Mechanical and Thermomechanical Evaluation of Geopolymeric Concrete Derived from Demolition Waste and its Comparison with Conventional Portland Cement Concrete

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Brick, mortar and concrete demolition wastes were mechanically treated by crushing, grinding and screening processes, and then used as raw material in the manufacture of geopolymer cements, which were subsequently used for the manufacture of geopolymer concretes by adding controlled amounts of aggregates and sodium hydroxide solution. At the same time, conventional Portland cement concretes were manufactured. All the manufactured concretes, conventional and geopolymeric, were evaluated by optical microscopy, finding similarities between both materials, with the presence of two well differentiated phases, on the one hand, a continuous binder phase and, on the other hand, a phase of aggregates enveloped by the binder phase. The studied concretes were mechanically and thermomechanically characterized in a single prototype equipment, finding for both types of materials a systematic softening with increasing test temperature, from ambient to 350 °C, and then a hardening of the materials with increasing test temperature from 350 to 550 °C. The mechanical aspects evaluated were maximum strength, stiffness and degree of deformation. In the comparison between the two types of concrete studied, a better mechanical response was found in the conventional concrete. Finally, with the apparent and real density data (obtained by helium pycnometry), the porosity of the materials was determined and the influence of porosity on the mechanical response of the materials was analyzed.

Keywords: mechanical, thermomechanical, geopolymeric, demolition waste.

1. Introduction

Cement, a key and costly ingredient in the manufacture of concrete, is responsible for between 5% and 7% of global carbon dioxide (CO2) emissions. Likewise, the manufacture of one ton of cement requires 2.8 tons of raw materials, making it a process that depletes a large amount of natural resources, and its production also releases one ton of CO2. [1,2] This reality is alarming, so it is urgent to find ways to reduce CO2 emissions from cement industries [3,4]. Geopolymers represent a category of inorganic synthetic materials that are formed at room temperature through a chemical process known as geopolymerization. This process involves the solubilization of amorphous phases of aluminosilicates present in various substrates, such as industrial solid wastes, calcined clays and natural minerals, through the action of an alkaline activator in an aqueous solution [5,6]. In recent years, these new materials have attracted considerable attention within the scientific community due to their versatility for a wide range of applications [7,8]. Due to their durability, fire resistance, chemical resistance and low porosity, geopolymers are used in a variety of applications, ranging from infrastructure construction to hazardous waste encapsulation. They are also being studied for use in the manufacture of sustainable building materials and in the remediation of contaminated soils. [9,10]. Similarly, the main challenge of concrete blocks is their high cement consumption, which contributes significantly to the greenhouse effect and global warming [11], and also implies a massive use of natural resources such as sand, gravel and crushed rock, as well as large amounts of fresh water, as well as energy consumption at all stages of the manufacturing process and use of concrete, with fossil fuels as the main source of energy [12,13]. [12,13].

Some research works reported that geopolymer concrete demonstrates a remarkable ability to develop up to 70% compressive strength in the first 4 hours of curing at a suitable temperature, in contrast to conventional Portland cement, which requires several weeks to reach similar levels. In addition, geopolymer concrete experiences minimal shrinkage during curing, showing 5 to 7 times less shrinkage than conventional Portland cement concrete after one year. [14,15]. Other research found geopolymer concrete improves its compressive strength at 800°C, while Portland cement loses all of its residual strength at 400°C due to Ca (OH)2 decomposition. Given these favorable properties, geopolymers are a promising option to replace conventional Portland cement in the manufacture of various sustainable products, including building materials and concretes [16]. The use of demolition waste in the creation of geopolymer pavers is one way to combat the problem of waste and environmental pollution caused by their improper disposal. These pavers can be used in a variety of projects, such as pavements, walls, slabs and beams. In addition, adding these wastes to concrete improves its thermal and mechanical properties, as well as its fire and corrosion resistance.

2. Materials and methods

Raw material

Demolition waste (bricks, mortars and concrete) was collected from informal deposits located in peripheral areas of the city of Arequipa (Peru). About 100 kg of waste were collected, which were taken to the laboratory and then subjected to consecutive processes of separation, crushing, grinding and sieving (ASTM # 200 mesh). The powder obtained was of two types (i) hardened cement (RC) with minor amounts of fine sand and silt, derived from demolition mortars and concretes and (ii) calcined clay (CC), derived from demolition bricks.

The RC and CC powder was then physically and microstructurally characterized.

The RC or CC powder was mixed with controlled amounts of sodium hydroxide solution (12 molar concentration) to obtain new geopolymer cements, which were used to obtain geopolymer concretes. In parallel, and for the purpose of comparison, conventional Portland cement concretes (CC) were manufactured.

Figure 1 shows the macroscopic appearance of the manufactured samples.

Figure 1. Macroscopic appearance of manufactured concrete.

Fabrication of concretes

Cylindrical concretes of 10 cm in diameter and 20 cm in height were manufactured from the mixture of binder, aggregates and liquid phase. Two types of concrete were produced:

(i) conventional concrete (CC): where Portland cement was used as binder, a mixture of coarse aggregate (TMN ¾" stone) and fine aggregate (coarse sand) as aggregate, and water as liquid phase, and (ii) geopolymer concrete (GC), where hardened cement powder (RCGC) or calcined clay powder (CCGC) was used as binder raw material, mixture of coarse aggregate (TMN ¾" stone) and fine aggregate (coarse sand) as aggregate and 12 molar sodium hydroxide solution as liquid phase.

For the manufacture of concrete, in all cases, the ratio in Table 1 was used.

Table 1. Mass ratio of components in conventional and geopolymer concretes manufactured.

Binder	Fine aggregate	Coarse aggregate	Liquid phase
1	2.29	2.27	0.65

The manufacturing procedure for the concretes studied followed the procedure suggested by the ACI 210 method and considering NTP 060. It started with the mixing of solid materials (binder and aggregates) and then the addition of the liquid phase. The wet mix obtained was placed in standard cylindrical molds and tamped until the entire mold was filled. The molded concretes 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 manufactured materials were evaluated mechanically and thermomechanically after 28 days of curing.

From the simple measurement of the mass and dimensions of each manufactured concrete, the average bulk density was determined, then by helium pycnometry the real density of all the manufactured materials was determined and with the data of bulk and real density the porosity was calculated. Table 2 shows the data.

Table 2. Bulk density, real density and porosity of conventional and geopolymer concretes manufactured.

type of concrete	apparent density (g./cm^3)	real density (g./cm^3)	porosity (%)
CC	1.9091	2.5079	24
RCGC	1.7541	2.5753	31
CCGC	1.9803	2.5052	21

Physical, microstructural, mechanical and thermomechanical characterization of concretes

The physical characterization of the manufactured concretes was carried out by means of tests to determine the geometric and real density; the geometric density was determined by measuring the masses and dimensions, while the real density was obtained by helium pycnometry (Micromeritics brand, model AccuPyc II 1345). The microstructural characterization was carried out by observations of polished surfaces of the samples studied, this characterization was performed using a CoolingTech model 1600X optical microscope. Finally, the mechanical and thermomechanical characterization was carried out under uniaxial compression conditions at variable temperatures (ambient, 350 and 550 °C), in ambient atmosphere and at a constant compression speed of 3500 N/sec.

The mechanical studies were carried out on a HUDA Technology model HUD-B616-3 universal testing machine integrated to a SAFTHERM model STGL-310-12 vertical tubular furnace, which together with a hermetic controlled atmosphere system (of our own design), constitute a unique prototype in Peru (Figure 2).

Figure 2. Prototype equipment for the mechanical, thermomechanical and controlled atmosphere evaluation of materials of standardized size

3. Results and Discussion

Microstructural, mechanical and thermomechanical characterization of fabricated concrete

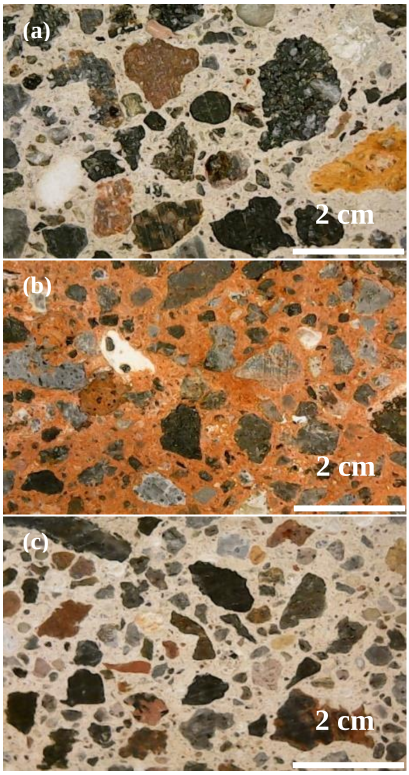

Figure 3. Optical microscopy micrographs of (a) CC (b) CCGC and (c) RCGC

Figure 3 shows micrographs of conventional and geopolymer concretes studied, a very similar microstructure was found, identifying two clearly differentiated phases, on the one hand, a phase consisting of unconnected aggregate particles surrounded by another continuous phase corresponding to the binder.

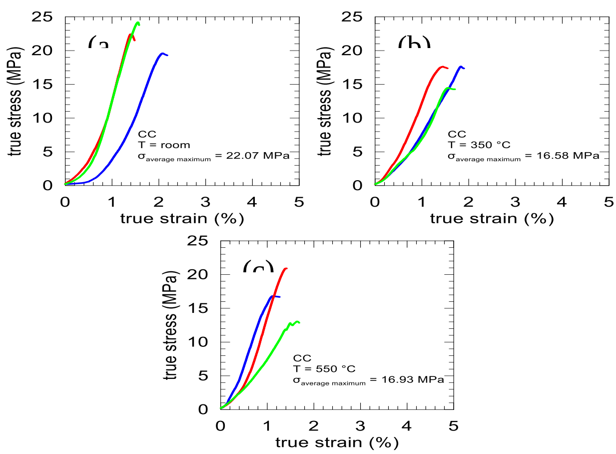

Figure 4. Stress vs. strain curves for conventional Portland cement concretes tested at (a) room temperature, (b) 350°C and (c) 550 °C.

Figure 4 shows average mechanical stress values of Portland cement concretes tested in compression and at various temperatures. It was observed the reduction of the average maximum strength (from 22.07 MPa to 16.58 MPa) when passing from ambient test temperature to 350 °C and then a slight increase of the average mechanical strength (from 16.58 MPa to 16.93 MPa) when passing from 350 to 550 °C test temperature.

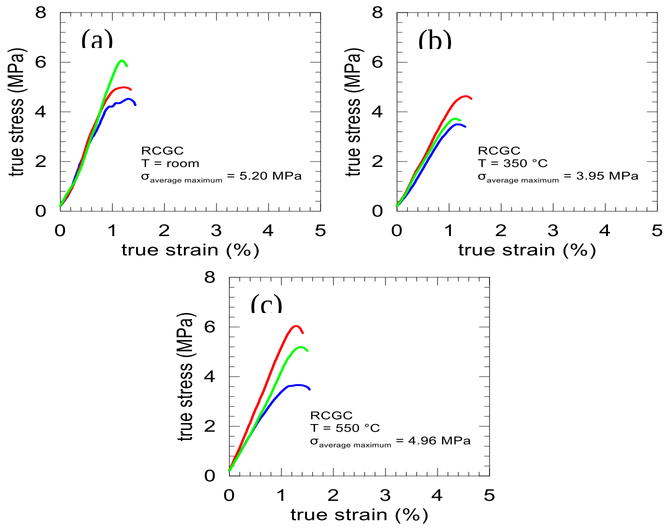

Figure 5. Stress vs. strain curves for geopolymer concretes derived from hardened cement and tested at (a) ambient temperature, (b) 350°C and (c) 550 °C.

Figure 5 presents the mechanical and thermomechanical results of geopolymer concretes obtained from hardened cement powder, finding similar results to those shown in Figure 4 for conventional Portland cement mortars. A reduction in the average peak strength (from 5.20 MPa to 3.95 MPa) was observed when moving from ambient to 350 °C test temperature and then a slight increase in the average peak strength (from 3.95 MPa to 4.96 MPa) was observed when moving from 350 °C to 550 °C test temperature.

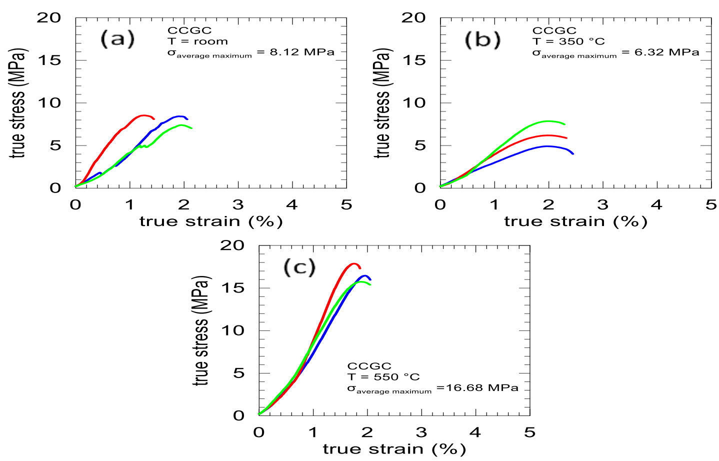

Figure 6. Stress vs. strain curves for geopolymer concretes derived from calcined clay and

tested at (a) room temperature, (b) 350°C and (c)550 °C.

On the other hand, Figure 6 shows the mechanical and thermomechanical results of geopolymer concretes obtained from calcined clay powder, finding similar results to those shown in Figure 4 and 5 for conventional Portland cement concretes. It was observed the reduction of the average maximum strength (from 8.12 MPa to 6.32 MPa) when passing from ambient test temperature to 350 °C and then a remarkable increase of the average maximum strength (from 6.32 MPa to 16.68 MPa) when passing from 350 °C to 550 °C test temperature.

Figure 7 presents the results of the average Young's modulus for conventional and geopolymer concretes, this figure reveals that the stiffness of the materials changes with temperature change, similar to what was observed in the values found for the average maximum strength (Figures 4, 5 and 6). The systematic reduction of the stiffness of the materials studied was evidenced when the test temperature was increased from room temperature to 350 °C, and then the increase of stiffness when the test temperature was increased from 350 to 550°C.

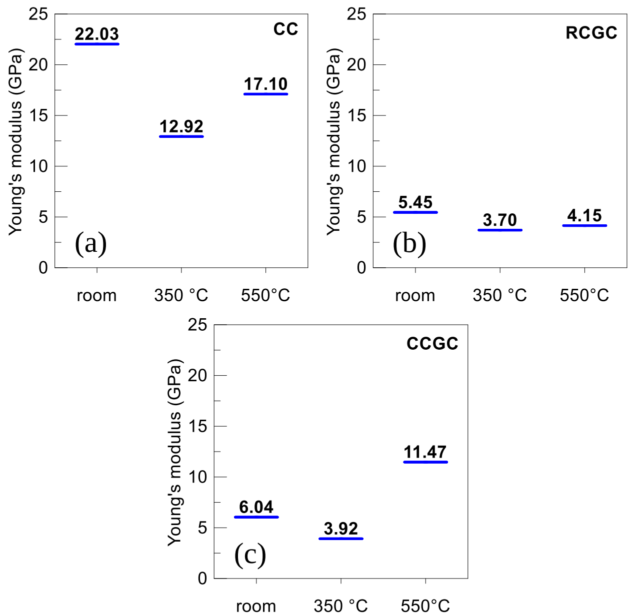

Figure 7. Young's modulus for studied concretes (a) conventional Portland cement - CC, (b) geopolymeric hardened cement - RCGC and (c) geopolymeric calcined clay - CCGC.

4. Conclusions

Conventional Portland cement and geopolymeric concretes from demolition waste were successfully manufactured.

Geopolymer concretes made of hardened cement powder showed higher porosity (31%) than conventional Portland cement concretes (24%), while geopolymer concretes made of calcined clay powder showed lower porosity (21%) than conventional Portland cement concretes (24%).

The microstructure found in conventional and geopolymer concretes was very similar, with aggregate particles dispersed within a continuous, interconnected binder phase.

The average maximum mechanical strength of conventional and geopolymer concretes showed a very similar behavior, with the systematic reduction of mechanical strength when the test temperature was increased from ambient to 350 °C and the increase of the average mechanical strength when the test temperature was increased from 350 to 550 °C.

With respect to Young's modulus, for all the materials studied, a systematic reduction in stiffness was found when the test temperature was raised from ambient to 350°C, and then an increase in stiffness when the test temperature was raised from 350°C to 550°C.

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References

1. Ahmed, H. U., Mohammed, A. A., Mohammed, A. S., et al. (2021). Compressive Strength of Geopolymer Concrete Composites: Modeling and Comprehensive Systematic Review. PREPRINT. Available at Research Square. https://doi.org/10.21203/rs.3.rs-611987/v1
2. Guo, X., Shi, H., & Dick, W. A. (2010). Compressive strength and microstructural characteristics of class C fly ash geopolymer. Cement and Concrete Composites, 32(2), 142-147. https://doi.org/10.1016/j.cemconcomp.2009.11.003
3. Davidovits, J., & Davidovics, M. (1991). Geopolymer: ultra-high temperature tooling material for the manufacture of advanced composites. Sampe, 36(2), 1939–1949.
4. Davidovits, J. (1994). Properties of Geopolymer Cements. In First International Conference on Alkaline Cements and Concretes (pp. 131-149).
5. Omaa, E., Sargon, S. P., Kashosi, C., Gheni, A., & ElGawady, M. (2020). Mechanical Properties of High Early Strength Class C Fly Ash-Based Alkali Activated Concrete. Transportation Research Record Journal of the Transportation Research Board, 2674. https://doi.org/10.1177/0361198120915892
6. Duxson, P., Fernández-Jiménez, A., Provis, J. L., et al. (2007). Tecnología de geopolímeros: el estado actual del arte. J Mater Sci, 42, 2917–2933. https://doi.org/10.1007/s10853-006-0637-z
7. Krishna, R. S., & F. S. (2021). Mine tailings-based geopolymers: Properties, applications and industrial prospects. Elsevier, 47, 17826-17843. https://doi.org/10.1016/j.ceramint.2021.03.180
8. Cui, Y., Gao, K., & Zhang, P. (2020). Experimental and Statistical Study on Mechanical Characteristics of Geopolymer Concrete. Materials, 13, 1651. https://doi.org/10.3390/ma13071651
9. Harma, N. K. (2017). Properties of concrete containing polished granite waste as partial substitution of coarse aggregate. Elsevier, 151, 158-163. doi:10.1016/j.conbuildmat.2017.06.081
10. Kishan, L. J., & Radhakrishna. (2013). Estudio comparativo de bloques de mampostería de hormigón de cemento y geopolímero. IJRET: Int. J.Res. Ing. Tecnología, 361-365. https://doi.org/10.15623/ijret.2013.0213068
11. Murugesan, S., Ramaswamy, J., & Parshwanath, R. (2020). Fly Ash Geopolymer Mortar:

Impact of the Substitution of River Sand by Copper Slag as a Fine Aggregate on Its Thermal Resistance Properties. Journal of Cleaner Production, 279, 123766. https://doi.org/10.1016/j.jclepro.2020.123766

12. Mehta, P. K. (2001). Reducir el impacto ambiental del hormigón. Internacional concreta, 23(10), 61-66.
13. Mamani, H., Mayta-Ponce, D. L., & Rodríguez-Guillén, G. P. (2021). Mechanical Characterization of New Geopolymeric Materials Based on Mining Tailings and Rice Husk Ash. IOP Conference Series: Materials Science and Engineering, 1054, 012001. https://doi.org/10.1088/1757-899X/1054/1/012001
14. Ferone, C., Colangelo, F., Cioffi, R., Montagnaro, F., & Santoro, L. (2013). Use of reservoir clay sediments as raw materials for geopolymer binders. Advances in Applied Ceramics, 112(4), 184-189
15. Joni Safaat Adiansyah, Michele Rosano, Sue Vink, Greg Keir, Jason R. Stokes, “Synergising water and energy requirements to improve sustainability performance in mine tailings management”, Journal of Cleaner Production, vol. 133, 2016, pp. 5-17
16. Teara, A., Doh Shu, I., & Vivian WY, T. (2018). The use of waste materials for concrete production in construction applications. IOP Conference Series: Materials Science and Engineering, 342(1), 012062. https://doi.org/10.1088/1757-899X/342/1/012062