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Thermal Properties of Rocks and Environmental Sustainability: A Review

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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 aims to provide directions to enhance the knowledge base for future research to analyze thermal properties of rocks occurring in Pakistan and how strategically these rocks may be utilized to reduce global warming through environment sustainability and zero carbon emissions for achieving 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 (Moiceanu and Dinca, 2021) and eventually cause global warming. According to a report of United Nations Environment Program (Moiceanu and 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 increases 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 (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 et al., 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, et al., 2022). It is also suggested that understanding dimension stone thermal properties is crucial for industrial applications and cultural heritage preservation, as it helps to 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. In order to forecast the thermal conductivity of rocks Kang and Gao (2021) referred to four input variables: moisture content, porosity, density, and P-wave velocity, whereas 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 study incorporated few rocks or specific categories; most researches utilized only one of many practical methods with specific equipment(s) to identify one or few thermal properties of rock(s) specific case study for a specific purpose. In 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 study has been carried out in context of rocks occurring in Pakistan in general and commercially available dimension stones of Pakistani origin in particular to gather valuable data on their thermal properties, and 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 collect 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 studies in context of thermal properties (b) objectives of previous studies conducted on thermal properties of rocks (c) materials and methods applied in previous researches for the assessment of thermal properties of rocks and (d) conclusions of previous studies on rock's thermal properties.

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 determining those qualities.
2. Research paper lacking a DOI was not considered 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 study.

Major Rock Types: Thermal Properties

The research papers consulted for this study covered the thermal characteristics of various rocks. This classification is neither based on pure geological nor commercial, but based 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 rocks are covered under the main term "stones" and sub-term "building materials and building stones". Other than these rocks, sedimentary rocks are referred as "other sedimentary rocks". Few research studies cover all three types of rocks—igneous, sedimentary, and metamorphic (Moiceanu and Dinca, 2021). The rocks are identified as "multiple categories of rocks" in such circumstances. Igneous rocks such as gabbro, diorite, 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. Because these are addressed in relation to dimension stones and ornamental stones, rocks like marble, granite, slate, and basalt, referred as "stones". Figure 1 shows the pie chart distribution of these rocks discussed in various research studies from 2021 to 2023.

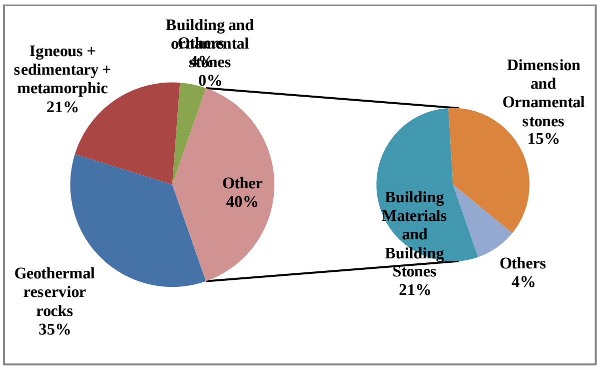

Fig. 1 Pie chart of various rocks discussed in the previous researches for assessment of their thermal properties.

Objectives of Previous Studies

During the last decade extensive research has been carried out on 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. 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 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 of these rocks.

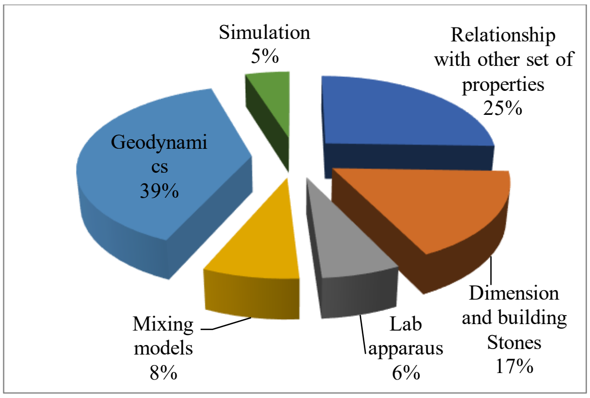

Fig. 2 Pie-chart showing percentage of different research objectives selected by various research groups during earlier studies

Simulation of several models

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

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 2021-23. From the pie chart, it can be observed that 25% of the papers sought to estimate thermal properties of rocks and their relationships with other petrophysical, mechanical, and engineering properties for general purposes, such as addition to the 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. Whereat, 8% of research papers focused on estimating mixing models for indirect assessment of the thermal properties of various rocks, and 6% of papers aimed at showcasing laboratory apparatuses used for estimation of the thermal properties of rocks. While 17% of research papers discussed thermal properties of dimension stones and other building stones, materials, and rocks used for the similar purposes and 5 % of the research study 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 on 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)

In reference to the research publications, shortlisted for this study, 48% used steady state methods to estimate thermal characteristics, while 44% used transient state approaches, and 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 study. The pie-chart representation of the percentage distribution of articles describing optical scanning methods, divided bar methods, transient methods, and indirect estimating approaches (Fig. 3).

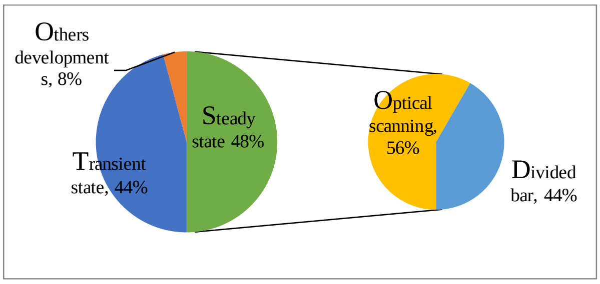

Fig. 3 Pie chart of different methods selected in earlier researches to measure thermal properties of rocks.

Methods utilized by various authors, for research purpose, have been described in Table 2. However, few researchers have used more than one technique to determine thermal properties, termed as Multiple techniques (Table 2), while few others used mixing models or other techniques such as Fourier's Law and such cases are termed as Others in Table 2.

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 (Eljufout and Alhomaidat, 2021) used ISOMET-2104 for conducting research primarily on construction and dimension stones and other related natural materials, whereas only a small number of researchers (Lawal et al., 2022) used ISOMET-2114. To conduct research on thermal properties of building materials, sandstone, and other sedimentary and igneous rocks, few researchers (Heisig et al., 2023) used the TPS-2500S, whereas a smaller number of researchers used the TPS-2200 (Sharo et al., 2022).

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

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 (Xie et al., 2023). Geothermal gradients, virgin rock temperatures, and thermal properties of different rocks must be thoroughly understood in order to plan the ventilation and refrigeration requirements for deep mines (Jones, 2015; Trofimov et al., 2020). A thermal conductivity map might be helpful to start ground-source heat pump projects during the pre-design phase (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 (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, makes it suitable for use in outdoor applications (Khwayyir et al., 2022). Researchers concluded that the thermal and hygric inertia of the dimension stones (travertine) envelop has a significant impact on indoor thermal comfort and energy efficiency (Medjelekh et al., 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, 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**	**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 and measurement method.	Sugamoto et al. (2023)
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) Thermal properties of stones in general and building, and dimension stones in particular have been the point of concern for the purpose of identification of their suitability towards thermal comforts in residential and commercial buildings. 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 useful than artificial or cultured stones for generating thermal comforts. Natural stones as building material or as dimension stones may contribute optimally in future global norms of building practices to reduce greenhouse gases emissions. 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.

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