



Characterization of Ceramic Brick and Metakaolin Waste Geopolymers as Alternative to Portland-Cement Mortar

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Abstract. The valorization of construction and demolition waste (CDW) is a significant precondition of establishing sustainable and circular economy (CE). This study investigates the use of ceramic brick waste (CBW) and metakaolin waste (MKW) as precursors in geopolymer mortar systems as sustainable alternatives to conventional Portland cement-based materials. Experimental investigations evaluated the mechanical performance, microstructural development, and thermal resistance of CBW–MKW geopolymer mixtures. The developed geopolymer mortars demonstrated strong early-age performance (compressive strength) and formed a dense N–A–S–H gel matrix during curing. Exposure to 900 °C resulted in microstructural degradation in all mixtures; however, the mortar composition with the CBW–MKW ratio 1/1 (S2) retained the highest residual compressive strength and preserved the most coherent matrix structure. The results highlight that combining crystalline CBW with amorphous MKW improves thermal resistance and mechanical stability. The findings support the potential of CBW–MKW geopolymers as sustainable construction materials that can significantly contribute to CE and construction in the Baltic region.

Keywords: Valorization · ceramic brick waste · metakaolin waste · geopolymer mortar · alternative to Portland cement

1 Introduction

Construction and demolition waste (CDW) stands for one of the largest waste stream in the European Union (EU) and constitutes a significant share of total waste generation in the Baltic States. In Estonia, Latvia, and Lithuania, mineral construction waste (i.e. concrete, bricks, ceramics, and asphalt) forms the dominant fraction of CDW streams. Despite improvements in waste management systems and increasing recycling rates, a

considerable percentage of these materials is still down-cycled into low-value aggregates or used for backfilling purposes. This means that circular economy high-value recycling pathways remain underdeveloped. Therefore, innovative material solutions capable of transforming mineral construction waste into new construction materials, such as geopolymer binders, represent an important opportunity to increase material circularity and reduce reliance on virgin resources across the Baltic region [1, 2]. CDW represents a relevant secondary resource for the Baltic construction sector. A significant share of buildings constructed during the twentieth century in Estonia (e.g. largest share, 35.4% of the Estonian Building Stock [3]), Latvia, and Lithuania utilized ceramic brick masonry structures. Ongoing demolition, but also reconstruction of these aging building stocks generates substantial quantities of CBW.

In recent years, geopolymer materials have gained increasing attention as sustainable alternatives to Portland cement due to their lower environmental footprint, reduced CO₂ emissions, and favorable mechanical and durability properties. The growing emphasis on circular economic principles has further encouraged the use of secondary raw materials, enabling the development of greener construction products without compromising performance. In this context, industrial waste-derived aluminosilicate precursors have become particularly relevant for producing geopolymer binders. Ceramic brick waste (CBW) waste has found to be valuable, sustainable resource that can be repurposed in construction industrial applications, [4, 5] where it can be recycled as an aggregate substitute in concrete, an asphalt additive, or a supplementary cementitious material when ground into powder. Metakaolin waste (MKW) is a high-activity, silica- and alumina-rich byproduct primarily generated during industrial processes like expanded glass manufacturing. It is increasingly utilized in construction as a sustainable additive to enhance the mechanical properties, density, and durability of high-performance and geopolymer concretes [6–8]. Phosphogypsum (PG) is a solid waste product that is generated in the phosphoric acid manufacturing process, most of which is currently sent to landfills rather than recycled [9].

Previous studies [10–12] have established that a ternary alkali-activated binder system formulated from CBW, MKW, and PG forms a dense gel matrix and significantly improves mechanical properties. Low-calcium geopolymers cured under ambient conditions achieve good strength due to the uniform formation of Sodium Aluminosilicate hydrate, i.e. N-A-S-H gel. An optimal Na₂SiO₃/NaOH ratio results in a denser matrix and higher compressive strength of the geopolymers. Geopolymers also exhibit significantly better high temperature resistance (up to 1000–1200 °C) compared with cementitious binders, whose microstructure begins to degrade at around 400 °C due to Ca(OH)₂ decomposition, and which may lose up to 95% of their strength at 1000 °C. Their thermal stability is attributed to a dense inorganic matrix and a lower susceptibility to moisture induced damage [13].

Although CBW and MKW have been extensively investigated as precursors in geopolymer systems, limited research exists on the high temperature behavior of their combined CBW–MKW systems. Therefore, the present study aims to evaluate the strength and microstructural transformations of the CBW–MKW geopolymer mortar before and after heating, with the goal of understanding the relationship between thermal resistance. The aim of the study is also supported by the fact that in urgent need

for transition to CE, innovative material technologies that enable the valorization of secondary mineral resources can significantly reduce environmental impacts associated with traditional construction materials [1].

2 Materials and Methods

2.1 Composition of Geopolymer Mortar

The geopolymer binder was produced from CBW and MKW, both finely milled aluminosilicate precursors with comparable particle sizes ($\sim 11\text{--}13\ \mu\text{m}$) and high fineness. CBW is quartz rich and predominantly crystalline, while MKW contains a high amorphous fraction and elevated Na_2O due to residual glass. Phosphogypsum (PG), was added at a constant 5 wt% as a calcium source, promoting accelerated geopolymerization. Three precursor blends (Table 1) were activated using soluble glass (SG) and 10 M NaOH solution (SH) at SG/SH ratios of 1.0. To evaluate the effect of natural sand aggregate on the mortar, three different binders to aggregate ratios were used: 2/1, 1/1, and 0.5/1. The geopolymer mortar was mixed using an electric mixer, with the alkaline activators premixed beforehand.

Table 1. Composition for geopolymer mortar samples, wt%.

Sample	Precursor (P), wt%			AA/P ratio	Sand/P ratio
	CBW	MKW	PG		
S1 1:2	47.5	47.5	5	0.55	2
S1 1:1	47.5	47.5	5	0.55	1
S1 2:1	47.5	47.5	5	0.55	0.5
S2 1:2	22.5	72.5	5	0.65	2
S2 1:1	22.5	72.5	5	0.65	1
S2 2:1	22.5	72.5	5	0.65	0.5
S3 1:2	0.0	95.0	5	0.75	2
S3 1:1	0.0	95.0	5	0.75	1
S3 2:1	0.0	95.0	5	0.75	0.5

2.2 Preparation, Curing, Heating, Cooling and Compressive Testing of Geopolymer Mortar Samples

The prepared geopolymer mortar was then cast into cubic molds ($40\text{ mm} \times 40\text{ mm} \times 40\text{ mm}$), compacted on a vibrating table, and covered with a film to prevent moisture loss (Fig. 1a).



Fig. 1. Comparison of geopolymer mortar prior to heating (a) and after thermal exposure at 900 °C (b).

Altogether, 36 geopolymer samples were prepared. Each value represents the mean of three samples $\pm$ standard deviation. The samples were cured for 24 h under ambient conditions (20 ± 2 °C, 45% RH) removed from molds, and subsequently oven cured at 60 °C for 24 h to enhance early strength. Further curing continued for 3, 7, and 14 days, after which compressive tests were performed for geopolymer samples. The high-temperature regime was applied using a constant heating rate method, increasing the temperature at 5 °C/min up to 900 °C. The target temperature was held for 2 h. After heating, nine samples were allowed to cool naturally inside the furnace, and the residual compressive strength was subsequently determined.

Scanning electron micrograph (SEM) images were taken and prepared to illustrate the microstructure and, thus, to evaluate the performance of geopolymer mortar in elevated temperature (900 °C) conditions.

3 Results and Discussion

3.1 Compressive Strength of Geopolymer Mortar

The compressive strengths of geopolymer samples of three precursor ratios (1/2; 1/1, 2/1) times three binder to aggregate ratios (CBW/MKW) were compared at the age of 3, 7 and 14 days (Fig. 2). After 3 days, the geopolymer mortar typically reached a significant initial compressive strength (38.5 MPa on average, ranging from 26.0 to 43.1 MPa), as alkaline activation reactions proceeded intensively and N–A–S–H gel formed rapidly. At this stage, most of the early binding products that determine the structure of the matrix were generated. After 7 days, the compressive strength (39.1 MPa on average, ranging from 28.8 to 45.3 MPa) continued to increase as the reaction products became denser, the porosity of the samples decreased, and the gel matrix stabilized. By this time, geopolymers usually achieve about 70–85% of their final strength. After 14 days, the compressive strength increased further (59.1 MPa on average, ranging from 32.9 to 60.4 MPa), although in some precursor and binder to aggregate ratios the reactions approached equilibrium as the microstructure became denser and more consolidated. At this point, the geopolymer mortar typically reached a nearly stable (final) strength, which, however, could be verified at the age of 28 days.

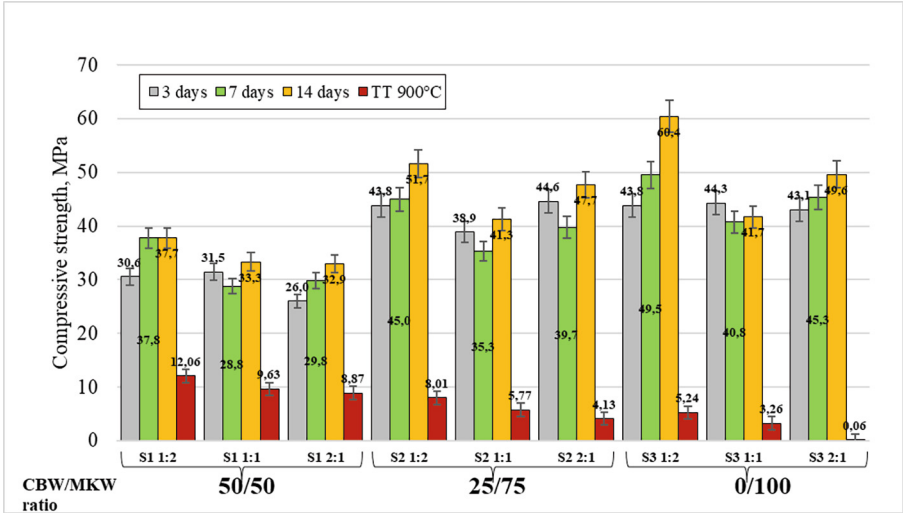


Fig. 2. Compressive strength of geopolymer mortar samples prior to and following an exposure to 900 °C. The sample types are listed in Table 1.

3.2 Residual Compressive Strength of Geopolymer Mortar at Elevated Temperature

To evaluate the effect of high temperature, compressive strength values before and after thermal treatment were compared. Figure 2 shows a pronounced reduction in compressive strength after exposure to 900 °C. The initial samples exhibited higher strength due to a continuous gel matrix, but high temperature caused microstructural degradation, increased porosity, and the formation of microcracks, resulting in a significant loss of residual strength. This confirms that extreme heating critically affects the structural integrity of the geopolymer binder. The optimal mixture was the one that achieved the highest compressive strength before heating and retained the greatest residual strength after exposure to 900 °C, meaning it experienced the smallest loss of mechanical properties. The optimal mixture was the one that maintained both mechanical strength and structural integrity after exposure to 900 °C. While the S3 mixtures developed the highest early compressive strength due to their high metakaolin content, their dense and brittle matrix led to severe cracking after thermal treatment (Fig. 1b). In contrast, the S2 series—combining MKW with CBW - showed significantly better thermal stability. Among them, the S2 1:1 composition provided the most balanced performance: it achieved sufficient initial strength and retained the highest residual strength without structural failure after heating. This indicates that the combination of MKW and CBW, together with a moderate sand-to-precursor ratio, produced a geopolymer matrix capable of withstanding extreme thermal stress more effectively than the other tested formulations.

3.3 Impact of Elevated Temperature on the Microstructure of Geopolymer Mortar

SEM images in Fig. 3 illustrate the microstructural evolution of the S2 1:1 geopolymer mortar before and after exposure to 900 °C, highlighting the changes responsible for its mechanical behavior. In the unheated state (Fig. 3a), the mortar matrix appears dense and well-consolidated, with a continuous N–A–S–H gel phase binding the precursor particles and filling the pore spaces. The microstructure shows limited cracking and a uniform distribution of reaction products, which corresponds to the good initial compressive strength observed for this mortar.

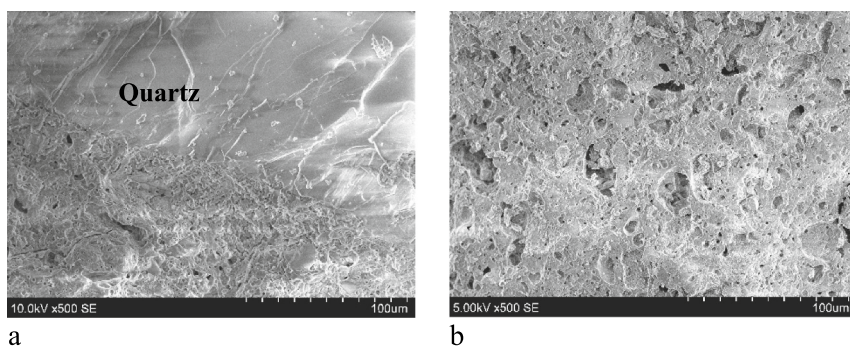


Fig. 3. SEM images of S2 1:1 geopolymer mortar prior to (a) and following exposure to 900 °C (b).

After thermal exposure (Fig. 3b), noticeable microstructural degradation becomes evident: microcracks propagate throughout the matrix, the gel phase shows signs of shrinkage and partial decomposition, and the overall structure becomes more porous. Despite these changes, the S2 1:1 sample retains a more coherent matrix compared with other formulations, indicating that the combined CBW–MKW precursor system provides improved thermal stability. This microstructural resilience explains why S2 1:1 maintained the highest residual strength after heating and was identified as the most thermally resistant mixture in the study. From CE angle, the use of CBW–MKW in geopolymer binders can be interpreted as a form of industrial symbiosis, where waste streams from one process are utilized as inputs for another [14]. In the Baltic States, collaboration between demolition companies, waste sorting facilities and construction material producers could facilitate the recovery and valorization of mineral waste streams, support local resilience and regional supply chains, while reducing landfill disposal and the demand for virgin resources.

4 Conclusions

The study demonstrated that CBW–MKW–PG–based geopolymers can be successfully produced using industrial waste precursors and that their mechanical and thermal performance strongly depends on the precursor ratio and aggregate content. All mixtures

developed substantial early strength due to rapid N–A–S–H gel formation, reaching near final strength within 14 days. However, exposure to 900 °C caused significant degradation of the gel matrix, increased porosity, and microcracking, resulting in a notable reduction in compressive strength. Among the tested formulations, the S3 mixtures, despite their high initial strength, exhibited severe cracking after heating due to their dense and brittle MKW rich matrix. In contrast, the S2 series, which combined MKW with CBW, showed markedly better thermal stability. The S2 1:1 composition proved to be the most resilient, retaining the highest residual strength and preserving a more coherent microstructure after heating. These findings indicate that incorporating both crystalline CBW and amorphous MKW, together with a balanced sand to precursor ratio, enhances the thermal resistance of geopolymer mortar. Overall, the results highlight the potential of CBW–MKW-based geopolymers as sustainable, thermally stable construction materials and underscore the importance of precursor synergy in optimizing high-temperature performance. The results of this research highlight that CBW–MKW can serve as promising precursors for geopolymer binders, contributing to more circular material use in the construction sector. From a circular economic perspective, the valorization of such mineral waste streams could be further supported through industrial symbiosis between demolition companies, waste sorting facilities and construction material manufacturers. However, wider implementation in the Baltic States may be constrained by limited economic incentives and fragmented institutional coordination. Policy instruments such as green public procurement, improved material traceability and the development of technical standards for secondary construction materials could help accelerate the transition toward circular construction systems in the region.

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