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Experimental evaluation of thermo-mechanical performances of candidate rocks for use in high temperature thermal storage

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HIGHLIGHTS

- Rock performances evaluation for use in high temperature TES applications.
- Rocks thermo-mechanical behavior during thermal cycling and parameters influencing their lifetime have been discussed.
- Empirical equations were developed for estimation of rock hardness.
- Carbonated, foliated and coarse-grained rocks are unsuitable for high temperature thermal storage.
- Rhyolite showed excellent ability for use in high temperature TES.

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ABSTRACT

Packed-bed of rocks using air as heat transfer fluid (HTF) are identified as a promising alternative and cost effective solution for thermal energy storage (TES) in concentrating solar power plants (CSP). Desert sands, igneous and other rocks are being intensively tested for heat storage at high temperature. This paper focuses on the study of several candidate rocks for heat storage. Thirteen samples are collected from diverse places in Morocco and thermally cycled between 20 °C and 650 °C. The chemical and thermo-physical properties influencing the lifetime of rocks are identified. Vickers hardness test has been used to evaluate the compressive strength of the samples and the effect of thermo-mechanical stress during thermal cycling. The obtained results show that quartz and calcite are the principal minerals controlling rock physical properties. Limestone, marble and granite have not withstood thermal cycling. Their hardness decreases after each cycle. Rhyolite and quartzitic sandstone show excellent ability during thermal cycling. When comparing their principal characteristics, rhyolite seems to be the most promising candidate for high temperature TES.

1. Introduction

The growing energy demand and the alarming consequences of climate change are two major challenges facing the world today. Renewable sources of energy are capable of addressing such issues by guaranteeing a sustainable development. Thermal solar power plants are considered as a key technology for the electricity production [1–5]. Solar power technologies have reached an important level of penetration and are expected to grow in the near future. However, the intermittency of such sources impacts on security of energy supply. Energy storage is recognized to play a major role in the management of fluctuating and intermittent renewable energies. Making solar electricity available at night or at peak times requires the storage of heat generated during diurnal sunny hours. Thermal energy storage (TES) involves three categories: sensible heat storage, latent heat storage and thermo-chemical heat storage [6–11]. Thermal storage by combination of the first two types is considered as well [12,13]. Gil et al. [14] reviewed a list of the materials used in high temperature TES applications divided into the three previous main types of storage. Medrano et al. [15] presented an updated review of more than 25 case studies of high temperature storage systems in CSP plants. The storage in molten salt has been, so far, the most adopted solution in CSP plants [6,16–19]. Nevertheless, other materials are used like steam [20,21], concrete [19,20,22–26] and phase change materials [12,19,27–31]. Recently, a special interest has been devoted to packed-bed of rocks with air as heat transfer fluid [4,32–36]. This

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method offers some advantages compared to the other methods listed above. Also, it is simple, economical and environmentally-friendly. The criteria defining the suitability of a material to store sensible heat are mainly the thermal capacity and conductivity, particle size and shape, cost effectiveness and environmental impact [9,10,37]. The use of rocks as materials for thermal storage addresses widely the previous criteria. They are economically attractive and locally available enabling low cost of investment and transportation.

This study is part of the project of CSP Pilot-scale developed by Airlight Energy and located at Ait-Baha (South of Morocco) [34]. In this plant, energy storing is performed in packed-bed of rocks consisting of quartzitic sandstone, a metamorphic rock, because of their abundance in the river of Oued Souss surrounding the plant and their almost spherical shape, which is an important criterion allowing a stable thermal stratification for an efficient discharge operation. Our contribution consists in the potential evaluation of some candidate rocks for high temperature TES. Numerous researchers studied the influence of temperature on the mechanical behavior of rocks. But, few rigorous experimental data were published on the degradation of rocks during thermal cycling at high temperature and on the suitability for rock-bed thermal storage. The present work develops an experimental approach which consists in identifying the behavior of rocks subject to three constraints: time (thermal cycling), high temperature and mechanical pressure, to trace out their situation over time in the bed. The parameters influencing rock lifetime have been evaluated. The surface of samples has been analyzed after each cycle. Based on this assessment, we have cited the rock types that should not be used in a storage tank, so as to save time during selection. We have also proposed some empirical equations linking thermo-physical and mechanical properties of the studied rocks. The best selected rocks have been compared with quartzitic sandstone from the Airlight Energy rock bed [34]. The selection criteria have been shown in this comparison. The analyses in this paper enable to compare the rock samples and to assess their suitability for high temperature TES.

2. Description of tested rocks

Several candidate rocks have been collected from different regions in Morocco. Only thirteen were selected to evaluate their performance for TES. These rocks belong to the three categories described by Allen et al. [38]. Table 1 summarizes the designation, type, class and origin of the various studied rocks.

The rocks selected for this study are: four types of limestone, two of granite, three of rhyolite and four of marble. The main characteristics of the four types are:

Table 1
Types and origin of rocks studied.

Designation	Type	Category	Origin
C_1	Limestone	Sedimentary	Lakhssas
C_2	Limestone	Sedimentary	Agadir Oufella
C_3	Limestone	Sedimentary	Oued Souss
C_4	Limestone	Sedimentary	Oued Souss
G_1	Granite	Igneous	Tafraout
G_2	Granite	Igneous	High Atlas
R_1	Rhyolite	Igneous	Sidi Ifni
R_2	Rhyolite	Igneous	Anti-Atlas
R_3	Rhyolite	Igneous	Imi Miki
M_1	Marble	Metamorphic	Bejaâd
M_2	Marble	Metamorphic	Khénifra
M_3	Marble	Metamorphic	Tiflet
M_4	Marble	Metamorphic	Benslimane

- *Limestone:* homogeneous sedimentary and carbonate rock. It may contain diverse proportions of secondary minerals in micro-cracks. It is composed of more than 95% of calcium carbonate ($CaCO_3$) with the presence of magnesium carbonate $MgCO_3$, quartz and small amounts of organic matter.
- *Granite:* acid plutonic rock. It is characterized by visible minerals to the naked eye (coarse-grained structure). It lacks cement and it is composed of cardinal minerals: quartz, alkaline feldspars (orthoclase), plagioclase feldspars and biotite appearing in black lamellas.
- *Rhyolite:* volcanic rock similar to granite with fluidal texture (fine-grained structure and well cemented). It contains the same crystals as the granite with the presence of metal oxides (hematite).
- *Marble:* compact metamorphic and carbonate rock resulting from the transformation of pure limestone. It presents a meshed aspect and a brilliant surface. It consists of calcium carbonate $CaCO_3$ and magnesium carbonate $MgCO_3$.

Samples in the massive or crushed state are taken from these rocks and have undergone various analyses: petrographic, mechanical and thermo-mechanical analysis (hardness variation depending on the thermal cycles).

3. Results and data processing

3.1. Petrographic analysis

The most important parameters influencing the mechanical strength of rocks are petrographic characteristics, grain size and microstructure [39–41]. Merriam et al. [40] studied the influence of quartz content on the mechanical properties of granites. Willard and McWilliams [42] reported that the microstructure, including grain boundaries and micro-cracks, has an important effect on the rock strength. Onodera and Kumara [43] noticed that the resistance of magmatic rocks decreases linearly with increasing grain size. Irfan et al. [44] indicated that the physical properties of rocks are strongly influenced by the type, texture and percentage of rock-forming minerals. In our work, macroscopic examination was performed on collected samples (shape, color, grain size and texture). Unlike rhyolite and granite, it was very difficult to evaluate the mineral grain size of limestone and marble. These samples exhibit thick layers between grains. The estimation was realized thanks to optical microscopy. The studied samples exhibit the following salient features:

- Granite is composed of four major minerals: plagioclase, feldspar, biotite and quartz, appearing as the main component. It has coarse-grained structure and contains particles with a diameter exceeding 1 mm (Table 2). Granite G_2 presents the highest content of mica (biotite and muscovite), because of its black color. But, the quartz content is less than in the granite sample G_1.
- Rhyolite is not fully crystallized, but it is well cemented unlike granite. The examination by the naked eye shows the presence of quartz and a low proportion of rectangular whitish minerals (plagioclase) tangled by mafic minerals (biotite and muscovite). The red color of rhyolite R_3 indicates the presence of an important amount of iron oxide compared to two other rhyolites. It should be noted that quartz has a high thermal conductivity compared to other minerals (7 W/m K). This characteristic ensures the thermal stratification in the bed and increases the rate of heating and cooling of the rock during thermal cycling. The thermal conduction between the particles is negligible compared to the thermal conduction inside a particle (rock) in the bed.