Ash-based thermal insulator for solar cookers – A case study from Ayacucho, Peru

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Abstract. The aim of this paper is to present an ecological, sustainable option for thermal insulator bricks to be used mainly in solar cookers. The bricks were prepared using ash produced in rural cookers in the Ayacucho region, a gel extracted from prickly pear cladodes and hydrogen peroxide. The crystal characterization of the ash was performed by XRD, resulting that calcite is the main component. Thermal characterization of the ash-based thermal insulators gave values in the interval (0.042 - 0.063) W.m⁻¹.K⁻¹ results comparable with that of commercial thermal materials.

1. Introduction
To contribute to the reduction of the deterioration of our environment, there is a need to consolidate the recycling of organic and inorganic compounds that allow their reuse. In various applications of solar technology, the use of thermal insulators is essential. As in the case of solar cookers or water heaters, where fiberglass, polyurethane, polystyrene and others are used as conventional insulating material. Some of these insulating materials such as fiberglass can generate dermatitis [1] and polystyrene can create considerable contamination. Nowadays, new mineral and synthetic materials are being developed. The shortage of non-renewable resources motivates the search for alternative and ecological solutions. Mercier et al. [2] refer that in order to select a natural insulator, several factors must be considered, such as availability, cost, application, ecological and energetic impact, which are as important as its thermal performance.

Different thermal insulating materials for different applications are being investigated; Novais and his collaborators [3] developed geopolymers based on biomass fly ash, where they used hydrogen peroxide (H₂O₂) as a pore-forming agent in relation to the amount of peroxide, obtaining geopolymers with thermal conductivity of 0.107 W.m⁻¹.K⁻¹ and density of 560 kg.m⁻³. On the other hand, Feng et al. [4] also studied low conductivity ash geopolymers, concluding that the higher the H₂O₂, the higher the porosity, the lower the resistance to compression, the lower thermal conductivity and the irregularity of the pore morphology. They also evaluated the effect of temperature on the morphology of the pores, the increase in thermal conductivity and the gain in compression resistance.

The bottom ash of biomass combustion has been used in calcium silicate samples in building materials with thermal insulation properties, obtaining samples with optimum values of compressive resistance ranging from 25.21 to 61.11 MPa and thermal conductivity from 0.564 to 0.773 W.m⁻¹.K⁻¹ [5]. Zhang et al. [6] developed a new type of thermal insulating material using coal fly ash by the foaming method and slip casting process obtaining sintered insulating material with average thermal conductivity of 0.0511 W.m⁻¹.K⁻¹.
In the present work, thermal insulators were prepared and characterized based on ash produced by the combustion of firewood in the family stoves of Ayacucho.

2. Preparation and characterization of the ash-based thermal insulator bricks

2.1. Materials and preparation of the bricks

For the preparation of the ash-based thermal insulators bricks, three components were used (see figure 1): ash collected from rural stoves (a), gel, used as a binder and extracted from prickly pear cladodes (b) and hydrogen peroxide (3% w.t.) (c). Table 1 displays the density of each of the components.

![Figure 1](image)

**Figure 1.** Materials used for the preparations of the ash-based thermal insulators: (a) ash collected from a rural stove, (b) prickly pear stalk segments (cladodes) and (c) ash, gel (green) and hydrogen peroxide ready to mix.

| Materials               | ρ (g/cm³) |
|-------------------------|-----------|
| Not compact ash         | 0.32      |
| Compact ash             | 0.63      |
| Prickly pear cladodes gel | 0.95    |
| Hydrogen peroxide       | 1.00      |

To begin with, gel and ash were manually mixed until a homogenous mud was obtained. Then, hydrogen peroxide was added in different amounts (see table 2) to get samples with different porosity, as displays in table 2.

| Sample | Ash (g) | Gel (g) | Hydrogen peroxide (ml) | Density (g/cm³) |
|--------|---------|---------|------------------------|-----------------|
| M-I    | 109     | 61.6    | 50                     | 0.61            |
| M-II   | 109     | 61.6    | 60                     | 0.44            |
| M-III  | 109     | 61.6    | 70                     | 0.36            |

The mud was inserted in cylindrical molds (see figure 2a) for about four hours, then the block was removed and placed in a solar dryer (see figure 2b) for almost three days.
2.2. Characterization of the bricks

XRD analysis was performed to determine the mineral composition for the ash, the diffractometer used was a Bruker D8 with CuKα radiation (1.5406 Å wavelength) operated at 40 kV and 30 mA and the data was processed using the ICDD-JCPDS database. The thermal characterization of the bricks was developed using the KD2 Pro thermal analyser, manufactured by the company Decagon Devices, Inc., whose principle of measurement is based on the method of Transient Line Heat Source [7]. For determination of thermal conductivity, a KS-1 single needle sensor was used, and for diffusivity and volumetric specific heat, a SH1 dual needle sensor was used (see figure 3).

Preliminary mechanical compression measurement was performed in a homemade system. Results are displayed in table 3.

3. Results

3.1. X-ray diffraction

The crystallographic structure of the ash is displayed in figure 4. It is clearly possible to recognize the presence of rhombohedral-cubic phase of calcite, CaCO₃ (JCPDS 00-005-0586), as well as the hexagonal phase of hydroxylapatite, Ca₃(PO₄)₂(OH) (JCPDS 00-009-0432) and triclinic phase of kyanite, Al₂SiO₅ (JCPDS 00-011-0046). Very small reflection peaks were assigned to silicon oxide, SiO₂ (JCPDS 00-040-1498) and periclase, MgO, (JCPDS 00-045-0946).
3.2. Thermal properties

The KD 2 Pro thermal analyser determined the measurement of the thermal conductivity of the samples with the KS-1 sensor located in the centre of the sample, repeating up to four times each measurement. Table 4 displays the average of the measurements and the temperature of the sample during the testing process. The thermal conductivities of the samples were between 0.046 and 0.063 W.m\(^{-1}\).K\(^{-1}\) showing an inverse expected correlation with the amount of hydrogen peroxide. The former allowed the formation of more cavities inside the bricks.

Table 4. Thermal conductivity and resistance of the samples at shown temperatures.

| Sample | Thermal conductivity (W.m\(^{-1}\).K\(^{-1}\)) | Temperature (°C) |
|--------|-----------------------------------------------|-----------------|
| M-I    | 0.063                                         | 20.3            |
| M-II   | 0.052                                         | 22.0            |
| M-III  | 0.046                                         | 18.9            |

Thermal diffusivity and volumetric specific heat were measured using the same equipment, as for thermal conductivity, but the SH-1 sensor (with dual needle) was used. The results are shown in table 5.

Table 5. Thermal diffusivity and volumetric specific heat of the samples at the shown temperatures.

| Sample | Thermal diffusivity (mm\(^2\)/s) | Volumetric specific heat (MJ/m\(^3\) K) | Temperature (°C) |
|--------|---------------------------------|----------------------------------------|-----------------|
| M-I    | 0.146                           | 0.692                                  | 22.1            |
| M-II   | 0.132                           | 0.628                                  | 24.6            |
| M-III  | 0.129                           | 0.518                                  | 22.9            |

Considering the preliminary mechanical results (see table 3) and the thermal properties of the samples, M-II ash-based insulator was selected for additional evaluations, because it displayed a good compromise between mechanical and thermal properties. So, M-II sample was placed inside an oven where the thermal conductivity was measurement for temperatures from 27°C to 52°C (see figure 5). The thermal conductivity changed slightly in the evaluated interval from 0.054 to 0.057 W.m\(^{-1}\).°C\(^{-1}\).
To evaluate the performance of M-II sample as an insulator inside a solar cooker, bricks of 11.7 cm × 11.7 cm × 1.7 cm were constructed to be placed in the bottom of the cooker, as it is shown in figure 6a. To compare the thermal behavior of the ash-based brick to a commercial material, an identical solar cooker was implemented with fiberglass placed in a similar position as the ash-based bricks (see figure 6b). Then, both cookers were evaluated simultaneously (see figure 6c), for heating and cooling processes while solar irradiation was around 560 W.m⁻². Figure 7 shows the evaluation performed between 11:00 and 15:00, where both insulators show very similar profile, but for temperatures higher than 110°C, the commercial material gained slightly higher temperatures than the ash-based insulator.

Figure 6. (a) Solar cooker using ash-based insulator bricks, (b) solar cooker using fiberglass for insulation and (c) simultaneous temperature evaluation of (a) and (b) solar cookers.

Figure 7. Heating and cooling performance for showing thermal insulators (fiberglass and ash-based) evaluated in a solar cooker.
4. Conclusion
The ash-based thermal insulator prepared with prickly pear cladodes gel and increasing amounts of hydrogen peroxide displayed thermal conductivities from 0.063 to 0.046 W.m\(^{-1}\).K\(^{-1}\) with thermal diffusivities from 0.146 mm\(^2\).s\(^{-1}\) to 0.129 mm\(^2\).s\(^{-1}\) respectively.

From the heating and cooling evaluation of two identical solar cookers using the ash-based thermal insulator and fiberglass, it was possible to establish very similar behaviour for temperatures between 30°C and 130°C.

The ash insulation turns out to be an ecological option as an insulating material, taking advantage of a product that is often discarded in the Ayacucho region. The use of this insulation has the possibility of adapting to bioclimatic housing requirements for high Andean rural areas.

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