RESEARCH ARTICLE

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Synthesis and Mechanical Evaluation of Geopolymeric Mortars Reinforced with Alpaca Wool Fibers

D.M.M. Gallegos-Florez*, D.L. Mayta-Ponce, F.A. Cuzziramos-Gutiérrez, G.P. Rodríguez-Guillén and F.A. Huamán-Mamani

The effect of the addition of alpaca fibers on the mechanical response of geopolymeric mortars was studied using uniaxial compression tests. The studied mortars were manufactured by mixing mining tailings, fine sand and variable percentages of alpaca wool fibers. The mechanical results show a higher degree of deformation, up to 6%, for the mortar mixtures with higher amounts of wool fiber in their composition, that is, the decrease in maximum compressive strength was demonstrated as the volume increased of added fibers, the values were from 32 to 9 MPa for samples with 0 and 8 % Vol. of added fibers, respectively. On the other hand, studies of the real density and the average porosity were carried out, obtaining values of 2.59 g/cm³ and 31 %, respectively. Additionally, the morphological analysis was carried out using microscopy in which a continuous binder geopolymer phase could be seen and within this phase a phase of sand and fibers.

Introduction

Cement is the most widely used material in the construction industry as a concrete binder, mainly due to its low cost and durability. However, its production is unsustainable due to the notable 1) environmental damage that represents 5-10% of CO_2, NO_X and SO_X emissions 2) the important consumption of fossil fuels and 3) the high consumption of raw materials [**1,2**].

Within the measures to reduce greenhouse gas emissions from the cement industry, they focus on improving the thermal efficiency of the kilns to avoid burning more fuel than necessary [**3**]. On the other hand, physical and chemical methods of CO_2 absorption are used, for example, in the case of commercially available amine solutions, they have a maximum CO_2 absorption capacity of up to 320 TN/day, which is less than a third of the emissions produced by a 500 MW plant, so they are not viable due to the high cost that it represents [**4**].

Today there are also industrial products such as ecological cements added with slag, limestone and pozzolana that, by using less fuel in their preparation, can reduce emissions by up to 30% [**3**].

Unfortunately, the CO_2 emissions produced by the cement industry cannot be eliminated either by improving efficiency or by partially substituting the raw material [**4**], which is why much more efficient approaches are sought in total substitution of raw material.

In recent decades, eco-friendly alternatives to Ordinary Portland Cement (OPC) have been developed, the most effective alternative is geopolymeric technology due to: 1) its manufacture from industrial waste such as fly ash, slag, rice husks, tailings, etc. [**5,6**] 2) superior mechanical properties and durability, 3) excellent resistance to acid attacks and high temperatures [**7,9**] and 4) up to 80% reduction in CO_2 emissions compared to OPC [**9,10**].

As well as due to its ability to immobilize toxic substances thanks to the binding of heavy metals, hence its success in replacing conventional construction materials.

However, geopolymers face the problem of greater fragility and lower tensile strength compared to OPC concrete [**11**]. In response to this phenomenon, studies were carried out on the addition of fibers to OPC concrete in order to increase toughness. of the material and improve its resistance to crack propagation and impact [**11,12**].

On the other hand, various investigations studied the mechanical behavior of OPC concrete reinforced with natural fibers of animal and vegetable origin, as is the case with jute, cotton, cane or wool fibers [**12,13**], its implementation in concrete seeks replace the use of synthetic reinforcements to improve the sustainability of the material and revaluation of waste.

Wool fibers have been studied, as in the case of sheep wool fibers, which have shown to have a high modulus of elasticity, excellent resistance to abrasion, and have shown to improve the thermal and acoustic insulation properties of cementitious materials [**14**], however, there are no studies

Universidad Católica San Pablo, Arequipa, Perú, Campus Campiña Paisajista s/n Quinta Vivanco, Barrio de San Lázaro, Arequipa, Peru

Web of Science Researcher ID: AFN-1836-2022

*Corresponding author:
E-mail: dailygallegos0@gmail.com

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that use alpaca wool fibers as a reinforcing material in geopolymeric technology.

Comparative studies of reinforcement with sheep and alpaca wool fibers indicate that the use of alpaca fibers obtains better results of resistance to compression, additionally it is known in the textile industry that alpaca wool fiber is lighter, warmer and it tends to deteriorate more slowly than other fibers [**17**].

In the present work, a methodology was developed for the manufacture of geopolymeric mortars using as raw material both waste from the informal mining industry (tailings) which have a high content of aluminosilicates, and waste from the textile industry (alpaca wool), in order to obtain an eco-friendly, sustainable material with improved mechanical properties.

Experimental

Raw materials and Fabrication of mortars

The following materials were used to manufacture control mortars (C) and reinforced geopolymeric mortars (R):

- Control mortars (C): Type I cement (binder), fine sand through mesh ASTM # 140: 106 microns (aggregate) and drinking water (activating liquid phase).
- Reinforced mortars (R): Mining tailings through mesh ASTM # 140: 106 microns (binder), fine sand through mesh ASTM # 140: 106 microns (aggregate), alpaca wool fibers mesh ASTM # 140: 106 microns (reinforcer) and 12M sodium hydroxide solution (activator liquid phase).

Due to comparative purposes, mortars C (without fibers) and mortars R were manufactured, the volumetric fraction of alpaca fibers added was considered as independent variable (i) for mortars R, and as dependent variables the maximum resistance to uniaxial compression, rigidity, density and porosity, for C and R mortars. It should be noted that for C and R mortars a water/cement ratio of 0.6 and a binder:fine sand ratio of 1:3 have been considered. The components of the R mortars can be seen in **Table 1**.

Table1. Components of studied R mortars.

Sample	relationship binder:fine sand	volume of fiber added (%)
1		0
2		2
3	1:3	4
4		6
5		8

The R mortars were prepared by mixing the binder and the reinforcement until a homogeneous dry mix was achieved, then the activating liquid phase was added and mixed for 5 minutes. From the obtained paste, cylinders with a diameter of 20 mm were molded using a pressure of 50 MPa for 2 minutes. Finally, they were placed in an airtight environment for setting. In the case of mortars C, the setting was carried out in water for 7 days.

Characterization tests

Micromeritics helium pycnometer, model AccuPyc II 1345, was used to determine the real density of the raw materials. The microstructural and morphological observation was carried out in a Cooling Tech model 1600X optical microscope, the specimens were prepared in a polisher using lubricating liquid and 6 µ diamond paste. Finally, the mechanical compressive strength tests were carried out. at a speed of 1 mm/minute until the fracture of the material with dimensions of nominal diameter of 20 mm and height of 40 mm.

Results and discussion

Microstructure and density analysis

The actual density data was used to determine the mass portions of the mixtures studied in **Table 1**. The average values obtained for the fibers of alpaca wool, fine sand, type I cement and tailings were 1.3569, 2.7569, 3.1236 and 2.7375 g/cm^3, respectively. The real density and average porosity of the C mortars was 2.6435 g/cm^3 and 27%, and for the R mortars it was 2.5901 g/cm^3 and 31%.

The micrographs obtained by optical microscopy are shown in **Fig. 1**. In all cases, the presence of 3 clearly differentiated phases could be observed, the first one belonging to the binder as a continuous phase and, on the other hand, two discontinuous phases within the first phase. Discontinuous phases are distinguished by their elongated shape in the case of fibers, and polygonal in the case of grains of fine sand.

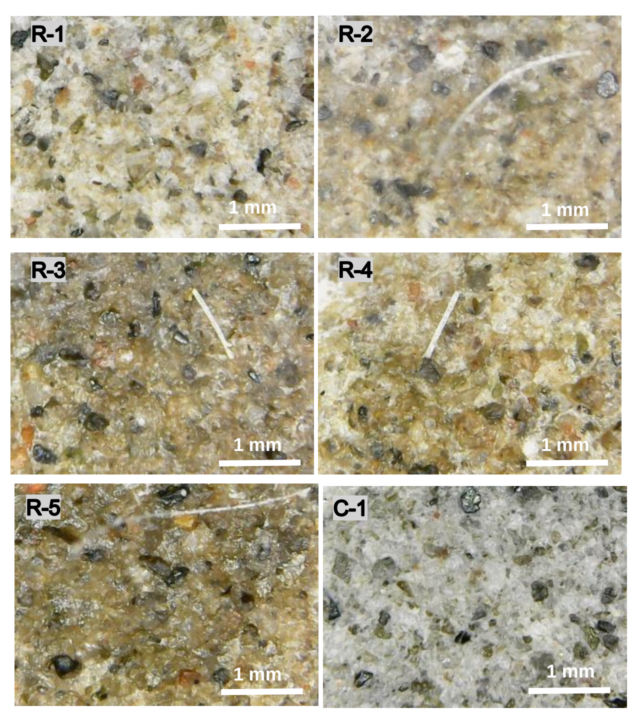

Fig. 1. Micrografías por microscopia óptica de morteros geopoliméricos reforzados con fibras de lana (R1, R2, R3, R4 y R5) y control de OPC (C1)

Mechanical performances

Fig. 2 shows the stress vs. curves. deformation for mortars C and R. From the mechanical data found, it was possible to verify the systematic reduction of the maximum compressive strength values, by increasing the volumetric fraction of added fibers. The average maximum resistance values in uniaxial compression varied from 9 to 32 MPa in R mortars, when the volumetric concentration of alpaca wool fibers decreased from 8 to 0 %, respectively.

The results presented in **Fig. 2** are comparable with other reported results of the behavior of concrete mixed with jute fiber, rice straw, sugar cane fibers, which conclude that the compressive strength of these does not improve, however, the bending load, as well as the energy absorption capacity improves with respect to the OPC values [**13**].

Likewise, it is observed that the samples with a higher percentage of fibers added in the matrix, have a more elastic behavior compared to the OPC and the geopolymer with 0% vol of alpaca fibers, this observation is derived from the stretching of the curve of effort vs. deformation, unlike the control samples and sample 1, which have a brittle behavior typical of concrete without the addition of fibers.

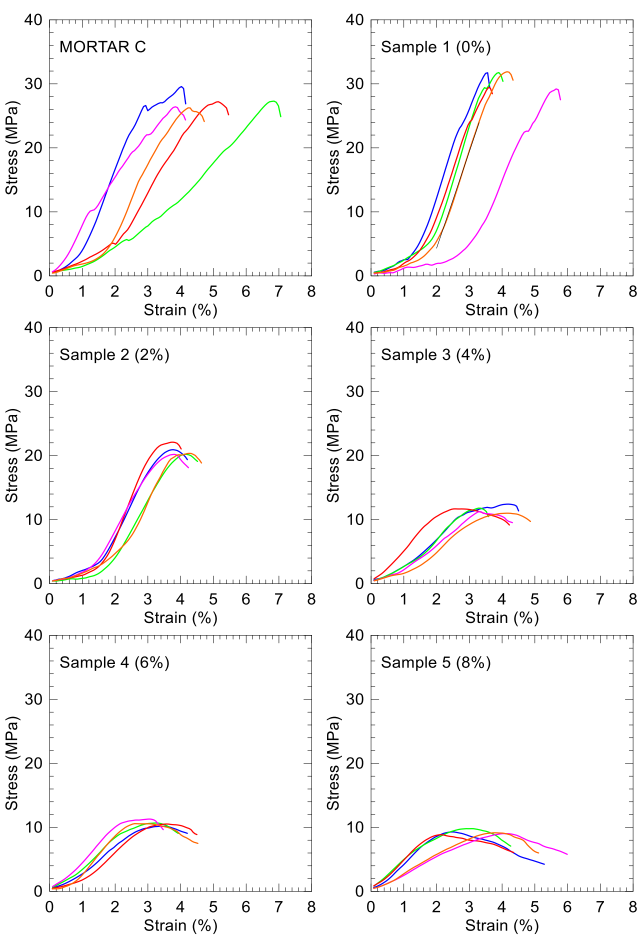

Fig. 2. Stress vs. Strain curves for C and R mortars.

Fig. 3 shows the upper and lower limits of the tests performed for the control sample and samples with 0, 2, 4, 6 and 8% volume of added fibers. **Fig. 3(a)** shows the variations of the geometric density, a systematic reduction can be identified for the samples with added fibers from 1.92 g/cm3 to 1.71 g/cm3 for the 0% and 8% of added volume, respectively; **Fig. 3(b)** shows the real density, a progressive reduction of the values can be identified as the amount of fibers added increases, various studies agree with the progressive decrease in the real density of geopolymeric compounds as their content increases of fibers, mainly due to the increase in its porosity and the agglomeration tendency of its fibers [**14**]; **Fig. 3(c)** shows the maximum resistance to compression, a progressive reduction can be identified in the values of the samples that have a greater volume of added fibers, from 32 MPa to 9 MPa for the samples of 0% and 8% of volume added respectively, **Fig. 3(d)** shows the Young's modulus, a progressive reduction can be identified in the values from 15.1 to 4.1 GPa for the samples of 0% and 8% of volume added respectively and, finally, in the **Fig. 3(e)** shows the porosity, a systematic increase can be identified for the samples with added fibers from 27.23% to 32.94% for the 0% and 8% of added volume, respectively; the amount of intergranular pores in the microstructure may correspond to the tendency of the fibers to group together during mixing, trapping spaces filled with water that become empty spaces after curing [**14**].

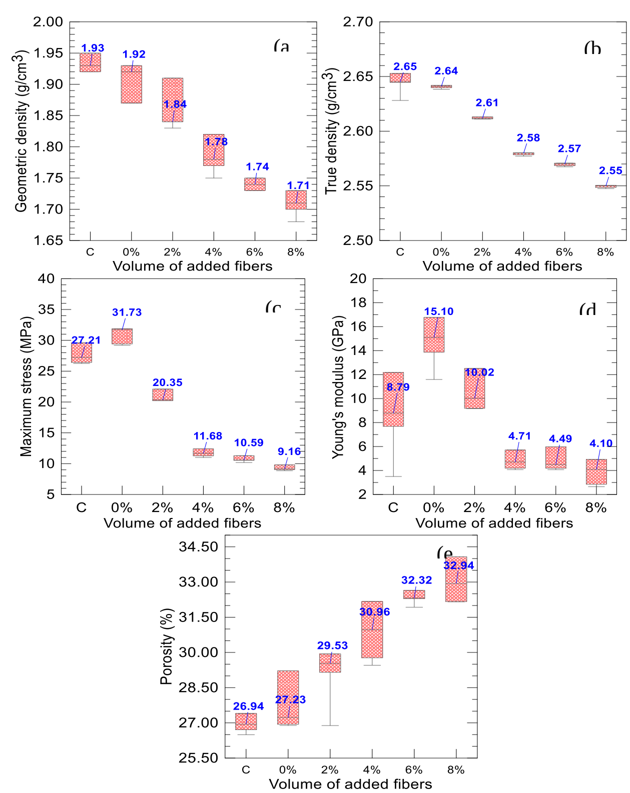

Fig. 3. Comparison of geometric density, absolute density, compressive strength, Young's modulus and porosity data for the control sample and samples with added fibers.

Conclusion

- Geopolymeric mortars reinforced with alpaca wool fibers were successfully made from a mixture of mine tailings, fine sand, reinforcement (wool fibers), sodium hydroxide and water.
- The real density tests showed results of 2.59 g/cm3 and porosities of 31%, on average for each case.
- Microphotographs revealed the presence of three clearly differentiated phases: a continuous binder phase and two discontinuous phases located within the continuous phase. The discontinuous phases were differentiated by their shape, elongated in the case of alpaca wool fibers and polygonal in the case of fine sand grains.
- A clear reduction in the maximum compressive strength values was verified by increasing the volumetric fraction of fibers in the reinforced mortar mixtures.
- The uniaxial compression mechanical tests for R mortars showed a decrease in average maximum resistance from 9 to 32 MPa with an increase in the volume of alpaca wool fibers from 8 to 0 %, respectively.
- It was possible to appreciate the increase in the percentages of deformation of the mortars R due to the increase in the amount of volume of alpaca fibers added to the mixture.

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Conflicts of interest
There are no conflicts to declare.

Keywords

Synthesis; mechanical behavior; geopolymeric; mortars reinforced; alpaca wool fibers

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Authors biography

Materials engineer. Master's student in the Materials Science and Technology Research Group (CITEM) of the San Pablo Catholic University (Peru).
Research lines: composite materials, sustainability in materials.

Graphical abstract

Geopolymeric mortars were manufactured by mixing mining tailings with textile waste from the alpaca wool industry, in order to study their mechanical strength by performing compression tests and analyzing their microstructure by optical microscopy, in which inversely proportional values of density and porosity, and maximum resistance values from 32 to 9 MPa for samples with 0 and 8 Vol.% of added fibers, respectively.