Geopolymers: Highly Efficient Green Materials for Energy Storage Applications

Giannopoulou Ioanna[1], Georgiou Loizos[2], Michaelides Alexandros[3], Nicolaides Demetris[4]

1. Introduction

In recent decades, renewable energy sources such as the wind, geothermal and solar power, have gradually assumed a more substantial role in the European Union's (EU) energy landscape. However, the transition from the existing fossil fuel-based energy systems to green and sustainable systems that will be based almost entirely on renewables is associated with important challenges, like the operational variability, the grid stabilization and the balancing, management and responding to high loads demand.

The thermal energy storage systems capture and store the excess thermal energy (heat) produced during periods of low demand for later utilization, in the peaks of energy demand. These systems can have both small and large scale applications, such as heating/cooling of houses and power generation in industries and are considered as flexible systems that can be designed according to the requirements of the application area. TES systems can be divided into three main categories, as sensible heat, latent heat and thermochemical.

Sensible heat TES systems are able to store energy by increasing the temperature of a material, such as water, rocks, ceramics and concrete. In these systems, temperature and energy remain proportional, so the more energy is stored in a material, the higher its temperature [1]. For large scale and high temperature applications, sensible TES are based on solid materials as they are more stable in the long term, cost-effective and avoid problems such as freezing, evaporation or leakage. A suitable solid material for sensible TES should have specific thermal properties at high temperatures, such as high heat capacity and thermal conductivity, low density, and chemical stability [1].

Ordinary Portland Cement (OPC)-based concrete is a widely used construction material that gains increasing attention as a TES medium, due to the low cost and the advantageous properties, like as thermal stability, high storage performance and durability for a large number of thermal cycles [2]. Indeed, the applicability and performance of OPC-based concrete as TES have been largely investigated at research centers and validated in solar thermal applications [2-5]. However, the durability and thermal stability of concrete is largely controlled by the formed C-S-H gel, the most important hydration product of OPC, which degrades at temperatures between 400 and

[1] Frederick Research Center, 7 Filokyprou Str., Lefkosia 1036, CYPRUS;
E-mai of Corrsponding Author: ioangian@outlook.com
[2] RTD Talos, 1 Diogenous Str., 2404 Engomi - Lefkosia, CYPRUS
[3] RTD Talos, 1 Diogenous Str., 2404 Engomi - Lefkosia, CYPRUS
[4] Frederick Research Center, 7 Filokyprou Str., Lefkosia 1036, CYPRUS;

600 °C. This fact prohibits the use of the OPC-based concrete TES modules in Concentrated Solar Plants (CSP) and the Solar Process Heat (SPH) applications that necessitate high temperatures, up to about 1000 °C.

Geopolymers are innovative and pioneering materials with great potential to be used in sensible TES applications. They are formed through the alkali activation of solid materials rich in silicate and aluminosilicate reactive phases, under a temperature below 100 °C. Alkali activation involves a sequence of chemical reactions that give rise to the development of a partially or fully amorphous polymeric structure (network), consisting of the molecular units (or chemical groups) Si–O–Si and/or Si–O–Al. The resulted materials possess excellent physicochemical, mechanical and thermal properties, such as micro- or nano-porosity, low water absorption and permeability, thermal stability, chemical and fire resistance, high mechanical strength, negligible shrinkage and low thermal expansion at high temperatures (up to 800 °C). Due to the unique structure of the geopolymeric network, these materials present thermal and mechanical stability at temperatures much higher than those that OPC-based concrete can withstand.

This paper aims at exploring the potential use of geopolymers as TES modules, alternative to the OPC-based concrete, since they can withstand running temperatures higher than 500 °C. To this end, the thermal and mechanical behavior of geopolymers based on Construction and Demolition Waste (CDW), Fly Ash (FA) and Blast Furnace Slag (BFS) is investigated at temperatures higher than 500 °C. Moreover, a comparison between geopolymers and the conventional solid materials used currently as sensible TES devices is performed, in order to better quantify the potential use of geopolymers in this engineering application.

2. Geopolymers in Sensible TES Applications

As raw materials, four different industrial wastes were used for the preparation of geopolymers, specifically waste bricks (WB) and waste ceramic tiles (WCT) provided by a Cyprus CDW recycling plant and fly ash (FA) and blast furnace slag (BFS) imported in Cyprus for the cement industry. All these materials were ground to a particle size below 150 μm. The chemical and mineralogical composition of raw materials was fully determined in a previous paper [6], where the experimental procedure followed for the preparation of the geopolymers is also described in details, along with the analyses and tests performed for the evaluation of the final materials. The performance of geopolymers at high temperatures was assessed trough their thermal stability and compressive strength after 2 hours residence time to temperatures up to 1050 °C, using a muffle furnace (Fig. 1).

According to the experimental results, all studied geopolymers presented excellent thermal stability at the temperature of 600 °C. After their exposure to 800°C, only a few intensive surface cracks, without any other sign of spalling or deformation, were visible on the specimens of the CDW-based geopolymers. It is important to note that these cracks disappeared after the exposure of geopolymers to 1050 °C, due to the sintering of the viscous geopolymeric gel phase occurred at this temperature.

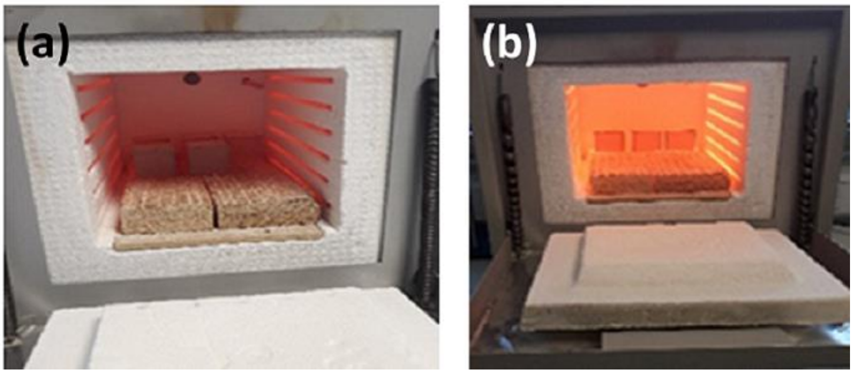

Figure 1: The used laboratory electric furnace in operation, at (a) 800 °C and (b) 1050 °C

The mechanical behavior of geopolymers varied, depending on the raw material. The BW-based geopolymers kept an almost constant compressive strength after their thermal treatment, while the compressive strength of the FA- and BFS-based geopolymers was increased after their exposure to the selected high temperatures. Finally, the compressive strength of the CTW-based geopolymers was drastically decreased after their exposure to 600 and 800 °C. Regarding the high temperature compressive deformation of materials, the BW-, FA- and BFS-based geopolymers behaved as ceramic materials up to 1000 °C, while the CTW-based geopolymer exhibited plastic behavior at temperatures higher than 600 °C, undergoing permanent deformation.

Overall, this work demonstrated that geopolymers are promising materials to be used as TES systems, and especially in CSP and SPH industries, providing sustainability and high efficiency. An intensive study, including measurements of different thermal properties of geopolymers, like the specific heat, thermal diffusivity and thermal conductivity in the studied temperature range is necessary, as well as the design of prototypes to scale up the obtained values to real operating conditions.

3. Conclusions

This work explored the possible use of geopolymers in sensible TES applications and specifically at high temperature ranges, as alternative to the OPC-based concrete. The investigated geopolymers presented excellent thermal stability and good compressive strength to temperatures between 600 and 800 °C.

According to the results, the geopolymer-based TES systems are very promising and should be considered as alternatives in energy sector, providing both sustainability and high performance.

4. References

[1] S. Kuravi, J. Trahan, D. Y. Goswami, M. M. Rahman, E. K. Stefanakos, Thermal energy storage technologies and systems for concentrating solar power plants, Progress in Energy and Combustion Science 2013, 39 (4), 285-319.

[2] K. Ndiaye, S. Ginestet, M. Cyr, Thermal energy storage based on cementitious materials: A review. AIMS Energy 2018, 6, 97–120.

[3] N. Hoivik, C. Greiner, J. Barragan, A. C. Iniesta, G. Skeie, Long-term performance results of concrete-based modular thermal energy storage system. Energy Storage 2019, 74, 100735.

[4] Skinner, J.E.; Strasser, M.N.; Brown, B.M.; Panneer Selvam, R. Testing of high-performance concrete as a thermal energy storage medium at high temperatures. Solar Energy Engineering 2014, 136, 021004.

[5] V.A. Salomoni, C. E. Majorana, G. M. Giannuzzi, A. Miliozzi, R. Di Maggio, Thermal storage of sensible heat using concrete modules in solar power plants. Solar Energy 2014, 103, 303–315.

[6] I. Giannopoulou, P.M. Robert, K.-M. Sakkas, M.F. Petrou, D. Nicolaides, High temperature performance of geopolymers based on construction and demolition waste, Journal of Building Engineering 2023, 72, 106575.