Fabrication and Mechanical Characterization of Geopolymeric Pavers Obtained by Using Demolition Waste

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Demolition residues (bricks, mortars and concrete) were collected, separated, crushed, ground and sieved into powder. The powder obtained was mixed with sodium hydroxide solution of various molar concentrations (9, 12 and 15 molar) until workable plastic pastes were obtained. The pastes obtained were used as binders in geopolymeric mortars and pavers, which were evaluated physically, microstructurally and mechanically (at 14 and 28 days of curing). In parallel, and for comparison purposes, conventional Portland cement mortars and pavers were manufactured. The microstructure found in conventional and geopolymeric mortars and pavers was similar, presenting two well differentiated phases, a continuous one of binder and a discontinuous one of unconnected fine aggregate particles. In general, the geopolymeric materials manufactured presented less porosity than the conventional ones and their mechanical strength was lower, although sufficient for their application as type I pavers (according to the Peruvian technical standard - NTP 399.611).

Keywords: cement, demolition waste, geopolymeric, pavers.

1. Introduction

The construction industry in the economic development of countries and how urbanization and infrastructure require large quantities of concrete, which in turn drives the demand for cement [1,2]. The environmental impact of cement production and the need to reduce CO2 emissions is a prime need, especially considering that this industry is responsible for 36% of global energy use and 40% of carbon dioxide emissions to the atmosphere [3,4]. Cement is a fundamental building material worldwide, being mainly used in the production of concrete. The latter is a mixture that includes inert mineral aggregates such as sand, gravel and crushed stones, together with cement [5,6]. Another problem that is currently growing, is construction and demolition waste, currently it is argued in favor of its reuse or recycling to minimize the environmental load [7,8]. Studies investigating the use of waste materials in the production of bricks and blocks as an alternative to conventional methods, which could reduce resource depletion and environmental degradation associated with traditional brick production, are mentioned. [9,10]

The increasing demand for cement has led to research on more environmentally friendly alternatives, such as geopolymers, an alternative to Portland cement in concrete production, highlighting its lower carbon footprint and comparable mechanical properties and durability [11,12]. Some research discusses the technical challenges and commercial barriers to the widespread adoption of geopolymers in the construction industry, as well as the possibilities of producing geopolymer bricks from coal fly ash and construction and demolition waste [13,14]. The latter argues for their reuse or recycling to minimize the environmental burden, and reduce the environmental impact of the construction industry through reuse and their effective recycling [15,16]. Traditional concrete production as well as brick production cause various environmental impacts and there is a clear need to look for more efficient and durable alternatives [17,18].

Geopolymer which is a synthetic inorganic material obtained from the reaction of solid aluminosilicates with concentrated alkaline solutions, has gained attention as an alternative binder, standing out for its early compressive strength, low permeability, good chemical resistance and excellent fire resistance behavior [19]. These properties make it a promising alternative to ordinary Portland cement for a variety of applications in the manufacture of building materials, fire-resistant coatings, fiber-reinforced composites, and waste immobilization solutions for various industries [20]. The use of demolition waste in the manufacture of geopolymeric pavers contributes to mitigating the problem of solid waste and environmental pollution associated with the inadequate disposal of these materials. In addition, these concretes can be used in a variety of applications, including pavements, walls, slabs, beams and other structures. Furthermore, the incorporation of RCD can improve the thermal and mechanical properties of concrete, as well as its resistance to corrosion and fire.

2. Materials and methods

Raw material

Calcined clay powder (CC) and hardened cement (HC) were obtained from demolition residues (bricks, mortars and concrete) collected from informal dumps in the city of Arequipa, Peru (located in peripheral areas of the city). CC and HC powder were mixed with sodium hydroxide solution (9, 12 or 15 molar) to obtain new geopolymer cements, which were then used for the manufacture of geopolymer mortars and pavers, adding controlled amounts of fine aggregate. On the other hand, and for the purpose of comparison, conventional Portland cement mortars and pavers were obtained following a conventional manufacturing route.

Fabrication of mortars

Cubes of 5 x 5 x 5 cm3 were manufactured from the mixture of binder, fine aggregate and liquid phase. Two types of mortars were manufactured:

(i) conventional mortars (CM): where Portland cement was used as binder, fine sand as aggregate and water as liquid phase, and.

(ii) geopolymeric mortars (GM), where calcined clay powder (CCGM) or hardened cement powder (HCGM) was used as binder raw material, fine sand as aggregate and sodium hydroxide solution as liquid phase.

In all cases, 500 g of binder (or binder raw material in the case of GM), 1375 g of fine sand and 242 ml of liquid phase were used (in the case of GM, Na(OH) solution with molarities of 9, 12 and 15 molar was used).

The mortar manufacturing procedure followed the route suggested by the ASTM C109 technical standard. It started with the mixing of the solid materials (binder and fine sand) and then the addition of the liquid phase. The wet mixture obtained was placed in standard cubic molds and tamped until the entire mold was filled. The molded mortars were left for 24 hours in the mold and then were taken to the hardening process, in water for conventional mortars and in an airtight environment for geopolymeric mortars. All the manufactured materials were mechanically evaluated at room temperature at 14 and 28 days of curing.

From the measurement of the mass and dimensions of each fabricated cube, the average bulk density was determined, then by helium pycnometry the real density of all the fabricated materials was determined and with the data of bulk and real density the porosity was calculated. Table 1 shows the values found.

Table 1. Apparent density, real density and porosity of conventional and geopolymeric manufactured mortars.

Type of mortar	Apparent density (g./cm^3)	True density (g./cm^3)	Porosity (%)
CCGM	1.7621	2.3494	25
HCGM	1.8925	2.5100	25
CM	1.7663	2.5412	30

Fabrication of pavers

Pavers of 20 x 10 x 4 cm3 were manufactured from a mixture of binder, fine aggregate, and liquid phase. Two types of pavers were manufactured:

(i) conventional pavers (CP): Portland cement was used as binder, a mixture of 40% fine sand and 60% coarse sand as fine aggregate and water as liquid phase; and

(ii) geopolymer pavers (GP): calcined clay powder (CCGP) or hardened cement powder (HCGP) was used as binder raw material, a mixture of 40% fine sand and 60% coarse sand as fine aggregate and sodium hydroxide solution as liquid phase.

In all cases, 482 g of binder (or binder raw material in the case of GPs), 1495 g of fine aggregate and 225 ml of liquid phase (in the case of GPs, Na(OH) solution with molarities of 9, 12 and 15 molar was used to obtain one unit of paving stone). The density (real and apparent) and porosity of the manufactured pavers were determined (table 2).

Table 2. Apparent density, real density and porosity of conventional and geopolymer manufactured pavers.

Type of pavers	Apparent density (g./cm^3)	True density (g./cm^3)	Porosity (%)
CCGP	2.0050	2.4933	20
HCGP	2.0028	2.5178	21
CP	1.9383	2.5544	24

Physical, microstructural and mechanical characterization of mortars and pavers

The physical characterization of the manufactured mortars and pavers was carried out by means of tests to determine the apparent and real density, the apparent density was determined by simple measurement of the masses and dimensions and the real density was carried out by helium pycnometry (Micromeritics brand, model AccuPyc II 1345). On the other hand, the microstructural characterization consisted of observations of polished surfaces of the samples studied, this characterization was carried out using a CoolingTech optical microscope model 1600X. Finally, the mechanical characterization was carried out under uniaxial compression conditions at room temperature and at a constant compression speed of 900 N/sec. A HUDA Technology model HUD-B616-3 universal testing machine was used for the mechanical studies.

3. Results and Discussion

Microstructural and mechanical characterization of fabricated mortars

Figure 1 shows micrographs of conventional and geopolymeric mortars, for both types of mortars a very similar microstructure was found, two well differentiated phases were identified, on the one hand, an interconnected continuous phase of small grains of binder and, on the other hand, fine aggregate particles uniformly distributed within the continuous phase of binder, the fine aggregate particles were larger and were not connected.

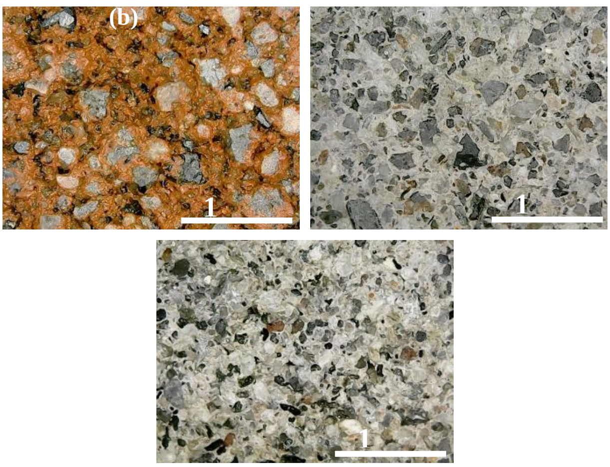

Figure 1. Optical microscopy micrographs of (a) calcined clay powder geopolymer mortar, (b) hardened cement powder geopolymer mortar and (c) conventional Portland cement mortar.

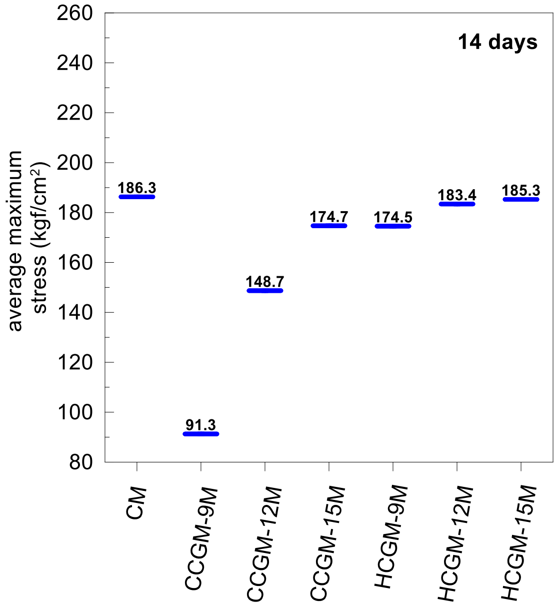

Figure 2. Average maximum stress values as a function of the type of mortar studied, evaluated at 14 days of curing.

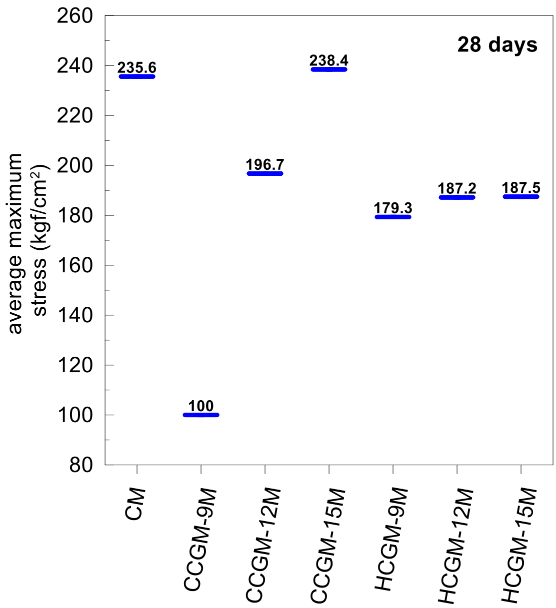

Figure 3. Average maximum stress values as a function of the type of mortar studied, evaluated at 28 days of curing

Figure 2 and figure 3 show average maximum strength data of mortars manufactured and with 14 and 28 days of curing, respectively. From figure 2, a systematic increase in the average maximum strength of geopolymer mortars was observed as the molarity of the hardener solution increased. The highest values of maximum strengths occurred when the molarity of the hardener solution was 15M (175 MPa for CCGM-15M and 185 MPa for HCGM-15M). The HCGM-15M geopolymeric mortars presented similar maximum strength values to Portland cement mortars (186 MPa).

At 28 days of curing (Figure 3), all mortars increased their maximum mechanical strengths, reaching maximum values of 236, 238 and 188 MPa for CM, CCGM-15M and HCGM-15M.

Microstructural and mechanical characterization of fabricated pavers

The microstructure found on polished surfaces of geopolymeric and conventional Portland cement pavers was very similar (figure 4). Two well differentiated phases were identified (i) a homogeneous and interconnected binder phase in light gray contrast (for CP and HCGP) or in red-orange contrast for CCGP and (ii) a discontinuous and unconnected phase of fine aggregate particles (fine and coarse sand) located within the continuous binder phase. In contrast to the microstructure found in the mortars studied in this work, the presence of larger particles (approximately 2 mm) was evidenced, revealing the presence of coarse sand.

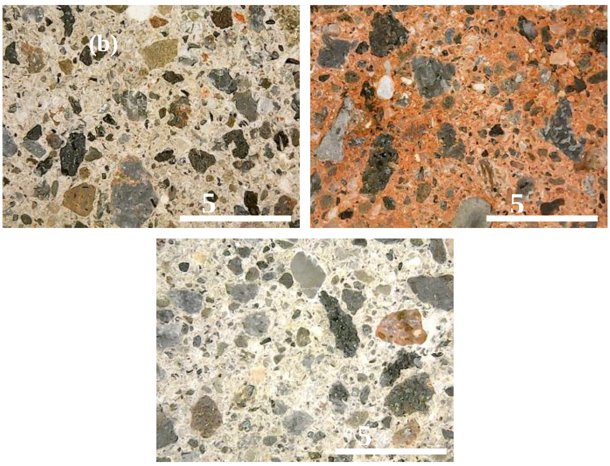

Figure 4. Optical microscopy micrographs of (a) conventional Portland cement pavers (b) geopolymer pavers made of calcined clay powder and (c) geopolymer pavers made of hardened cement powder.

Figure 5 and figure 6 show average maximum mechanical strength values of pavers studied in this work (conventional and geopolymeric) cured at 14 and 28 days, respectively. The data presented in Figure 5 reveal a gradual increase in the maximum strength of CCGP when the molarity of the hardener solution used in the geopolymerization reaction increases from 9 to 15 molar, however, a reduction in the average maximum strength of HCGP geopolymer pavers was observed when the molarity of the hardener solution increased from 12 to 15 molar. From this result, it could be suggested the crystallization of some sodium salt compound within the paver structure, which negatively impacts the mechanical response of the paver.

Similar to what was described in the previous paragraph, it could be observed in Figure 6 that the CCGP and HCGP geopolymer pavers systematically reduce their average maximum strength when going from 12 to 15M molarity in the alkaline hardener solution.

All the pavers studied exceeded the minimum required value of 320 kgf/cm2 for use as type I pavers for urban pedestrian walkways (according to the Peruvian technical standard in force).

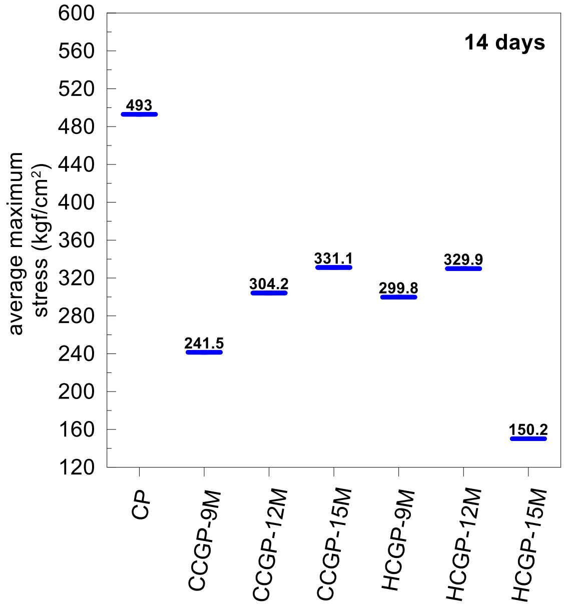

Figure 5. Average maximum stress values as a function of the type of pavers studied, evaluated at 14 days of curing.

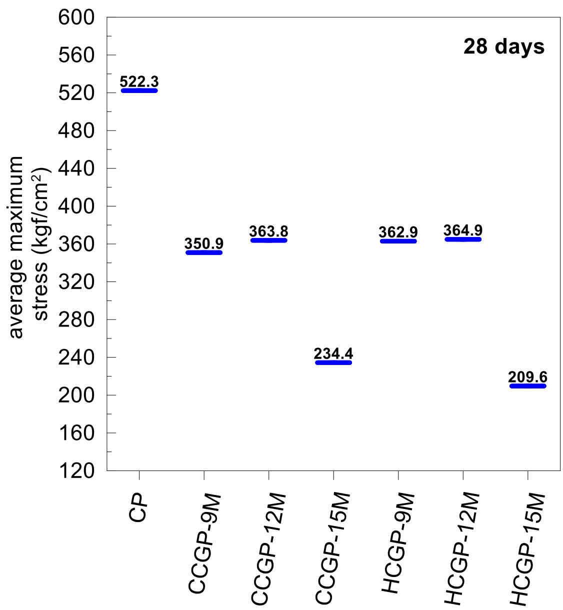

Figure 6. Average maximum stress values as a function of the type of pavers studied, evaluated at 14 days of curing.

4. Conclusions

Conventional and geopolymeric mortars and pavers were successfully manufactured.

Geopolymer mortars and pavers showed lower porosity than conventional Portland cement mortars and pavers.

The microstructure found in conventional and geopolymeric mortars was very similar. The same microstructural similarity was found in conventional and geopolymer pavers.

The microstructure found for all the materials studied consisted of two distinct phases, on the one hand, an interconnected continuous binder phase and, on the other hand, an unconnected phase of fine aggregate particles completely enveloped by the continuous binder phase.

The average maximum mechanical strength was always higher in conventional mortars and pavers than in geopolymeric pavers; however, geopolymeric pavers derived from calcined clay powder and hardened cement were able to reach sufficient mechanical response values (greater than 320 kg/cm2) for their potential use as type I pavers, according to current Peruvian technical standards.

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