Geopolymer with brick and concrete demolition constructions waste

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ABSTRACT: The production of building materials impacts non-renewable resources through excessive raw material extraction and fossil resource consumption. This study investigates alternatives to Portland cement concrete by valorizing construction and demolition waste (CDW), including brick and reinforced concrete. The objective is to replace or eliminate clinker using geopolymers while incorporating CDW as recycled aggregates. Sustainable concretes were developed, such as geoconcrete with 0% clinker and 50% recycled aggregate, along with blends containing varying CDW percentages for structural applications. Results indicate that geopolymers with 100% ground granulated blast furnace slag (GBFS) achieve properties comparable to reference concrete. However, mixtures with recycled brick and concrete show lower strength due to low molarity and recycled aggregate usage. Elastic modulus increases with 100% GBFS but decreases by less than 10% with CDW. In beams, breaking moments reduce by up to 30% with 25% CDW, while brick-based mixtures demonstrate higher energy absorption.

KEY WORDS: Geopolymer; Construction waste; Sustainability.

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RESUMEN: Geopolímeros con residuos de ladrillo y hormigón de construcción. La producción de materiales de construcción impacta los recursos no renovables por la extracción excesiva de materias primas y el consumo de combustibles fósiles. Este estudio explora alternativas al hormigón con cemento Portland mediante la valorización de residuos de construcción y demolición (RCD), como ladrillos y hormigón armado. Se propone sustituir o eliminar el clínker mediante geopolímeros e incorporar áridos reciclados derivados de RCD. Se desarrollaron hormigones sostenibles, desde geopolímeros con 0% de clínker y 50% de árido reciclado hasta mezclas con diferentes proporciones de RCD para aplicaciones estructurales. Los resultados revelan que los geopolímeros con 100% de escoria granulada de alto horno (GBFS) alcanzan propiedades comparables al hormigón convencional. No obstante, mezclas con ladrillo y hormigón reciclado presentan menor resistencia debido a la baja molaridad y al uso de áridos reciclados. El módulo elástico aumenta con 100% GBFS, pero disminuye menos del 10% al incorporar RCD. En vigas, los momentos últimos disminuyen un 30% con 25% RCD, mientras las mezclas con ladrillo mejoran la absorción de energía.

PALABRAS CLAVE: Geopolímeros; Residuos de construcción; Sostenibilidad.

1. INTRODUTION

Concrete is one of the most widely used materials in construction (1), resulting in solid, easy-to-execute, and resilient structures. The main ingredient of concrete is cement, and the primary component of cement is clinker. The high greenhouse gas emissions during the production and distribution of concrete, especially from clinker as the essential component of cement, have generated significant interest in alkali-activated cements.

Alkali-activated cements work through the reaction of a precursor rich in aluminosilicates with a high-concentration alkaline activator (2). The precursors can be materials with pozzolanic properties and low calcium content, forming cements based on the ternary system of Silicon-Calcium-Aluminum.

These alkaline cements, once hydrated, generate amorphous gels known as NASH and C-A-S-H. NASH gels (sodium, aluminosilicate, and hydrated) are formed in the Silicon-Aluminum binary diagram, being common in materials such as metakaolin and Class F fly ash, and are considered by some authors to be geopolymers. C-A-S-H gels (calcium, aluminosilicate, and hydrated) are formed in the calcium silicate-aluminate diagram, as seen in blast furnace slags and Class C fly ash, typical of power plants that burn sulphur-rich coals.

The gels produced by the hydration of these cements are known as NASH and C-A-S-H gels, both of which are amorphous products (lacking ordered crystalline structure). The gels formed in the Silicon-Aluminum binary diagram are known as sodium hydrated silicoaluminates (NASH), which in cement chemical nomenclature derives from Sodium (N), Aluminum (A), Silica (S), and water (H), as is the case with metakaolin and Class F fly ash. The NASH gel is what some authors refer to as a geopolymer.

The gels formed in the calcium silicate-aluminate diagram, known as C-A-S-H (Calcium (C), Aluminum (A), Silica (S), and water (H)), would be derived from materials such as blast furnace slag or Class C fly ash (from power plants that use fluidized bed combustion of high-sulphur coals and calcium carbonate for desulfurization), as shown in Table 1.

However, it is common to require additions to these gels, naming the minority component in parentheses.

Thus, in the case of adding calcium to a NASH gel, it would result in a N(C)ASH gel, and the addition of sodium to a CASH gel would yield a C(N)ASH gel. The calcium would be part of the pyramid in space, serving as the fourth point of the tetrahedron, which, when represented in two dimensions, appears as a triangle (Figure 1). For this simplification, the addition of sodium is considered at 3%.



FIGURE 1. Ternary phase system.

In this regard, any material rich in aluminosilicate could be a precursor for the design of geopolymers (2). In this sense, the use of CDW as sources of aluminosilicates in alkali-activated mixtures (3) can address two current issues: on one hand, the high greenhouse gas emissions generated during clinker production, and on the other, the significant environmental problem posed by CDW in Europe. Thus, the use of construction waste is part of one of the key environmental strategies for recycling, circular economy, and sustainability.

Komnitsas et al. (4) use brick remnants as a source of aluminosilicates for producing geopolymers. These geopolymers exhibit higher mechanical properties compared to those made solely from concrete waste, achieving a compressive strength of 58 MPa after 7 days of heat curing. In the literature, several studies recommend incorporating additional precursor sources such as Ordinary Portland Cement, granulated blast furnace slag, metakaolin, and fly ash (5, 6) to enhance the density and strength of geopolymers.

The reactivity of Construction and Demolition Waste (CDW) progresses at a notably slow pace, resulting in minimal or negligible early-age strength development, likely due to its lower calcium content

 TABLE 1. Fundamental models of alkali-activated precursors.

	Precurs	sors
System materials	Si-Al	Ca-Si-Al
Main hydratation product	Sodium Aluminosilicate	Calcium Aluminosilicate
Nomenclature	NASH	CASH

and predominantly crystalline structure. M. Tuyan et al. (7) show that waste bricks alone exhibit no significant strength development in early stages, but when combined with slag, compressive strength improves substantially. Rakihmova et al. (8) also report that waste bricks can be used in combination with slag in proportions up to 60%, as slag provides calcium, which releases substantial amounts of Ca^{2+} , Si^{4+} , and Al^{3+} during activation, promoting rapid strength gain.

During the geopolymerization process, precursors rich in calcium typically require lower concentrations of alkaline activators. According to Krivenko and Kavalerova (9), binders derived from fly ash and metakaolin require activator concentrations between 5% and 20%, while slag-based geopolymers can be activated with a much lower range of 2% to 8%. The calcium present in slag helps modify the sodium aluminosilicate gel (NASH) by partially replacing sodium ions with calcium, which aids in the formation of C-(N)-ASH gels. These gels contribute to increased stiffness in geopolymer mixtures, especially under ambient temperature conditions (10). The availability of free calcium ions during the geopolymerization process can enhance the dissolution of aluminosilicate materials, thereby increasing the exothermic reaction associated with hydration and accelerating the development of mechanical strength (11).

Adding calcium oxide (CaO), usually in the form of calcium hydroxide, to geopolymer mixes can further improve both strength and durability by enhancing the reactivity of aluminosilicates in waste materials and accelerating the setting process (12). However, when the CaO content exceeds 20%, the material tends to set too quickly, making it less suitable for geopolymer production.

Geopolymers derived from clay-rich construction and demolition waste (CDW), such as red clay bricks, tiles, and hollow bricks, primarily form NASH gels with zeolite-like structures. On the other hand, precursors with higher calcium levels, like Ground Granulated Blast Furnace Slag (GGBFS), typically generate CASH gels, which resemble those formed during the hydration of Ordinary Portland Cement (OPC). Low-calcium sources, such as calcined clays and fly ash, generally result in the formation of amorphous NASH gels that later develop into three-dimensional network structures (13).

In geopolymer synthesis, sodium hydroxide (NaOH) and potassium hydroxide (KOH) are commonly used to dissolve aluminum and silicon atoms, and their concentration (in molarity) plays a crucial role. A highly alkaline environment is necessary for efficient hydrolysis of aluminosilicate particles. While increasing hydroxide concentration tends to improve the mechanical properties of the geopolymer, this effect is not linear, and an optimal alkali concentration exists that maximizes the leaching of silica and alumina. At lower NaOH concentrations, the insufficient alkalinity can limit the dissolution of silica and alumina, hindering the geopolymerization process. As the concentration of NaOH rises, the number of hydroxide ions increases, promoting faster dissolution of silicon and aluminum, which results in higher concentrations of Al⁴⁺ and Si³⁺ in the activator solution. These dissolved ions then form aluminosilicate oligomers, which further condense into gels that enhance the geopolymer's strength and rigidity (4).

However, excessively high molarity can be detrimental, as it may lead to the dissolution of the aluminosilicate oligomers, breaking them down into aluminate and silicate ions, which impairs the polycondensation process (14). Moreover, high alkalinity can cause sodium ions (Na⁺) to adsorb onto the surface of the precursor material, interacting with the Al-OH and Si-OH groups. This interaction can weaken the bond between the solid particles and the aluminosilicate gel, ultimately reducing the structural integrity of the geopolymer matrix (15). Additionally, in mixtures with low water-to-binder (W/B) ratios, high molarity NaOH solutions may induce shrinkage, likely due to the increased viscosity of the activator, which slows the leaching of Al and Si atoms. As a result, the ratio of alkaline activator to precursor material needs to be carefully balanced when formulating geopolymer mixtures.

According to Komnitsas et al. (4), the compressive strength of geopolymers can be significantly enhanced when the particle size of construction and demolition waste (CDW) is reduced to less than 150 μ m. Their research revealed that geopolymers derived from tilebased materials and activated with 10M NaOH experienced over a 50% increase in compressive strength when particle size was reduced from 477 μ m to

140 µm. Similarly, CDW sourced from bricks achieved compressive strengths nearing 35 MPa when the particle size was decreased from 350 µm to 140 um. Additionally, geopolymers produced from concrete waste displayed a two-fold improvement in compressive strength when finer particles (190 µm) were used instead of larger ones (400 µm). While several studies suggest that only particles smaller than 125 µm can be effectively activated by alkali due to their higher reactivity, other researchers (16, 17) recommend that CDW-based materials should have particle sizes finer than 75 μ m for optimal use as precursors (Figure 2). However, compressive strength has a limited influence on the behaviour of bending elements (beams). Akduman et al. (18) showed that although the final strength was similar in beams made with geopolymers from clay-rich waste bricks, they exhibited a significant reduction in ductility, which could reach up to 30% if recycled aggregates were also used.



FIGURE 2. Particle size distribution measure by grading curves of aggregates.

On the other hand, Zheng and Xiao (19), compared the behaviour of geopolymers made with recycled brick aggregate and found, as expected, that the substitution of conventional aggregates with recycled aggregates reduces compressive strength, tensile strength, and adhesion, which decrease more rapidly in geopolymers than in concretes made with OPC.

For this purpose, two types of CDW were used in this article: bricks and concrete. These two CDWs were ground in a ball mill and added to Ground Granulated Blast Furnace Slag (GBFS) to increase their Al, Si, and Ca content. The same CDWs were used as aggregates, replacing 50% of the gravel content.

The experimental research included thorough tests of the geopolymerization process and the mechanical results obtained for compressive strength, tensile strength, modulus, and structural behaviour in beams.

The results show that the compressive and flexural strengths of the geopolymers made with 100% GBFS have properties similar to those of the reference concrete, while those mixed with additions of brick and concrete reach much lower strengths. This reduction, in addition to the presence of recycled aggregates in their granular skeleton, may also be due to the low molarity of the mixture chosen to avoid surface efflorescence. However, the elastic modulus of the concrete was affected. The results indicated that the elastic deformation modulus increases when using concrete with 100% GBFS, while it decreases when using CDW from bricks and concrete. Nevertheless, the decrease in this modulus when combining finely ground brick or concrete as a precursor for geopolymerization and simultaneously using brick or concrete waste as aggregate is minimal, with reductions of less than 10%, which is lower than the 20% reduction introduced by EC2 when using lightweight aggregates.

However, in beams, the experimental moment of failure is similar to the theoretical moment calculated

according to Eurocode 2. Nevertheless, the experimental moment is between 20% and 30% lower in concretes with 25% recycled concrete and 25% brick. It can be observed that the elastic displacements Δy are 8.5% higher for the 100% GBFS concrete and 8.5% and 22.6% lower for the mixes 25HOR65GR and 25LAD65GR.

The results show that geopolymers with 100% GBFS exhibit mechanical properties similar to those of reference concrete, while mixtures with additions of brick and concrete have significantly lower strengths, attributable to the low molarity used to prevent efflorescence and the inclusion of recycled aggregates. The elastic deformation modulus increases with 100% GBFS but decreases with CDW from brick and concrete, although the reduction is less than 10%. In beams, the experimental moment of failure is up to 30% lower in concretes with 25% recycled concrete and 25% brick. Additionally, the energy absorption index is 56.1% higher in mixtures where part of the GBFS was replaced with finely ground brick.

2. MATERIALS AND METHODS

In the research, different CDW materials (brick and concrete) were used, which were previously ground in a ball mill for 72 hours as a source of aluminosilicate. After grinding, the CDW samples were initially sieved through mesh screens to achieve the necessary Blaine fineness of 75 µm. The particle size of the precursor materials is a key factor influencing the properties of geopolymers. Smaller particles typically exhibit higher reactivity and promote a more efficient geopolymerization process, resulting in a stronger paste with a more compact microstructure. This is mainly due to the increased specific surface area of finer particles, which accelerates the dissolution process and enhances the reaction rate, leading to faster setting times and quicker strength development. However, to optimize mechanical performance and durability, it is essential to balance the increased water demand that comes with finer materials.

Laser diffraction was employed to analyze the particle size distribution of the raw materials, with the findings presented in Figures 3 and 4, and summarized in Table 2.

The characterization results highlighted the significant potential of the CDW materials, as they contain a high concentration of key elements essential for the geopolymerization process, including silica, calcium, and aluminum, as detailed in Table 3.

Bricks typically contain high amounts of SiO_2 (10-15%) and smaller amounts of Al_2O_3 (4-5%), which is similar to the composition of concrete waste. Both



FIGURE 3. Specific surface area of CDW and slag.

materials have comparable levels of SiO₂ and Al₂O₃ (Table 3). As a result, the high concentrations of Al and Si ions can be effectively stabilized during the activation process, allowing them to participate in the formation of Si-O-Al bonds (K. Komnitsas et al, 2015). Therefore, maintaining a proper balance of key elements—SiO₂, Na₂O, Al₂O₃, and CaO—is essential for optimizing the geopolymerization process and achieving effective geopolymer synthesis.

Sodium hydroxide (NaOH) was employed as the activator for the precursor materials. The NaOH used was in pellet form, with a purity of 98%, while the remaining composition included sodium carbonate and sodium chloride. To prepare the necessary concentrations (ranging from 6 to 18 M), the NaOH pellets were dissolved in water in varying amounts. Attention was given to carefully adjusting the concentration, as

higher molarities of NaOH can lead to pronounced efflorescence formation in geopolymer concrete.

	main components of CDW.					
	COMPOSITION CONCRETE (%)	COMPOSITION BRICK (%)				
H_2O	1.578	1.679				
CO ₂	34.14	27.27				
Na ₂ O	0.144	0.184				
MgO	3.783	2.755				
A ₁₂ O ₃	3.3	4.59				
SiO ₂	11.8	14.47				
P ₂ O ₅	0.114	0.0718				
SO ₃	1.27	3.243				
Cl	0.0472	0.0373				
K ₂ O	0.809	1.438				
CaO	41	41.1				
TiO ₂	0.194	0				
V_2O_5	0.0093	0.014				
Cr ₂ O ₃	0.0071	0.0087				
MnO	0.0257	0.0395				
Fe ₂ O ₃	1.638	2.607				
CuO	0.0063	0.0012				
ZnO	0.0075	0.00974				
Rb ₂ O	0.0027	0.00645				
SrO	0.0799	0.09944				
Y ₂ O ₃	0.0012	0.001				
ZrO ₂	0.011	0.0138				
BaO	0	0.028				

 TABLE 3. Chemical composition of the



FIGURE 4. Samples of CDW brick and concrete used as aggregate and precursor: (a) recycled brick powder 0,2 mm (b) recycled concrete powder 0,2 mm; (c) recycled brick aggregate 6/10 (d) recycled concrete aggregate 6/10.

Sample Name	d (0.1)	d (0.5)	d (0.9)	D [3. 2] - Surface weighted mean	D [4. 3] - Volume weighted mean
Slag	111.50	513.44	1049.88	274.65	546.08
Brick CDW	20.78	536.11	1169.77	40.99	571.87
Concrete CDW	5.33	154.82	861.79	14.03	311.58

TABLE 2. Specific surface area and volume.

The natural and recycled aggregates, both fine and coarse, were sourced locally from construction and demolition waste (CDW). The maximum particle sizes for the fine and coarse aggregates were 6 mm and 10 mm, respectively. These aggregates were sieved and separated into fine and coarse fractions, as shown in the Figure 2, to replace traditional aggregates in the geopolymer mix (Figure 4).

NaOH flakes were dissolved in tap water to create the sodium hydroxide solution at the desired concentration. After preparing the NaOH solution, the precursor materials and aggregates were added to a mixer and blended for 2 minutes. Next, the activator solution was poured into the mixer, followed by additional water, and the mixture was stirred for 5 minutes to ensure thorough reaction between the precursors and the activator. It is important to note that all procedures were standardized to maintain consistency and ensure reliable results. The geopolymer samples were cured under ambient conditions, without any external treatment, while the control sample made with Ordinary Portland Cement (OPC) was immersed in water until the specified testing age.

Microstructural characterization of the selected samples was performed using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), and pH measurements. For SEM imaging, samples of approximately 2 cm were prepared and gold-coated, while EDS provided detailed chemical analysis of specific regions. XRD analysis was carried out on roughly 20 mg of powdered sample to identify the crystalline phases present in the CDW-based geopolymer concrete. The XRD scans were conducted in the 5° to 50° 20 range, with a step size of 0.02° .

In this study, compressive strength, flexural strength, and deformation modulus were evaluated. Additionally, the structural performance of beam elements made from the geopolymer concrete was assessed. For this, geopolymer beams were subjected to testing using a four-point bending test, following a controlled displacement procedure. The base material, geopolymer concrete without CDW, served as the control variable in these tests. Four different base materials were used in the experiments: Reference, 100GBFS, 25HOR65GR, and 25LAD65GR, along with a reference concrete mix. The specific dosages for each material are provided in Table 4.

3. RESULTS AND DISCUSSION

3.1. Mechanical properties

Table 5 shows the compressive strength results at 7, 28, and 90 days obtained according to UNE-EN 12390-5, the flexural strength results at 28 days obtained according to UNE-EN 12390-5, and the deformation modulus results obtained according to UNE-EN 12390-13 at 28 days.

Dosage	w/b	Cement	GBFS	BP	СР	Water	Sand (0/4)	Grave (6/12)	NaOH	CBA	CCA
Ref	0.5	350	0	0	0	175	771.2	1156.8			
100GBFS	0.5	0	350	0	0	175	771.2	1156.8	26.9		
25HOR65GR	0.5	0	262.5	87.5	0	175	771.2	578.4	26.9		578.4
25LAD65GR	0.5	0	262.5	0	87.5	175	771.2	578.4	26.9	578.4	

TABLE 4. Mix proportions of concrete (geopolymer and OPC concrete by weight (kg/m³).

w/b: water/binder; GBFS: Ground Blast Furnace Slag; BP: Brick Powder from CDW CP: Concrete Powder from CDW CBA: CDW Brick Aggregate CCA: CDW Concrete Aggregate

TABLE 5. Compressive mechanical strength (fcm), flexural strength (ftcm), and deformation modulus (Ec).

		fcm (MPa)		fctm (MPa)	Ec (GPa)
Age	7d	28d	90d	28d	28d
Ref	25.32	33.69	46.75	4.8	31.5
100% GBFS	24.11	30.75	33.28	4.57	38.5
25HOR65GR	19.1	22.82	27.03	2.49	33.6
25LAD65GR	21.59	23.2	35.45	2.99	28.7

It can be observed that the compressive strength of the geopolymer made with 100% GBFS reaches an average of 86% of the reference concrete at the different ages tested, while the mixtures 25HOR65GR and 25LAD65GR only achieve between 67% and 76% of the reference concrete's strength. For the geopolymer with CDW from bricks, the compressive strength remained almost constant or decreased slightly with an increase in the replacement of aggregate up to 25% at curing ages of less than 90 days. Thus, between 7 and 28 days, while conventional concrete shows a strength increase of 33%, the substitution of 25% with ground brick and concrete reduces this increase to just 13.5% on average. However, for the geopolymer cured for 90 days, the compressive strength increased significantly (Figure. 5).



FIGURE 5. Compressive strength in MPa, at 7, 28 y 90 days.

This occurs because using finely ground brick (25%) as a precursor, with slag added to compensate for the lack of CaO, leads to limited or negligible strength development at early ages. This is likely due to the lower calcium concentration and its crystalline form. When waste bricks are used alone as precursors, no significant strength gain is observed at early ages. However, when combined with slag, compressive strength improves significantly starting at 56 days. This can be attributed to the fact that slag serves as a source of calcium, releasing substantial amounts of Ca²⁺, Si⁴⁺, and Al³⁺ during the activation process, which accelerates strength development.

Regarding the flexural strength, tests were conducted at 28 days on 2 prismatic specimens measuring 100x100x400 mm for each of the 3 mixtures made. The results of the flexural strength of the geopolymers with the addition of CDW are illustrated in Figure 6, showing that the geopolymer with 100% GBFS decreases from a strength of 4.57 MPa to 2.49 MPa after the incorporation of brick CDW, and a similar trend is observed, although with a slight improvement to a value of 2.99 MPa in the case of concrete.

The low compressive and flexural strength may be due to the low molarity of the mixture, aimed at avoiding the presence of surface efflorescence. Although a high molar concentration is positive for the geopolymerization process and, consequently, for final strength, it can lead to an excess of alkaline activator, which may induce surface efflorescence in geopolymers formulated from blast furnace slag and brick activated with NaOH. This phenomenon occurs due to the migration of Na⁺ ions to the surface, where they interact with CO2 from the air, forming sodium carbonate (Na₂CO₃), visible as salt deposits. In other words, excessive addition of NaOH accelerates the carbonation of concretes, potentially generating waste in the form of an amorphous silicate with a lower degree of polymerization. An excess of water facilitates the mobility of these ions during curing, exacerbated in humid environments. Therefore, the dosage of NaOH and the water content have been adjusted to mitigate this effect; however, these modifications have reduced the mechanical strength of the material.



FIGURE 6. Flexural strength in MPa at 28 days.

Regarding the elasticity modulus of concrete (Figure 7), the results showed that the elastic modulus of deformation increases when using concrete with 100% GBFS, while it decreases when using CDW from brick and concrete. However, the decrease in this modulus when combining finely ground brick or concrete as a precursor for geopolymerization and simultaneously using brick or concrete waste as aggregates is not significant, with reductions of less than 10%. These values are lower than the 20% reduction introduced by EC2 when using lightweight aggregates.

This good performance in the 25HOR65GR and 25LAD65GR mixtures is mainly attributed to the different reaction products, primarily the CASH gel. In addition to the high-rigidity gel phases, improved

interfacial transition zones are also responsible for the increased elastic modulus of the geopolymer concrete with the inclusion of slag (20). It can be observed that some of the unreacted CDW act as aggregates, increasing the rigidity of the 25HOR65GR and 25LAD65GR mixtures, while a higher degree of hydration of the slag leads to lower deformation moduli, whereas a higher degree of hydration of the slag (100% GBFS) results in higher deformation moduli.



FIGURE 7. Modulus of deformation in GPa at 28 days.

3.2. Microstructure

The presence of calcium within an optimal range positively influences the performance of the alkaline activation system. Consequently, maintaining a balanced composition of elements is crucial for successful geopolymerization and achieving ideal geopolymer synthesis. However, there remains a significant knowledge gap regarding how the components of CDW affect the reactivity and performance of the geopolymer system, particularly when analyzed through its microstructure.

The Si content in the matrix determines whether condensation occurs in Al-Si or Si-Si during geopolymerization caused by the polycondensation of hydrolysed Al and Si atoms. Condensation primarily occurs between Al-Si species at low Si/Al ratios, resulting in a polymeric structure of poly(sialate); however, as the Si/Al ratio increases, more Si species are produced due to the hydrolysis of SiO₂, resulting in oligomeric silicates. The increase in these proportions leads to the production of denser geopolymer gels that bind unreacted particles and directly improve resistance performance.

From the EDS analysis of the geopolymer 25HOR-65GR, the main chemical elements of the products are Si, O, Ca, Mg, Al, and Na. With a higher content of Ca in zone 1 (Figures 8 and 9), there is a transfer of this compound to the cracked zone. In large amounts of unreacted slag, waste concrete particles and significant microcracks can be observed, suggesting a low degree of geopolymerization under alkaline activation, resulting in fewer gel products and a loose, porous structure. These microstructural characteristics explain the low compressive and flexural strength observed in Figures 5 and 6.

The geopolymer with recycled brick 25LAD65GR as aggregate exhibited a morphology similar to that of limestone aggregates, with no visible capillary pores or cracks. Additionally, no microcrack rings were observed around the CDW gravel brick aggregate, indicating excellent cohesion between the aggregate and the geopolymer matrix up to a substitution percentage of 50% (Figure 10).

Overall, as the proportion of slag increased from 100% GBF, the addition of slag significantly enhanced the formation of cementitious products, improving the microstructure of the slag-based geopolymer when no recycled aggregates were used (Figure 11). This resulted in higher flexural strength compared to geopolymer mixtures that included CDW aggregates. As the slag content increased, and in the absence of recycled aggregates, the surface of the geopolymer microstructure became more uniform and compact, with fewer voids and a higher gel content. The structure appeared less fragmented and more cohesive. The internal matrix showed small surface pores and was largely crack-free. The gel structure exhibited more variety in its interactions, with gel layers stacked and locally raised in a convex pattern, contributing to a well-formed overall structure. This arrangement played a key role in the improved compressive strength observed at early curing stages.

Comparing the total pore size within the studied samples, it is evident that the pore volume was larger in the samples containing slag and CDW as precursors than in those containing only slag.

The geopolymer containing CDW aggregates displayed larger pore openings, cracks, and even the formation of larger pores, leading to increased porosity and reduced strength. In contrast, the mixture with 100% slag and natural aggregates exhibited fewer cracks and a more uniform pore structure. This suggests that incorporating slag into the mix can significantly refine the microstructure of the matrix. Additionally, the C-(A)-SH gel products formed by the combination of slag and CDW aggregates effectively filled internal microcracks, improving the overall structure. The presence of slag also enhanced the geopolymerization process, leading to the development of a denser and more cohesive network.

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FIGURE 8. SEM Images and 25HOR65GR Diffractogram.



FIGURE 9. SEM micro image 25HOR65GR.

The determination of the mineralogical composition of geopolymer concretes and their evolution over 28 days is conducted through X-ray diffraction (XRD), a technique that provides qualitative and quantitative information about the crystalline phases formed during the hydration process of compounds, making it very suitable for identifying crystalline phases in solids. In this case, although the technique does not allow for the exact quantification of the specific proportion of compounds such as calcite, quartz, or gypsum, this content can be estimated semi-quantitatively from the XRD results obtained. Comparative-



FIGURE 10. SEM images. XRD and Composition Analysis.



FIGURE 11. SEM micro images 100GBFS.

ly, the more amorphous mixtures, such as the 100% GBFS sample estimated by the XRD technique, show very similar results. Thus, a slight variation in the per-

centage of this crystalline phase is detected among the samples (Tables 6, 7 and 8).

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Compound Name	Formula	S-Q
Corundum, syn	A ₁₂ O ₃	10%
Calcite	CaCO ₃	29%
Dolomite	MgCa(CO ₃) ₂	8%
Quartz, syn	SiO ₂	5%
Muscovite-2M1	$K_{0.86}A_{11.94}(A_{10.965}Si_{2.895}O_{10})((OH)_{1.744}F_{0.256})$	2%
Gypsum	$Ca(SO_4)(H_2O)_2$	0,2%
Amorphous		46%

TABLE 6. C	Composition	of 25HOR65GR.
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 TABLE 7. Composition of 25LAD65GR.

Compound Name	Formula	S-Q
Corundum, syn	A ₁₂ O ₃	10%
Calcite	CaCO ₃	25%
Dolomite	MgCa(CO ₃) ₂	6%
Quartz, syn	SiO ₂	5%
Muscovite-2M1	$K_{0.86}A_{11.94}(A_{10.965}Si_{2.895}O_{10})((OH)_{1.744}F_{0.256})$	1,8%
Gypsum	$Ca(SO_4)(H_2O)_2$	0%
Amorphous		52%

TABLE 8. Composition of 100%GBFS.

Compound Name	Formula	S-Q
Corundum, syn	A ₁₂ O ₃	10%
Calcite	CaCO ₃	25%
Dolomite	MgCa(CO ₃) ₂	6%
Quartz, syn	SiO ₂	2%
Muscovite-2M1	$K_{0.86}A_{11.94}(A_{10.965}Si_{2.895}O_{10})((OH)_{1.744}F_{0.256})$	1%
Amorphous		63%

3.3. Beam structural behaviour

To evaluate the structural behaviour of the manufactured concrete, beams were constructed with the four previous dosages. The beams have a cross-section of 200 x 150 mm² and a total length of 2 meters. The longitudinal reinforcement consists of two 8 mm diameter bars on the top and two 12 mm bars on the bottom, along with transverse reinforcement made of closed stirrups of 8 mm diameter, spaced every 150 mm (Figures 12 and 13). The theoretical ultimate moment, considering concrete with a characteristic compressive strength of 25 MPa (C25/30 according to Eurocode 2 or HA-30 according to the Structural Code), and B500SD steel, is 14.89 m·kN, with a theoretical depth of the neutral axis of 40.78 mm, calculated under the assumption of a steel rupture strain of 10‰, placing the failure section at pivot A (according to Eurocode 2).



FIGURE 12. Reinforcement scheme, concrete beams and specimens waiting to be tested in the architecture laboratory of the UPCT.



FIGURE 13. Specimens casting in the Architecture Technology Laboratory of the UPCT.



FIGURE 14. Tests carried out on steel bars.



FIGURE 15. Beam prepared for testing on the frame with the transducers positioned on both sides.

In the tests carried out on the steel used (Figure 14) they have shown that its average yield strength for the four bars tested is 548.5 MPa and its tensile strength is 657.35 MPa complying with the requirements of B500SD steel.

A four-point test was carried out by loading at uniform distances of 600 mm (Figure 15) on the test machine of the Architecture and Building Engineering laboratory located. Vertical deformations were measured by a double reading on transducers placed on both sides of the beam.

The load was applied using a hydraulic actuator with a capacity of 2000 kN, at an application rate of 0.05 MPa/s, calculated for equivalent rectangular sections. To measure the deflection at the midpoint of the beam span, two vertical LVDT sensors were employed. From each mix, the compressive strength (fc) and flexural tensile strength (fctm) of the concrete were obtained. The beams were taken to failure to estimate their deformation capacity and the type of failure.

3.3.1. Results

The results obtained in the tests are shown in tables 9 and 10, and in the Figure 16.

3.3.2. Load-bearing capacity of beams

By analysing the section and the basic assumptions of force equilibrium and deformation compatibility according to Eurocode 2, an approximate estimation of the ultimate moment of the beam can be obtained.



FIGURE 16. Average tests result of load vs mid-span deflection.

These theoretical moments are compared with the experimental results obtained (Table 8), finding that only the reference beam made with OPC reaches a final moment similar to the expected one, while the beams made with 100% GBFS, 25% HOR65GR, and 25% LAD65GR present final moments that are 21%, 26%, and 35% lower than expected, respectively.

The low strength obtained in the 25% HOR65GR and 25% LAD65GR mixtures can be partially explained by the low ratio between flexural and compressive strength. This low flexural strength may induce premature failure, deteriorate the bond between concrete and steel, and justify the observed deformation behaviour (Table 10).

TABLE 9. Summary of Properties concrete of concrete made in beams, and tests results of beam in four-point frame.

Specimen name	F (KN)	M _u (mKN)	Mteo (mKN)	Mexp/ Mtheo
Refb	57,94	17,38	16,60	1,00
100GBFS	46,04	13,81	13,45	0,79
25HOR65GR	42,83	12,85	15,82	0,74
25LAD65GR	37,66	11,30	16,10	0,65

F: load apply by the press; M_u: ultimate moment;

Mteo; calculated theoretical ultimate moment

TABLE 10. Summary of tests results of	of deflection and energy ur	nder de curve load-deflection
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Specimen	d _y	d _u	d _{max}	$\mu_{d} = d_{u}/d_{y}$	E _y	E _u	$\mu_{E}=E_{u}/E_{y}$
name	(mm)	(mm)	(mm)		(KNmm)	(KNmm)	
Ref	9.2	19.2	45.0	2.1	262.5	1922.5	7.32
100GBFS	10.0	15.5	33.3	1.6	256.3	890.4	3.47
25HOR65GR	8.4	35.9	43.0	4.3	169.9	1202.6	7.08
25LAD65GR	7.1	25.1	49.8	3.5	127.1	1454	11.44

 d_y : Mid-span elastic deflection; d_u : Mid-span elastic deflection at the maximum loads; d_{max} : Mid-span elastic deflection maximum displacement previous to final beam collapse.

This low compressive strength leads to premature failure in the compressed zone, reducing the final load-bearing capacity. Additionally, it is accompanied by a quicker opening of cracks, driven by the lower tensile strength, which has consequences for the final deformation, as discussed later.

Nevertheless, it can also be observed that the experimental breaking moment is similar to the theoretical moment calculated based on the strength achieved by the concrete based on the pivot theory of Eurocode 2 and Spanish Structural Code 2021. However, the experimental moment is 20% and 30% lower in concretes where 25% recycled concrete and 25% brick are added (Table 9).

3.3.3. Load-Deflection Curve

The curves that describe the relationship between the applied load and the deformation measured at the central point of the specimens, as shown in Figure 16, can be broken down into four distinct mechanical phases: In the first phase, which corresponds to the regime prior to the initiation of cracks, all samples exhibited linear elastic behaviour in the load-deflection relationship. In the subsequent phase, between the moment cracks appear and the beginning of the creep regime, a progressive reduction in the slope of the curves is observed, indicating a gradual loss of the material's effective stiffness under incremental loading.

The deformation under elastic load ranged from 7.1 mm (span/253.5) to 10.0 mm (span/180), for loads of 28.16 kN and 41.18 kN, respectively. In this context, the analysis of the results must consider both the strength and the material's ability to deform under such loads, which defines its ductility. Ductility is a fundamental parameter in the plastic behaviour of structures, especially after the formation of plastic hinges, as it describes a structural element's ability to undergo additional deformations even close to its maximum load. This capacity not only provides warning signals before catastrophic failure but also enhances energy dissipation capacity, an essential aspect for optimizing structural response to seismic events.

The determination of the point at which the damage to an element can no longer be considered elastic is complex. It is observed, in any case, that the elastic displacements (Δ y) are 8.5% higher for the 100GBFS concrete and 8.5% and 22.6% lower for the 25HOR-65GR and 25LAD65GR mixes, respectively. However, if we consider that these elastic deformations were achieved under loads of 52.16 kN, 41.17 kN, 31.38 kN, and 28.16 kN for the Reference, 100GBFS, 25HOR65GR, and 25LAD65GR mixes, respectively, the analysis is modified.

Ductility can be evaluated using different indices, such as the plasticity index, which compares plastic deformation to elastic deformation ($\mu d = \delta u/\delta y$), or the energy absorption index, calculated as the ratio of the area under the load-displacement curve up to the ultimate deformation to the area corresponding to plastic deformation ($\mu E = Eu/Ey$), as shown in Figure 16. The specific values of these indices are detailed in Table 10.

The beam made with OPC has a $\delta y/\delta u$ ratio of 0.18 in the reference mix and values of 0.24, 0.27, and 0.25 in the 100GBFS, 25HOR65GR, and 25LAD65GR mixes, respectively. This means that elastic deformation is reached for an average deformation/load ratio of 0.25.

Regarding the plasticity index μ d, the 25LAD65GR beam achieves the highest value, despite having the lowest strength, which is logical since ductility tends to decrease as strength increases (21, 22). Conversely, the mix with the lowest μ d value is the 100GBFS, possibly due to its lower flexural strength.

Expanding the discussion to the displacement achieved at maximum load (δu), it is observed that the 25HOR65GR beam presents the highest value among the evaluated specimens. However, it is evident that the use of brick and finely ground concrete as activators has a negative impact on the final deformation, as seen in the 25HOR65GR and 25LAD65GR mixes, which exhibit significantly higher final deformations than the others. This behaviour can be attributed to the use of these materials as aggregates, which reduces the modulus of elasticity, thereby decreasing the material's stiffness and resulting in greater deformations under load. This effect has been documented in previous research, which notes the reduction of the modulus of elasticity when incorporating recycled or finely ground materials in geopolymers, leading to increased overall deformability of the structural element. Furthermore, this increase in deformation may be particularly relevant in applications where load capacity and stiffness are critical, as greater deformability can impact structural stability and service behaviour. This indicates that despite their lower resistance, these two dosages generate beams with a greater capacity to dissipate energy.

Similarly, by extending the study to the entire load-displacement curve beyond the maximum strength point, we can analyse the energy absorption index, calculated as the ratio of the area under the load-displacement curve up to the ultimate deformation to the area corresponding to plastic deformation ($\mu E = Eu/Ey$). This index is significantly higher in the beam made with the 25LAD65GR mix, showing

an improvement of 56.1% over the average μ E value (7.33). In contrast, the 100GBFS mix exhibits the lowest energy absorption index, with a value 47.4% below the average. These values are influenced by the final deformation, which is 16.4% higher than the average of all ultimate deformations in the 25LAD65GR mix, while in the 100GBFS mix, it is 22.14% lower. This fragility, induced by the lower tensile strength, is a determining factor.

3.3.4. Failures mechanism and crack behavior

The beam reaches its maximum strength peak with the breakage of the compressed area and with a stabilized cracking regime in the lower area (Figure 17). In this sense, and as has happened in previous research, and although the assessment is qualitative, in beams made with Portland cement the distance between cracks is more constant and reaches the stabilized cracking regime earlier than in beams made with geopolymeric concretes. However, in geopolymer concretes, a greater number of cracks is observed compared to conventional concrete, which is consistent with the findings of several authors (23-27). Nevertheless, due to the influence of reinforcement quantity on cracking, this should be an area for further study in future research.

4. CONCLUSIONS

The following conclusions can be drawn from the experimental work carried out:

- Geopolymer technology enables the valorisation of construction and demolition waste (CDW) into useful products, both as aggregates and in their chemical composition. The variation in alumina, silica, and calcium affects the final performance of the geopolymers.
- There remains a gap in knowledge regarding the impact of CDW components on the reactivity of geopolymers. Current research has focused more



FIGURE 17. Beam Break.

on the properties of the pastes rather than their scalability for structural elements.

- 3. The low compressive and flexural strength of geopolymers made with recycled brick and concrete is attributed to the low molarity of the mix, which is used to prevent efflorescence. Increasing the molarity improves strength but may lead to efflorescence.
- 4. The elastic modulus increases in concretes with 100% GBFS, while it slightly decreases (by less than 10%) when using brick and concrete waste as precursors and aggregates, showing better results than lightweight aggregates according to EC2.
- 5. The 25HOR65GR and 25LAD65GR mixes exhibit lower flexural and compressive strength, which may lead to premature failures. However, the experimental moment is similar to that calculated by Eurocode 2, although it can be up to 30% lower in certain cases.
- 6. The elastic displacement (Δy) is 8.5% higher in the 100GBFS concrete, while it decreases by 8.5% and 22.6% in the 25HOR65GR and 25LAD65GR mixes, respectively, indicating a variation in elastic capacity.
- 7. The 25LAD65GR beam exhibits the highest plasticity index (μ d), which is consistent with its lower strength, as greater ductility is typically associated with lower strengths. In contrast, the 100GBFS mix has the lowest μ d value.
- The 25HOR65GR beam shows the highest displacement upon reaching the maximum load, although the use of brick and ground concrete as activators negatively affected the final deformation in the 25HOR65GR and 25LAD65GR mixes.
- 9. The energy absorption index is 56.1% higher in the 25LAD65GR mix and 47.4% lower in the 100GBFS mix. This is related to the final deformation, where 25LAD65GR exceeded the average by 16.4%, while 100GBFS was 22.14% lower.
- Geopolymer concretes exhibit a greater number of cracks compared to conventional concrete. However, the influence of reinforcement on cracking requires further study.

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Authorship contribution statement

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Declaration of competing interest

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

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