

Alkali-activated building materials made with recycled construction and demolition wastes



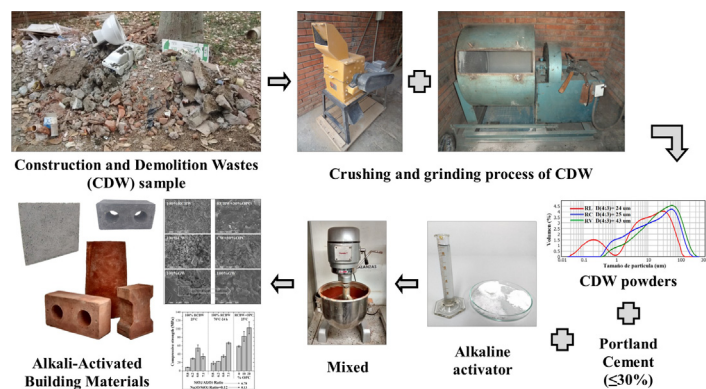
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HIGHLIGHTS

- Alkali-activated cements (AACs) based on construction wastes (CDW) are obtained.
- High compressive strengths of up to 102 MPa were obtained for AACs.
- Blocks, pavers, roof tiles and tiles (building materials) were made from AACs.
- The recycled of CDW through “Alkali activation technology” were demonstrate.

GRAPHICAL ABSTRACT



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ABSTRACT

The goal of this study was to test the viability of using red clay brick waste (RCBW), concrete waste (CW) and glass waste (GW) to produce alkali-activated cements (AACs) that can be used to fabricate blocks, pavers, roof tiles and tiles. The alkaline activators used were solutions of either NaOH or NaOH and water-glass. Ordinary Portland cement (OPC) was mixed with RCBW and CW in proportions of up to 30% to create hybrid cements. The AACs obtained with the RCBW, the CW and the GW exhibited maximum compressive strengths (28 days) of 102, 33 and 57 MPa, respectively.

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1. Introduction

The construction industry is considered one of the most influential sectors for improving the socioeconomic conditions of developing countries, and its dynamism is driven by the demand for housing and civil infrastructure. However, one of the consequences

of high demand is the generation of considerable volumes of waste, which have become a significant environmental problem, representing up to 30% of the solid waste generated globally. The search for sustainable solutions that exploit materials from construction industry waste (e.g., brick, glass, ceramics and concrete) is currently an urgent challenge for this sector [1–3].

Generally, construction and demolition waste (CDW) can be divided into three groups, depending on their origin: waste generated during the construction of new buildings, waste originating

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from the renovation and demolition of infrastructure (e.g., buildings, bridges and roads), including natural disasters and military conflicts, and waste originating from the ceramics industry (e.g., white and red clay) [2]. The largest producers of CDW are China, the U.S. and certain European countries, which generate more than 605.5 million tonnes per year [4–6]. It is estimated that approximately 54% of this waste comprises ceramic materials (i.e., bricks, tiles and other forms), and 12% is concrete [7]. Moreover, the ceramics industry discards approximately 3–7% of its production [8] despite the use of automation and monitoring in the production processes. For reference, the global production of brick red clay is approximately 1500 billion units per year [9,10]. In certain EU countries such as Germany, Denmark and the Netherlands, nearly 80% of CDW is reused, whereas in most other countries the rate is closer to 30% [11]. The EU directive 2008/98/CE (article 11.2.b) mandates a minimum reuse rate of 70% (by weight) of CDW before 2020 [12]. In Latin America, countries such as Brazil and Mexico have begun to implement processes for the production of recycled concrete aggregates.

CDW consists mainly of siliceous-aluminous materials (SiO_2 and Al_2O_3). Therefore, the alkaline activation process is considered a viable alternative for the increased use of this fraction (>75%) of the CDW. This process has been demonstrated to be highly practical for transforming industrial waste and by-products with suitable characteristics into useful materials. Puertas et al. [13] evaluated the use of residues from ceramic floor tile produced with red and white clays for geopolymeric cements, where the residue was activated with NaOH and waterglass ($\text{Na}_2\text{O}\cdot n\text{SiO}_2\cdot m\text{H}_2\text{O}$). The authors reported that samples cured for 8 days exhibited compressive and flexural strengths of 13 and 4 MPa, respectively. Allahverdi and Kani [14] developed a cement using waste from a brick production plant and activated it with NaOH in proportion of 8% Na_2O with respect to the binder. This cement had a compressive strength of 40 MPa after 28 days of curing. In a subsequent study, the same authors reported strengths of up to 50 MPa using a mixture of 60% concrete waste (CW) and 40% red clay brick waste (RCBW) activated with a solution of NaOH and waterglass (in concentrations of 1.4% and 8% Na_2O with respect to the binder). The authors stressed the importance of countering efflorescence in the final product [15]. Reig et al. [7] activated RCBW with a 7 M solution of NaOH and a $\text{SiO}_2/\text{Na}_2\text{O}$ ratio of 1.6 and measured a strength of 30 MPa in mortars after 7 days of curing at 65 °C. In subsequent studies, mixes with 40% calcium aluminate were prepared, and specimens exhibited a compressive strength approaching 50 MPa after 3 days of curing at room temperature [16].

Sun et al. [17] produced a geopolymeric cement from the alkaline activation of ceramic waste using waterglass and potassium hydroxide (KOH) as activators, and after 28 days of curing at 60 °C, the specimens exhibited a compressive strength of 71 MPa. Reig et al. [18] evaluated the influence of the alkaline activator concentration (NaOH and waterglass) and the use of $\text{Ca}(\text{OH})_2$ on mortars made with sanitary porcelain waste. Samples exhibited a strength of 36 MPa after 7 days of curing at 65 °C. Komnitsas et al. [19] studied the potential of geopolymeric cements made with various construction residues including bricks, tiles and concrete and observed compressive strengths of up to 49.5 and 57.8 MPa in samples made with RCBW and tile waste, respectively. However, cements made with CW and NaOH (in a 14 M solution) exhibited a strength of only 13 MPa after being cured at 90 °C for 7 days. These values were consistent with those reported recently by Zaharaki et al. [20]. Lampris et al. [21] used alkali-activated ground construction waste ($\leq 63 \mu\text{m}$) from recycling plants and obtained a compressive strength of 18.7 MPa after 7 days of curing at room temperature. Curing at 105 °C for 24 h increased the strength by 112%, and introducing 20% metakaolin as a source of soluble alumina increased the mechanical strength of the

geopolymer by 63%. Vázquez et al. [22] used NaOH and waterglass solutions with CW and 10% metakaolin, and after 28 days of curing at room temperature (25 °C), the cement made with CW exhibited a strength of 25 MPa, and the cement made with metakaolin exhibited a strength of 46 MPa.

A small percentage of CDW is glass waste (GW) from demolition, typically from windowpanes. Although this material is difficult to handle and reuse, several studies, such as those by Puertas et al. [23,24] and Cry et al. [25], have evaluated the possibility of recycling GW using alkaline activation, either as a source of SiO_2 for obtaining water glass or as a component of the activated cement. Important results on the microstructure, the mechanical properties and the durability were reported by Novais et al. [26].

This investigation considered the exploitation of RCBW, CW and GW using alkaline activation to obtain binders that can be used in the fabrication of various masonry construction products such as blocks, pavers, roof tiles and tiles. The residues were manually separated from actual CDW samples obtained from demolition activities on the campus of *Universidad del Valle* in Cali, Colombia. Using these residues to produce building materials would be a sustainable solution to the environmental problems associated with CDW.

2. Materials and experimental methodology

2.1. Materials

Table 1 presents the chemical compositions of the primary binders, RCBW, CW, and ordinary Portland cement (OPC), which was used as a supplementary source of CaO to obtain hybrid cements. RCBW and CW with high molar ratios of $\text{SiO}_2/\text{Al}_2\text{O}_3$ and GW with greater than 10% CaO and Na_2O , i.e., sodic calcic glass, were used. Fig. 1 shows the mineralogical compositions of the primary binders. It can be observed that the RCBW and the CW have a semi-crystalline structure, whereas the GW is amorphous.

A hammer crusher and subsequently a ball mill were used to reduce the size of the residue particles. Fig. 2 presents the granulometric distributions for the RCBW, CW and GW particles. The volume mean diameters, i.e., $D(4,3)$, of the RCBW, CW, GW and OPC particles were 24.25, 24.73, 43.12 and 21.65 μm , respectively. The angular morphology of the ground waste particles can be observed in Fig. 3. The presence of particles with reduced porosity and the significant fraction of small impalpable particles ($D < 10 \mu\text{m}$) are noted in the SEM images (Fig. 2).

2.2. Experimental methodology

Fig. 4 shows a diagram of the methodology followed in this investigation. The RCBW, the CW and the GW were obtained from a sample of actual CDW (Fig. 5) originating from demolition activities on the campus of *Universidad del Valle* (Cali, Colombia). The waste materials were separated, ground and characterized using laser granulometry, X-ray fluorescence (XRF), X-ray diffraction (XRD) and scanning electron microscopy (SEM). Based on the chemical compositions, the waste binders were activated using solutions of Na_2SiO_3 , i.e., waterglass (with the composition: 32.09% SiO_2 , 11.92% Na_2O , 55.99% H_2O), and/or industrial grade NaOH. OPC was used as a source of CaO in mixtures of less than 30% by weight with the RCBW and the CW to obtain hybrid cements.

The AACs were prepared in a Hobart mixer with a mixing time of 5 min. The liquid/solid ratio (L/S) used in all the mixtures was 0.23. The fresh pastes were molded into 20-mm cubes and subjected to vibration for 30 s in an electric vibrating table to remove trapped air. Then, the moulds were covered with a polyethylene film to control the evaporation of the free water, and the specimens were initially cured at temperatures of either 25 °C or 70 °C for 24 h. Subsequently, the specimens were removed from the moulds and placed in a curing chamber that maintained the relative humidity at approximately 90%, where the samples were remained for 27 days.

The compressive strengths of the AAC specimens were measured in an INSTRON 3369 universal testing machine, which has a capacity of 50 kN force, at a speed of 1 mm/min. For each mix, a minimum of three specimens were tested.

The following instruments and methods were used to analyse the specimens:

- Laser granulometry was performed using a Malvern Instruments Mastersizer 2000 particle size analyser and a Hydro 2000MU dispersion unit with distilled water as the dispersing medium.
- X-ray fluorescence (XRF) was performed using a Phillips-PANalytical MagiX Pro PW 2440 spectrometer with a maximum power of 4 kW and equipped with a rhodium tube.

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