the thermal and hygric inertia of the dimension stones (e.g. travertine) envelope has a significant impact on indoor thermal comfort and energy efficiency (Medjelekh, Ulmet, Abdou, & Dubois, 2016).

Table 3 shows different sets of conclusions obtained as a result of this study. These sets are named as thermal properties of rocks in general context; thermal properties of dimension stones; instruments used for rocks' thermal properties measurement; thermal properties of potentially geothermal rocks; and thermal properties' modeling.

Table 3 Different sets of conclusions drawn by the researchers during previous studies from 2021 to 2023.

Research Area	**Conclusion Summary**	**Authors (2021-2023)**
Thermal properties of rocks in general context	The researchers concluded that the thermal conductivity of rocks is affected by the presence of pores and fractures; water intrusion; mineralogy, mineral composition; and thermal conductivity of the mineral constituents. The thermal conductivity of rocks is strongly correlated with physical properties such as porosity, moisture content, density, and P-wave velocity. Pore pressure, particle size distribution; organic-matter content of the rocks; lithology and degree of saturation etc	C. Zhu et al. (2023); Yang and Zhang (2022), Yu et al. (2022); Ye et al. (2022); Curtis Neto et al. (2021); Shen et al. (2021); Tang et al. (2021); Heap et al. (2022); Yuan et al. (2021); W. Liu et al. (2021); Kan et al. (2021)
Thermal properties of dimension stones	Dimension stones' thermal conductivity is an important parameter to assess their potential of utilization and it is correlated P-wave velocity; with mineral composition; textural aspects; moisture content; water absorption; and thermal and ultrasonic properties of dimension stones can be used to determine their anisotropy.	Rahmouni et al. (2023); Cárdenes et al. (2023); Alzahrani et al. (2022); Coletti et al. (2021); Eljufout and Alhomaidat (2021); Khan and Bhattacharjee (2023); Hebib, Alloul, Belhai, and Derriche (2023);
Instruments used for rocks' thermal properties measurement	Numerous equipments used for field measurements or laboratory measurements of different thermal properties are effective and accurately measure these parameters, but each instrument requires a unique sample preparation	Sugamoto et al. (2023)

	and measurement method.	
Properties of potentially geothermal rocks	Potentially geothermal rocks' thermal conductivity is anisotropic, changes with mineral composition, stratigraphic age, porosity, permeability, burial depth, drilling depth, and laminae angle, and rises with rising relative humidity in the atmosphere.	Xie et al. (2023); Jiang et al. (2021); BİÇER (2021); Förster et al. (2021); BİÇER (2021);
Rocks' thermal properties' modeling	It has been demonstrated that using diverse physical and mechanical qualities as input factors in thermal conductivity modeling is an effective and efficient method for estimating the thermal conductivity of rocks in an indirect manner.	Aal, Shoukry, Sayed, and Ghramh (2018)

Conclusion

This study identifies that (a) The thermal properties of stones in general and building and dimension stones in particular has been the point of concern in many researches for the purpose of identification of their suitability towards thermal comforts in residential and commercial building. Globally thermal properties of geothermal reservoir rocks had also been under discussion for the purpose of identifying the potential as alternate energy resources. This infers that serious efforts have started for evaluating the importance of natural rocks and stones towards control over carbon emissions and green environments as a measure to reduce global warming. (b) Geodynamics, thermal comfort and the relationship between thermal, physical and engineering properties of rocks has been among the leading concerns of researches conducted during last decade. This infers that researchers are keen to assess interlinks of different rock properties to analyze how rocks behave under different in-situ rock conditions for alternate power generation source or how thermal comfort in building may be affected when the dimension stones are placed and exposed to different climatic conditions (c) both steady state methods and transient state methods of thermal properties measurement have been valued and yield reliable results (d) natural stones may prove competitively fateful than artificial or cultured stone for generating thermal comforts. Natural stones as building material or as dimension stones may contribute optimally in future may be the global norms of building practices to reduce greenhouse gases emissions.

Pakistan has been blessed with plenty of dimension stones' resources precisely in Southern; and Northern parts. The global trading potential of these valuable stones may be enhanced if these prove to contribute towards generating thermal comfort thereby reducing power requirements in buildings eventually resulting in low GHGs emissions from buildings sector. This may also reduce the financial burden on power sector resulting in managing current wave of inflation in Pakistan. However, in order to optimize the energy efficiency and thermal comfort of a structure, it is essential to comprehend the thermal behavior of these materials.

Recommendations

Finally, this research proposes certain future research directions:

- Detailed experimental study(s) to identify the thermal characteristics of various rocks and dimension stones and their response to annual variation in climatic temperature. This will assist in identifying the optimal place of utilization of these entities exclusively for cost-effective power management thereby controlling global GHGs emissions.

- A detailed integrated experimental study is required to identify the cumulative thermal comfort generated by various dimension stones other items such as furniture, doors, fireplaces etc used in buildings interiors. This is vitally important for architects and planners to design future green buildings with sustainable environments.

- Based on the thermal properties of various rock categories the planners need to develop thermal classes of rocks. This will not only help in identifying the potential utilization of each rock but also help in setting the global standards for these rocks in addition to their conventional relative parameters of color, appeal, durability etc.

There is also a dire need to develop rocks' thermal maps incorporating the in-situ thermal properties of every rock in the range. This will help assessment of thermal energy production potential and thermal waste storage.

References

Biçer, A. (2021). Certain Physical Properties of the Building Stones From Elazig-Tunceli-Erzincan-Bayburt Provinces. *Bartın University International Journal of Natural and Applied Sciences,* **4** (1), 33-39.

Bintarto, R., Purnowidodo, A., Darmadi, D. B., Widodo, T. D. (2022). The effect of composite thickness as thermal insulation roof coating on room temperature reduction. *Salud, Ciencia y Tecnología volume* (2), 192.

Cárdenes, V., Rubio-Ordóñez, A., García-Guinea, J. (2023). Fire resistance of roofing slates: Mechanical, mineralogical and aesthetic changes alongside temperature increase. *Construction and Building Materials,* **368**, 130376.

Carson, J. K. (2021). A Versatile Effective Thermal Diffusivity Model for Porous Materials. *International Journal of Thermophysics,* **42** (10), 141.

Carson, J. K. (2022). Modelling thermal diffusivity of heterogeneous materials based on thermal diffusivities of components with implications for thermal diffusivity and thermal conductivity measurement. *International Journal of Thermophysics,* **43** (7), 108.

Chae, B.-G., Park, E.-S., Kim, H.-C. (2023). Basic analysis of rock mechanical and thermal properties in South Korea. *Rock Mechanics Bulletin,* **2** (3).

Coletti, C., Borghi, A., Cossio, R., Dalconi, M. C., Dalla Santa, G., Peruzzo, L.,Galgaro, A. (2021). A multi-scale methods comparison to provide granitoid rocks thermal conductivity. *Construction and Building Materials, 304*.

Colinart, T., Pajeot, M., Vinceslas, T., De Menibus, A. H., & Lecompte, T. (2021). Thermal conductivity of biobased insulation building materials measured by hot disk: Possibilities and recommendation. *Journal of Building Engineering,* **43**.

Curtis Neto, J. A., Ribeiro, R. P., Kobelnik, M., Monticelli, J. P. (2021). Evaluation of the thermal behavior and physical–mechanical properties of different rocks from Limeira Intrusion (São Paulo State, Brazil). *Journal of Thermal Analysis and Calorimetry,* 1-10.

Eljufout, T., Alhomaidat, F. (2021). Evaluation of natural building stones' characterizations using ultrasonic testing technique. *Arabian Journal for Science and Engineering,* **46**, 11415-11424.

Förster, A., Fuchs, S., Förster, H.-J., Norden, B. (2021). Ambiguity of crustal geotherms: a thermal-conductivity perspective. *Geothermics, 89*.

Gegenhuber, N., & Dertnig, F. (2023). Correlation and interpretation of thermal properties of volcanic rocks from Austria. *Acta Geophysica,* **71** (3), 1251-1258.

Gerard, P., Vincent, M., François, B. (2021). A methodology for lithology-based thermal conductivities at a regional scale for shallow geothermal energy–Application to the Brussels-Capital Region. *Geothermics,* **95**.

Grigorev, B., Nikulin, S., Vazhenin, D., & Vakhnina, D. (2023). Development of Methods and Instruments for Thermal Conductivity Measurements of Standard Rock Samples for Petrophysical Studies. *Measurement Techniques,* volume. 1-7.

Heap, M. J., Jessop, D. E., Wadsworth, F. B., Rosas-Carbajal, M., Komorowski, J.-C., Gilg, H. A., Goupil, M. (2022). The thermal properties of hydrothermally altered andesites from La Soufrière de Guadeloupe (Eastern Caribbean). *Journal of Volcanology and Geothermal Research,* **421.**

Hebib, R., Alloul, B., Belhai, D., & Derriche, Z. (2023). Contribution of Natural Stones in the Sustainable Development of Constructions—Potentialities and Examples from the Algerian Alpine Chain. *Geoheritage,* **15** (3), 101.

Heisig, L.-M., Wulf, R., & Fieback, T. M. (2023). Investigation and Optimization of the Hot Disk Method for Thermal Conductivity Measurements up to 750° C. *International Journal of Thermophysics,* **44** (6), 82.

Jiang, X., Wu, C., Fang, X., & Liu, N. (2021). A new thermal conductivity estimation model for sandstone and mudstone based on their mineral composition. *Pure and Applied Geophysics, 178*(10), 3971-3986.

Jones, M. (2015). Thermophysical properties of rocks from the Bushveld Complex. *Journal of the Southern African Institute of Mining and Metallurgy,* **115** (2), 153-160.

Kan, A., Mao, S., Wang, N., Shi, B. (2021). Simulation and experimental study on thermal conductivity of nano-granule porous material based on lattice-Boltzmann method. *Journal of Thermal Science,* **30**, 248-256.

Kang, J., Yu, Z., Wu, S., Zhang, Y., Gao, P. (2021). Feasibility analysis of extreme learning machine for predicting thermal conductivity of rocks. *Environmental Earth Sciences,* **80** (13), 455.

Khan, N. A., Bhattacharjee, B. (2023). Development of design guidelines for thermal, visual, and noise insulation performance of building envelope of low-rise commercial office buildings in the Indian tropical climate. *Sādhanā,* **48** (3), 125.

Khwayyir, H. H., Hachim, D. M., Aboodi, A. M., & Alwan, K. J. (2022). Investigating the Unique Thermal properties of Thassos marble. *Journal of The Institution of Engineers (India): Series D,* **103** (1), 217-224.

Lasheen, E. S. R., Rashwan, M. A., Azer, M. K. (2023). Effect of mineralogical variations on physico-mechanical and thermal properties of granitic rocks. *Scientific Reports*, **13** (1).

Lawal, A. I., Kwon, S., Kim, M., Aladejare, A. E., Onifade, M. (2022). Prediction of thermal conductivity of granitic rock: an application of arithmetic and salp swarm algorithms optimized ANN. *Earth Science Informatics*, **15** (4), 2303-2317.

Li, Z.-W., Long, M.-C., Feng, X.-T., Zhang, Y.-J. (2021). Thermal damage effect on the thermal conductivity inhomogeneity of granite. *International Journal of Rock Mechanics and Mining Sciences, 138*.

Li, Z.-W., Xing, S.-C., Long, M.-C., Liu, Y. (2023). On the thermal conductivity anisotropy of thinly interbedded rock. *Acta Geotechnica*, *18*(4), 1967-1989.

Liu, N., Li, N., Li, G., Song, Z., Wang, S. (2022). Method for evaluating the equivalent thermal conductivity of a freezing rock mass containing systematic fractures. *Rock Mechanics and Rock Engineering*, ***55*** (12), 7333-7355.

Liu, W., Ma, L., Sun, H., Khan, N. M. J. I. P., Technology. (2021). An experimental study on infrared radiation and acoustic emission characteristics during crack evolution process of loading rock. **118**.

Medjelekh, D., Ulmet, L., Abdou, S., Dubois, F. (2016). A field study of thermal and hygric inertia and its effects on indoor thermal comfort: Characterization of travertine stone envelope. *Building and Environment*, **106**, 57-77.

Moiceanu, G., Dinca, M. N. (2021). Climate Change-Greenhouse Gas Emissions Analysis and Forecast in Romania. *Sustainability*, volume issue, 1-21.

Moiceanu, G., Dinca, M. N. J. S. (2021). Climate change-greenhouse gas emissions analysis and forecast in Romania. **13**(21).

Özdemir, E. (2022). Investigation of Some Property Changes of Light-Colored Turkish Natural Stones after High-Temperature Treatments.*Sustainability*, **14**(16), 10298.

Pandey, A., Kattamuri, P. K., Sastry, B. S. (2021). Measurement of thermal conductivity of sandstone using Lee's apparatus: A case study. *Mining, Metallurgy & Exploration*, **38,** 1997-2003.

Pearce, J. M., Parncutt, R. (2023). Quantifying Global Greenhouse Gas Emissions in Human. *Energies*, volume, 1-20.

Persson, B., Biele, J. (2022). Heat transfer in granular media with weakly interacting particles. *AIP Advances*, **12** (10).

Podugu, N., & Roy, S. (2022). Thermal conductivity of Deccan flood basalts. *Journal of Earth System Science*, **131** (2), 112.

Preux, C., Malinouskaya, I. (2021). Thermal conductivity model function of porosity: review and fitting using experimental data. *Oil & Gas Science and Technology–Revue d'IFP Energies nouvelles*, **76**, 66.

Rahmouni, A., Boulanouar, A., El Rhaffari, Y., Hraita, M., Zaroual, A., Géraud, Y.,Nabawy, B. S. (2023). Impacts of anisotropy coefficient and porosity on the thermal conductivity and P-wave velocity of calcarenites used as building materials of historical monuments in Morocco. *Journal of Rock Mechanics and Geotechnical Engineering*.

Rashwan, M. A., Lasheen, E. S. R., Azer, M. K. (2023). Thermal and physico-mechanical evaluation of some magmatic rocks at Homrit Waggat Area, Eastern Desert, Egypt: Petrography and geochemistry. *Bulletin of Engineering Geology and the Environment*, **82** (6), 1-22.

Redouane, M., Bellanger, M., Haissen, F., Sadki, O., Raji, M. (2023). The influence of thermal conductivity on the thermal state of Central and Eastern geological units of the Rif belt (Morocco). *Arabian Journal of Geosciences*, **16** (5), 1-15.

Rinne, R., Ilgın, H. E., & Karjalainen, M. (2022). Comparative Study on Life-Cycle Assessment and Carbon Footprint of Hybrid, Concrete and Timber Apartment Buildings in Finland. *Int. J. Environ.*

Samaei, M., Massalow, T., Abdolhosseinzadeh, A., Yagiz, S., & Sabri, M. M. S. (2022). Application of soft computing techniques for predicting thermal conductivity of rocks. *Applied Sciences*, **12** (18), 9187.

Sedara, S. O., Ray, L., Alabi, O. O. (2022). Evaluation of thermal conductivity values for the basement rocks of southwest Nigeria: an indirect method on geothermal prospects. *Arabian Journal of Geosciences*, **15** (10), 973.

Sharo, A., Rabab'ah, S., Taamneh, M., Aldeeky, H., Al Akhrass, H. (2022). Mathematical modelling for predicting thermal properties of selected limestone. *Buildings*, 2022, **12**, 2063.

Sharo, A. A., Taamneh, M. O., Rabab'ah, S. R. (2022). Enhancing insulation properties of building stones. *Arabian Journal of Geosciences*, **15** (16), 1381.

Shen, Y., Wang, X., Wang, Y., Zhou, K., Zhang, J., Zhang, H., Li, J. (2021). Thermal conductivity models of sandstone: applicability evaluation and a newly proposed model. *Heat and Mass Transfer,* **57**, 985-998.

Siegesmund, S., Menningen, J., Shushakova, V. (2021). Marble decay: towards a measure of marble degradation based on ultrasonic wave velocities and thermal expansion data. *Environmental Earth Sciences,* **80** (11), 395.

Sugamoto, H., Ishitsuka, K., Lin, W., Sakai, T. (2023). Measurement of thermal conductivities of drill cuttings and quantification of the contribution of thermal conduction to the temperature log of the Hachimantai geothermal field, Japan. *Geothermics,* **112**.

Tang, B., Zhu, C., Qiu, N., Cui, Y., Guo, S., Luo, X., Fu, X. (2021). Analyzing and estimating thermal conductivity of sedimentary rocks from mineral composition and pore property. *Geofluids,volume* 1-19.

Tatar, A., Mohammadi, S., Soleymanzadeh, A., Kord, S. (2021). Predictive mixing law models of rock thermal conductivity: Applicability analysis. *Journal of Petroleum Science and Engineering,* **197.**

Tiskatine, R., Bougdour, N., Idoum, A., Bazgaou, A., Oaddi, R., Ihlal, A., & Aharoune, A. (2023). Experimental investigation on rock thermal properties under the influence of temperature. *Thermochimica Acta*, **720.**

Trofimov, A. A., Atchley, J., Shrestha, S. S., Desjarlais, A. O., & Wang, H. (2020). Evaluation of measuring thermal conductivity of isotropic and anisotropic thermally insulating materials by transient plane source (Hot Disk) technique. *Journal of Porous Materials*, *27*, 1791-1800.

United Nations Environment Programme (2023). Emissions Gap Report 2023: Broken Record – Temperatures hit new highs, yet world fails to cut emissions (again). Retrieved from Nairobi.

Wang, Y., Chu, Z., Li, X., Zhao, P., Ji, Y. (2023). Derivation of the unifying model and its discussion on the effective thermal conductivity of isotropic, porous and composite media. *Case Studies in Thermal Engineering*. Volume issue number

Wang, Y., Wang, Z., Shi, L., Rong, Y., Hu, J., Jiang, G., Hu, S. (2021). Anisotropic Differences in the Thermal Conductivity of Rocks: A Summary from Core Measurement Data in East China. *Minerals,* **11**, 1135.

Wu, J., Morrell, R., Clark, J., Chapman, L. (2021). Characterisation of the NPL thermal conductivity reference material Inconel 600. *International Journal of Thermophysics*, **42,** 1-15.

Xie, F., Zhu, C., Tang, B. (2023). An experimental study on anisotropy of thermal conductivity in shale. *Energy Geoscience*, volume 100195.

Yang, Y.-L., & Zhang, T. (2022). Effects of water intrusion on thermal conductivity and durability of carbonaceous rocks. *Soils and Foundations,* **62** (1).

Ye, X., Yu, Z., Zhang, Y., Kang, J., Wu, S., Yang, T., & Gao, P. (2022). Mineral composition impact on the thermal conductivity of granites based on geothermal field experiments in the Songliao and Gonghe Basins, China. *Minerals,* **12** (2), 247.

Yu, R., Jiang, S., Wang, H., Du, F., Zhang, L., Wen, Y., Zhang, R. (2022). Estimation of thermal conductivity of plutonic drill cuttings from their mineralogy: a case study for the FORGE Well 58–32, Milford, Utah. *Geothermics,* **102**.

Yuan, J., Chen, W., Tan, X., Ma, W., Zhou, Y., & Zhao, W. (2021). An effective thermal conductivity model of rocks considering variable saturation and pore structure: Theoretical modelling and experimental validations. *International Communications in Heat and Mass Transfer,* **121.**

Zhu, C., Chen, C., Jiang, X. (2023). Numerical Simulation of Internal Factors that Influence the Thermal Conductivity of Rock. *International Journal of Thermophysics,* **44** (2), 24.

Zhu, Z., Yang, S., Wang, R., Tian, H., Jiang, G., & Dou, B. (2022). Effects of high temperature on the linear thermal expansion coefficient of Nanan granite. *Acta Geodaetica et Geophysica,* **57** (2), 231-243.