Potential Use of Brick Waste for the Production of Geopolymer Roof Tiles

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Abstract

The construction and demolition waste sector produces significant quantities of brick waste (BW), which can be repurposed for creating new eco-friendly materials. This study assesses the feasibility of utilizing waste brick in metakaolin-based geopolymers and measures their key physical and mechanical properties. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) served as the activating alkaline solution. Various formulations were developed, incorporating increasing amounts of brick waste. The molded samples were cured at room temperature for 24 hours, with their upper surfaces covered by a thin plastic film to minimize moisture loss. Following this initial curing, the specimens were demolded and further cured at room temperature for 28 days. Comprehensive analyses were conducted, including particle size distribution, chemical characterization, X-ray diffraction, specific gravity, and pozzolanic activity of the solid precursors. Additionally, physical and mechanical tests were performed on the geopolymer specimens, assessing flexural and compressive strength, ultrasonic pulse velocity, Leeb rebound hardness, real and apparent densities, water absorption, and porosity. The chemical and mineralogical analysis of the brick waste revealed a high concentration of reactive silica and alumina, essential components for geopolymer synthesis. The compressive strength achieved for geopolymers containing waste brick powder was approximately 30 MPa, with a metakaolin to brick waste ratio of 90/10, utilizing 10M NaOH and a hydroxide to silicate ratio of 1:2; the corresponding ultrasonic pulse velocity and Leeb hardness values were around 2000 m/s and 650 HLD, respectively. Geopolymeric mortars produced with a binder to aggregate of brick waste ratio of 1:3 exhibited promising mechanical properties (about 50MP) comparable to fired clay bricks. The findings suggest that incorporating brick waste into geopolymer binders and mortars can yield both environmental and economic advantages by providing an alternative to fired brick in construction.

Keywords: *Geopolymer, geopolymeric mortar, metakaolin, C&D waste, Brick waste, Reuse, Porosity, Compressive strength.*

1. Introduction

The construction sector is one of the largest contributors to global waste production, particularly through demolition debris such as waste bricks (WB), concrete, wood, glass, metals and plastic [1]. In recent years, the growing demand for sustainable building practices has driven research into the recycling or upcycling of such materials [2]. One promising avenue is the development of geopolymers, a class of inorganic polymers formed by the alkaline activation of aluminosilicate-rich materials (e.g., metakaolin, ground granulated blast-furnace slag, fly ash) [3] [4]. Geopolymers can form solid ceramic-like materials even at near ambient temperatures. In this way, they could offer a low-carbon alternative to Portland cement, reducing CO_2 emissions by up to 80% [5]. Among the materials suitable for geopolymer synthesis, metakaolin (MK) stands out for its high reactivity due to its amorphous structure and abundant aluminosilicate content. However, due to its cost and energy-intensive production, efforts have been made to partially replace it with cheaper, sustainable alternatives. In this context, WB has emerged as a potential candidate owing to its pozzolanic activity and availability in large quantities [6][7][8][9][10]. Therefore, WB is an aluminosilicate source for geopolymers, offering sustainable construction solutions [11].

The present study aims to evaluate the suitability of WB as a partial substitute for MK in geopolymer production. We investigate both powder forms of WB (referred to as RTC and RTT) in geopolymers and coarser WB fragments as aggregate in geopolymeric mortars. The study focuses on the physical and mechanical properties of the resulting geopolymer and geopolymeric mortar specimens, including apparent density, porosity, ultrasonic pulse velocity, Leeb hardness, and compressive and flexural strengths. The overarching goal is to assess whether geopolymers containing WB can be viable materials to produce roof tiles, offering environmental and economic benefits while maintaining adequate performance.

2. Material and methods

2.1 Raw materials

The geopolymer binders used in this study were formulated using metakaolin (MK) as the primary aluminosilicate source and two types of brick waste powders — RTC and RTT — as partial or total substitutions of MK. RTC and RTT brick wastes were also used as aggregates for geopolymeric mortar production. The RTC and RTT brick wastes were sourced from demolition debris and processed into two fractions:

- Brick Waste Powders (BWP): obtained by crushing red bricks using a jaw crusher followed by grinding with a planetary ball mill
- Brick Waste Aggregates (BWA): derived from mechanically ground bricks using a percussion mill.

Both RTC and RTT brick wastes exhibited pozzolanic characteristics, though their chemical and mineralogical compositions varied. The chemical compositions of MK, RTC, and RTT were determined via X-ray fluorescence (XRF) and the collected data are reported in Table 1. The particle size distributions were assessed using sieving method.

The alkaline activating solution was prepared by mixing commercial sodium silicate (Na_2SiO_3) with sodium hydroxide (NaOH, 10 M); to adjust the compositions and the amount of water an aqueous colloidal dispersion of nano-sized silica (30 wt.%) dispersed in water was added. The solution was aged for 24 hours before mixing.

Tab. 1. Chemical composition of metakaolin (MK) and brick wastes (RTC and RTT).

	MK	RTC	RTT
H_2O	0.68	2.20	2.13
Na_2O	0.24	1.52	1.42
MgO	0.10	3.71	4.88
Al_2O_3	43.64	20.56	16.02
SiO_2	52.84	53.55	54.46
P_2O_5	0.06	0.18	0.22
SO_3	0.10	1.15	0.68
K_2O	0.16	3.43	2.33
CaO	0.03	4.76	7.49
TiO_2	1.72	1.01	1.20
MnO	<0.01	0.13	0.16
Fe_2O_3 [a]	0.43	7.80	9.01

[a] total iron expressed as Fe_2O_3.

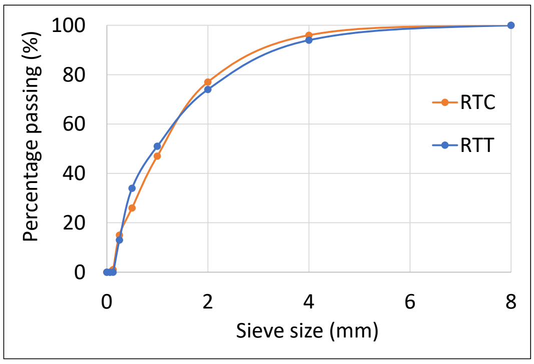

Fig. 1. Cumulative sieving curves of aggregates.

2.2 Geopolymer formulations and sample preparation

Several geopolymer and geopolymeric mortar mixtures were produced: 7 geopolymers, 24 geopolymers by replacing MK with either RTC and RTT powders, and 2 geopolymeric mortars by using RTC and RTT as aggregates. Figure 2 summarizes the compositions of the different geopolymer and mortar formulations.

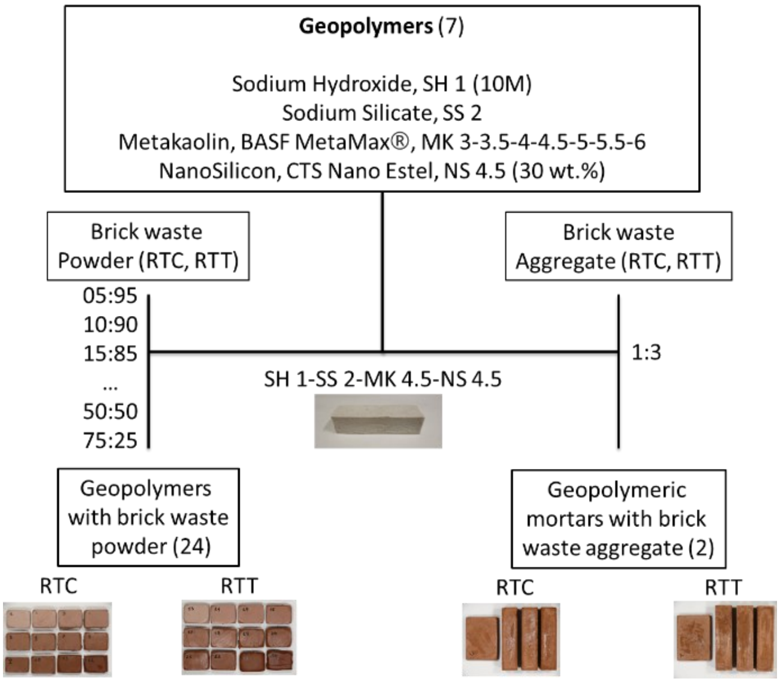

Fig. 2. Geopolymer and geopolymeric mortar formulations.

Mixing was carried out at room temperature using a planetary mixer. For geopolymer production, the dry powders (MK, RTT and RTC) were homogenized, followed by the gradual addition of the activating solution. In the case of geopolymeric mortars incorporating recycled materials, the aggregates were added to geopolymer of chosen composition and the mixtures were blended until a homogeneous consistency was achieved. After the mixing process, fresh specimens of geopolymer and geopolymeric mortar were poured into prismatic molds of 20×20×80 mm³ and 40×40×160 mm³, respectively, compacted on a vibrating table, and sealed with plastic sheets to prevent quick moisture loss. Curing was performed at room temperature (20 °C) for 24 hours, after which the samples were demolded and stored under laboratory conditions until testing at 28 days.

2.3 Characterization techniques

The hardened geopolymer and mortar specimens were tested for the following properties:

- Apparent density (EN 1015-10) [12]: determined on dried specimens by mass/volume ratio. The volume was determined from buoyant force, i.e. the upward force on the specimen in water [13]
- Water absorption coefficient due to capillary action of hardened mortar (EN 1015-18) [14]
- Water absorption and porosity (EN 1936) [15]: based on vacuum saturation.
- Leeb hardness: using a portable hardness tester (Equotip 550 Leeb rebound hardness tester, invented in the year 1975 by Leeb and Brandestini at Proceq SA) to evaluate surface resistance.
- Ultrasonic pulse velocity (EN 12504-4) [16]: assessed by a Proceq Pundit® PL-200 to infer internal compactness and homogeneity.
- Compressive and flexural strength (EN 1015-11) [17]: measured on a hydraulic testing machine.

Each test was performed on at least three specimens per formulation. Data were statistically analysed to assess the influence of WB type and replacement level on material properties.

3. Results and discussion

3.1 Workability and visual observation of the geopolymer and geopolymeric mortar samples

All fresh specimen mixtures exhibited acceptable workability at a Liquid/Solid ratio of 0.40, although those containing higher amounts of brick waste powder (particularly RTC 40) showed slightly reduced flow due to the higher water demand of the finer particles. Geopolymers incorporating high amount of BW (>50 wt.%) showed a slow rate in the polymerisation reaction. Mixes with coarse BW aggregates showed no segregation, and the surface finish was fully comparable to that of the reference geopolymer.

After curing, all specimens retained structural integrity, with minimal shrinkage and no visible cracking.

In the present case, the colour of metakaolin-based geopolymer was in the CIELAB space L* = 80.64, a* = -31.48, b*=4.77 and the colour difference of specimens incorporating WB was little influenced by the type of waste used, while it significantly increases in samples with higher RTC or RTT contents. The optimal model for predicting the color change of geopolymers based on the percentage of WB substitution is represented by the equation $\Delta E_{(100,0,0)}$=3.923E-05x^3-1.079E-02x^2+1.061E+00x+3.625E+01 with R^2 = 9.636E-01.

The geopolymers with RTC and RTT powders are characterised by reddish hues up to L* = 31.36, a* = 62.05, b* = 20.44. The geopolymeric mortars containing RTC and RTT aggregates exhibited also reddish hues, with the following colour parameters: for RTC, L* = 36.41, a* = 51.01, b* = 25.39; and for RTT, L* = 43.44, a* = 25.31, b* = 31.65. The difference in colour is mostly due to the presence of whitish patina of salts that is unevenly distributed.

3.2 Physical and mechanical properties of the geopolymer and geopolymeric mortar samples

3.2.1 Metakaolin-based geopolymers

In order to determine the properties of the geopolymers that could be produced with the available source materials and to choose the recipe with the best physical and mechanical properties, seven mixtures characterized by different metakaolin contents were prepared.

The molar ratios between the main components are reported in the Table 2.

Tab. 2. Molar ratios of the primary constituents of geopolymers.

	Si/Al	Al/Na	H_2O/Na_2O	H_2O/solid (w/w)
Sample 3.0	2.54	0.63	10.72	0.60
Sample 3.5	2.32	0.73	10.71	0.56
Sample 4.0	2.16	0.84	10.71	0.52
Sample 4.5	2.04	0.94	10.70	0.49
Sample 5.0	1.94	1.04	10.70	0.46
Sample 5.5	1.85	1.15	10.69	0.44
Sample 6.0	1.78	1.25	10.69	0.41

Apparent density decreased linearly with increasing MK content from 2.09 g/cm^3 to 1.94 g/cm^3 for Sample 3 and Sample 6.0, respectively.

The uniaxial compressive strength measured on metakaolin-based geopolymer samples are reported in Figure 3. Sample 4.5 demonstrates the highest values of Leeb hardness (HLD = 640 ± 14), ultrasound pulse velocity (UPV = 3079 ± 20 m/s), and uniaxial compressive strength (σ_c=58.52 ± 3.92 MPa). Therefore, its formulation will serve as the binder for all subsequent samples.

The linear correlations of the mechanical properties are as follows:

- UPV = 9.8732 HLD - 3262.4, R^2 = 0.951
- UPV = 31.392 σ_c + 1229, R^2 = 0.963

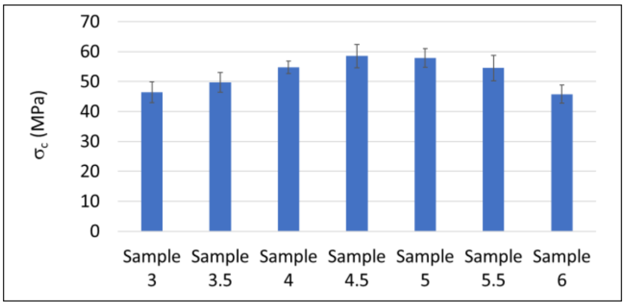

Fig. 3. Compressive resistance of metakaolin-based geopolymers.

3.2.2 Geopolymers incorporating brick waste powders

Geopolymer specimens created by replacing MK with BW powders in the formulation of Sample 4.5 exhibit distinct physical properties compared to the reference sample, primarily due to the increased water content required to meet the specific demands of BW powder in relation to MK. The apparent density values increase from 1.34 g/cm^3 (sample RTC0) to 1.48 g/cm^3 (sample RTC50) and then significantly increase up to 2.09 g/cm^3 (sample RTC100) in the RTC samples and from 1.34 g/cm^3 (sample RTT0) to 1.51 g/cm^3 (sample RTC50) and then up to 2.15 g/cm^3 (sample RTT100) in the RTT samples (Figure 4). Specimens with high BW contents (RTC75, RTC100 and RTT75, RTT100), unlike the other ones, are not hardened after 24 hours, but require about 7 days to do so. They are characterized by a significant shrinkage, which explains their low porosity.

Regarding mechanical properties, the Leeb hardness values range from 600 to 700 HLD (Figure 5), while UPV values, excluding RTC100 and RTT100 specimens, are on average 1818 ± 18 m/s for RTC specimens and 1835 ± 19 m/s for RTT specimens (Figure 6).

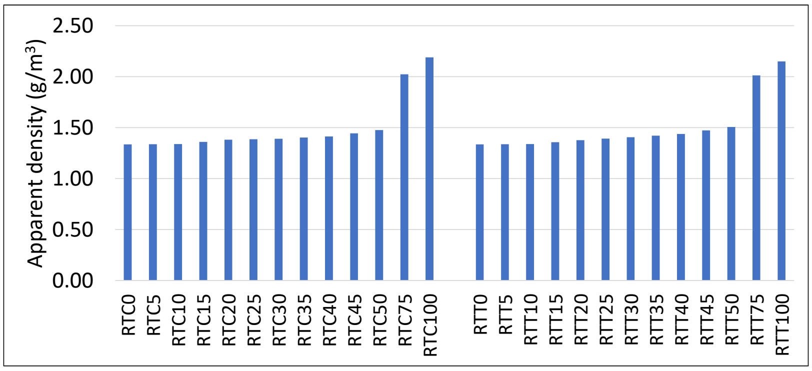

Fig. 4. Apparent density of geopolymers incorporating BW powders (RTC and RTT).
In the acronyms the number represents the percentage of BW that replaces the metakaolin.

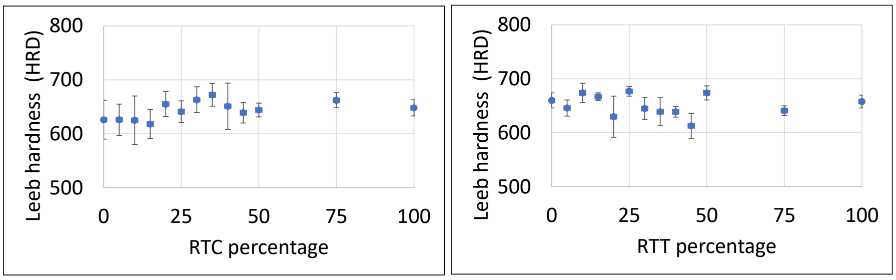

Fig. 5. Leeb hardness of RTC and RTT specimens.

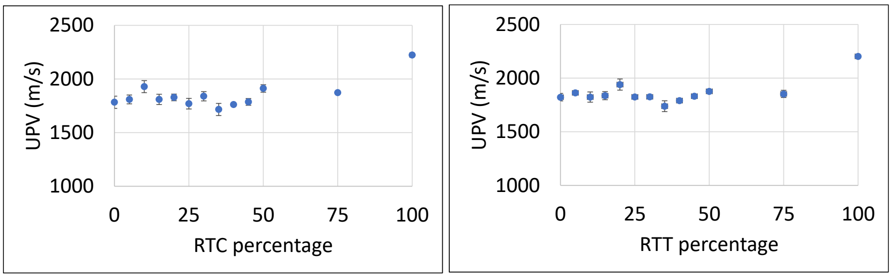

Fig. 6. UPV of RTC and RTT specimens.

Collected data indicate that BW substitutions lead to quite similar physical and mechanical properties of the geopolymers and confirm that BW powders are characterized by high reactivity in an alkaline environment, although slightly lower than that of metakaolin. The reduced reactivity index of BW powders, particularly due to their distinct chemical composition—which features a notably lower Al_2O_3 content compared to MK—primarily accounts for the slower polymerization rate observed when substitutions exceed 50%. This phenomenon arises when the Al/Na ratio in the geopolymer formulation is low.

3.2.3 Geopolymeric mortars with brick waste aggregates

The use of BW as aggregate in the geopolymeric mortar was tested making the MRTC and the MRTT specimens by using RTC and RTT brick waste, respectively. The binder/aggregate ratio was 1:3. The main physical properties of these samples are reported in Table 3, while in Figure 7 a comparison of uniaxial compressive strength values for roof tiles and geopolymeric mortars was showed.

The values of compressive resistance of MRTC and MRTT of approximately 50MPa are in good agreement with the values reported by Koronthalyova et al. [18] for clay brick fired at 1030°C (35-60 MPa).

Tab. 3. Main physical properties of geopolymeric mortars.

	G	γ_d	C1	CI	CI	P	IS
	g/cm^3	g/cm^3	g/m^2 * s$^{0.5}$	wt.%	% by vol.	% by vol.	
MRTC	2.64	1.71	6.94	16.4	27.9	35.4	79
St.Dev.	*0.01*	*0.01*	*1.56*	*0.6*	*0.9*	*0.1*	*3*
MRTT	2.64	1.68	31.55	18.5	31.0	36.5	85
St.Dev.	*0.01*	*0.01*	*5.08*	*1.2*	*1.9*	*0.1*	*5*

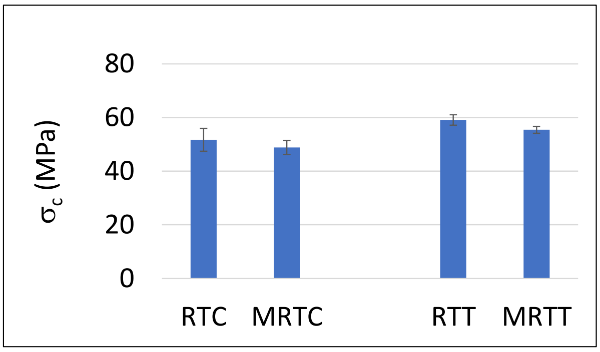

Fig. 7. Compressive strength of geopolymeric mortars. RTC = roof tile C; MRTC = geopolymeric mortar with roof tile C as aggregate; RTT = roof tile T; MRTT = geopolymeric mortar with roof tile T as aggregate.

The linear correlations of the mechanical properties are as follows:

- UPV = 3.5634 HLD + 1109.1, $R^2 = 0.7176$
- UPV = 38.678 σ_c + 844.34, $R^2 = 0.7874$

Despite the modest reduction in strength, the results suggest that geopolymeric mortars incorporating BW aggregate can meet the mechanical and physical performance requirements for roof tiles. Their reduced density, improved sustainability profile, and visual appeal further enhance their suitability for architectural applications.

4. Conclusions

This study evaluated the feasibility of using brick waste (BW) as a raw material for geopolymer materials aimed at producing roof tiles. Two types of BW powders (RTT and RTC) and their corresponding coarse fractions were assessed as partial replacements for metakaolin and as total replacement for natural sand in geopolymers and geopolymeric mortars, respectively.

The roof tile waste and other brick waste can be used to produce new roof tiles without firing using the knowledge of alkaline activated materials and more precisely by formulating geopolymer mortars containing as aggregate the crushed bricks. This study aimed to focus on the feasibility of reusing brick waste to create new eco-friendly geopolymer-based building materials. The preparation of the geopolymers involved utilizing a mixture of sodium hydroxide, sodium silicate as alkaline solution. First of all, the amount of metakaolin as precursor in a 1:2 ratio of Na-hydroxide and Na-silicate alkaline solution was optimized based on the mechanical strength of the final products. Next the selected geopolymer recipe was used as binder fraction for geopolymers with substitution of metakaolin with brick waste powders and for geopolymeric mortars with a 1:3 ratio of geopolymer and crushed brick aggregate.

The following conclusions can be drawn:

- The best geopolymer recipe among those produced by mixing metakaolin, sodium hydroxide and silicate and nano-silicon was the one with molar ratios $Al_2O_3/Na_2O = 1$ and $SiO_2/Al_2O_3 = 2$.
- Geopolymers with brick waste powder: up to 25% replacement of metakaolin with WB powders leads to only a moderate decrease in mechanical performance, while maintaining acceptable physical properties. Increased BW content tends to reduce density and surface hardness while increasing water absorption and porosity. Nonetheless, the values remain within acceptable ranges for non-structural applications.
- Geopolymeric mortar with brick waste aggregate: coarse brick waste aggregates can totally replace sand, though with a more noticeable impact on compressive strength and porosity due to their higher absorption and weaker matrix-aggregate bond. Ultrasonic pulse velocity results correlate with observed trends in porosity and strength, supporting the interpretation of internal compactness. Aesthetic qualities and the sustainability benefits of recycling demolition waste contribute positively to the material's overall appeal.

In conclusion, geopolymer and geopolymeric mortars incorporating moderate amounts of brick waste — both in powder and aggregate forms (< 25% wt.%) show promising potential to produce environmentally sustainable roof tiles, combining resource efficiency with acceptable performance. Further studies will focus on long-term durability and environmental impact assessments.

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