Open Access
Original paper

Budownictwo i Architektura / Civil and Architectural Engineering 25(2) (2026) 26017
https://doi.org/10.35784/bud-arch.8286

Performance evaluation of mortars incorporating recycled ceramic powder and low-density polyethylene: An experimental study

Houssam Eddine Abdelli[1,*], Salim Kennouche[2], Fatma Elif Genceli Güner[3], José Luís Barroso de Aguiar[4], Mariaenrica Frigione[5], Abdelhamid Karouche[6], El Mouatez Billah Boudjellal[7], Ilyas Hafhouf[8]

[1] *Department of Civil Engineering; Faculty of Technology; Setif 1 University - Ferhat Abbas; 19000 Setif, Algeria; houssameddine63@yahoo.fr*
[2] *Department of Civil Engineering; Faculty of Sciences and Applied Sciences; University of Bouira; 10000 Bouira, Algeria; kennouchesalim@gmail.com*
[3] *Department of Chemical Engineering; Istanbul Technical University; 34469 Istanbul, Turkey; gencelie@itu.edu.tr*
[4] *Department of Civil Engineering; Centre for Territory, Environment and Construction (CTAC); University of Minho; 4800-058 Guimarães, Portugal; aguiar@civil.uminho.pt*
[5] *Department of Innovation Engineering; University of Salento; 73100 Lecce, Italy; mariaenrica.frigione@unisalento.it*
[6] *Department of Civil Engineering; Faculty of Technology; Setif 1 University - Ferhat Abbas; 19000 Setif, Algeria; ka260374@yahoo.fr*
[7] *Department of Civil Engineering; Faculty of Technology; Setif 1 University - Ferhat Abbas; 19000 Setif, Algeria; mouatez.boudjellal@gmail.com*
[8] *Department of Civil Engineering; Faculty of Technology; Setif 1 University - Ferhat Abbas; 19000 Setif, Algeria; ilyas.hafhouf@gmail.com*

[*] *Corresponding Author*
Received: 26.08.2025; Revised: 04.12.2025; Accepted: 09.12.2025; Available online: 26.06.2026

Abstract:
In the efforts for eco-friendly and affordable substitutes, the construction industry uses recycled waste materials like ceramics and plastic, which can be used as reinforcement filler to address environmental problems from composites. This study is focused on evaluating the feasibility of industrial by-products for improving the properties of mortar using ceramic and plastic waste as partial replacements for cement and sand. The effect of using two wastes on density, compressive and flexural strength, water absorption, ultrasonic pulse velocity and high temperature behavior of mortar were evaluated for the different mortar mixes, as well as characterization analyses, were performed using X-ray diffraction (XRD), thermogravimetric analysis (TGA/DSC), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM). The findings prove that the heat-insulating capacity of mortar at high temperatures can be significantly increased through a waste ceramic application. Furthermore, the pozzolanic reactivity of the ceramic waste was detected by decreases in portlandite content and variations in hydration products, thermal phases, and mineral phases of the studied mortar, as observed using XRD, TGA/DSC, and FTIR measurements. It was also shown that plastic waste added to ceramic waste can effectively minimise capillary water absorption. This work provides applicable technical and environmental benefits for creating sustainable mortar using this waste.

Keywords:
mortar; recycled materials; ceramic powder; low-density polyethylene; waste management

1. Introduction

Ceramic materials are widely produced for various applications, such as tiling, sanitary ware, and thermal insulation, due to their unique characteristics, including high hardness, scratch resistance, and high chemical and thermal resistance [1]. They are made from raw materials such as clay, feldspar, and quartz, which are ground, mixed with water, formed into shapes, pressed or thrown, dried, and fired. Ceramic materials are widely used as the material of choice for wall and floor tiles in the building sector [2]. However, the ceramics industry is increasingly facing the challenge of managing the large volume of ceramic waste generated daily. Crushed ceramics are an effective solution for reducing waste, energy consumption, and production costs in the production of new building materials. This approach is ecologically friendly and economically favourable while maintaining or even enhancing material performance [3]. Several studies have investigated the use of ceramic waste as a partial substitute for cement in mortar mixes. As per Samadi et al. [4], cement replacement with ceramic waste significantly improved the long-term durability and sulphate resistance of the mortar. Mezidi et al. [5] studied the performance properties of mortars with 5%, 10%, 15%, and 20% utilisation of ceramic waste powder (CWP) and found that increased substitution led to reduced compressive strength and UPV. Hilal et al. [6] conducted tests on a mortar subjected to heat utilising CWP at 20%, 40%, and 60%, and noted that both increased substitution levels and increased fineness of the ceramic material reduced workability. The large surface area and water absorption capacity of the finely milled ceramics caused this decrease. Kannan et al. [7] investigated the application of CWP in high-performance concrete and demonstrated that it had no significant effect on cement hydration.

Ghonaim and Morsy [8] also discovered that the substitution of 10% cement with ceramic dust achieved the minimum water absorption owing to the pozzolanic and filler effects of the ultrafine ceramic particles. The plastic material is a mixture of binders, fillers, pigments, plasticisers, and additives, and is classified as thermoplastic or thermoset depending on its chemical and physical characteristics. For thermoplastics, the chain segments can be reversed many times; however, for thermosets, a mediated chemical reaction that forms a 3D network occurs once the thermo-formed products are heated [9]. Plastic waste generation, especially from single-use items, is now an urgent environmental issue, particularly in densely populated urban areas [10]. Several studies have investigated the feasibility of plastic waste as a substitute for natural aggregate in construction materials. Safi et al. [11] tested polyethene terephthalate (PET) waste, commonly used in bag manufacturing, as a fine aggregate in self-compacting mortars at replacement percentages ranging from 10% to 50%. The findings indicated that the compressive strength of the light mortars was maintained within the tolerable limits, with a bulk density of 1.5 kg/m³ at 28 days. Hannawi and Agbodjan [12] discussed that the substitution of sand by polycarbonate waste improved the mortar's workability owing to the smooth and rounded morphology of the plastic particles. It also had less water absorption than silica sand. Similarly, Badache et al. [13] observed an enhancement in ductility and a significant decrease of 73% in the dynamic modulus of elasticity of HDPE waste mortars. Aciu et al. [14] discovered that polyvinyl chloride (PVC) waste enhances the thermal insulation characteristics of mortars, thereby minimising heat transfer within the material. Suwansaard et al. [15] concluded that the incorporation of polystyrene (PS) waste into mortars resulted in water absorption values comparable to control mixtures composed of just sand but were considerably lower than those obtained in compositions with HDPE. As per the literature, this study adopts the following parameters: replacement of cement by 10% and 20% ceramic waste (particle size < 80 µm) and replacement of sand by 10% and 20% plastic waste (particle size < 4 mm). This study conforms to social, environmental, economic, and technological concerns regarding the conversion of industrial waste into value-added materials while improving the performance of building materials. The incorporation of waste into mortar design is consistent with the spirit of the circular economy and sustainable construction. This study demonstrates the mechanical and environmental benefits of using waste materials, helping to create more sustainable mortar mixes in line with current construction communities and sustainability requirements. This study is important for examining the effect of materials containing industrial waste on mortar performance by mixing cement with ceramic waste and replacing sand with plastic waste. These research studies aim to contribute to responsible production and consumption by reducing waste in the environment, greenhouse gas emissions, and the use of natural resources in construction, which currently do not take these clean production practices into account.

2. Materials and methods

2.1. Materials

The cement used in the present study was CEM II/B-L 42.5 R, conforming to Algerian standard NA 442-2013 [16] and European standard EN 197-1 [17]. The physical properties and chemical composition of the cement are presented in Table 1. The sand used in this study was crushed to a maximum size of 4 mm at a quarry in Setif city, with a density of 2630 kg/m³. Figure 1 shows the sand particle size distribution. Ceramic waste powder with a particle size of less than 80 µm was used as a cement replacement at 10% and 20%. The FTIR spectrum of the ceramic waste (see Fig. 2) reveals the presence of absorption bands that are most characteristic in the region of about 1000 to 1100 cm^{-1}, corresponding to asymmetric elongation vibrations of Si-O bonds in silicate (SiO_4) networks [18]. Other bands at lower frequencies are attributed to bending vibrations of Si-O bonds. The presence of quartz, a frequent component of ceramics, can be identified by specific bands, notably around 780-800 cm^{-1}. Bands in the high-frequency region (3400-3600 cm^{-1}) can also appear, indicating the presence of hydroxyl groups (-OH), either from adsorbed water or residual groups from the original clay minerals [19]. Low-density polyethene (LDPE) waste plastic was also incorporated into the mortar mixes as a partial sand replacement at the same percentages of 10% and 20%. Figure 3 shows the X-ray diffraction (XRD) patterns of the ceramic powder and cement. The spectra indicate the presence of crystalline clinker phases in the cement, such as C3S, C2S, and C3A, as well as of calcite and gypsum. High-intensity quartz peaks were observed in the ceramic powder, indicating its principal mineralogical composition.

Table 1. The physical properties and chemical analysis of cement. Source: own study

Properties	Value
Normal consistency (%)	26.5 ± 2
Blaine fineness (cm^2/g)	3700 - 5200
Withdrawal at 28 days (µm/m)	< 1000
Expansion (mm)	≤ 3
Loss of ignition (%)	10 ± 2
Sulfate content SO_3 (%)	2.5 ± 0.5
Magnesium oxide content (%)	Max 5%
Chloride content (%)	< 0.1

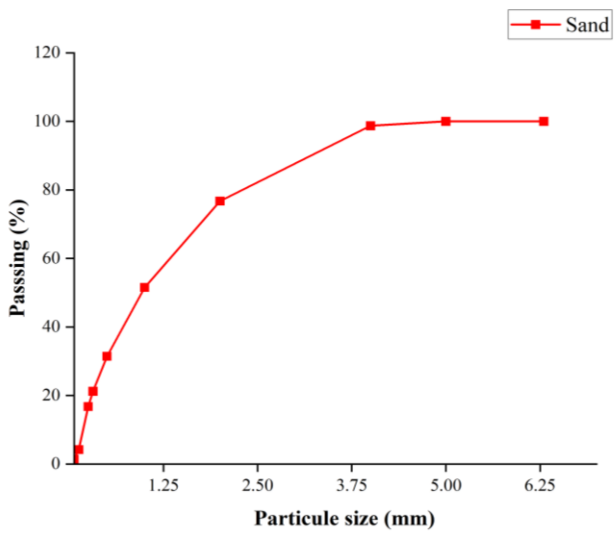

Fig. 1. Particle size analysis of sand. Source: own study

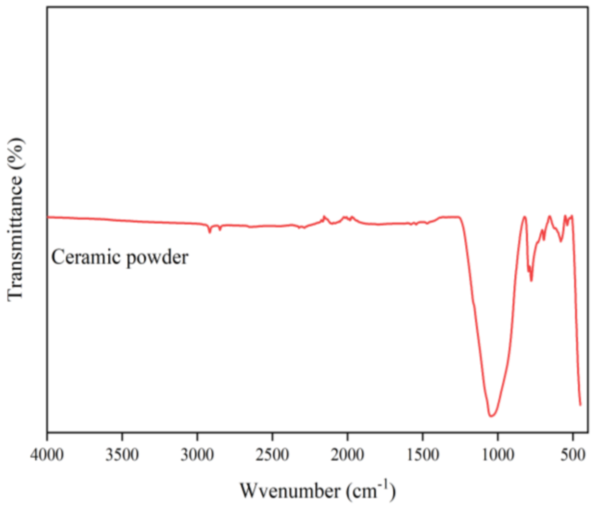

Fig. 2. FTIR spectra for ceramic powder. Source: own study

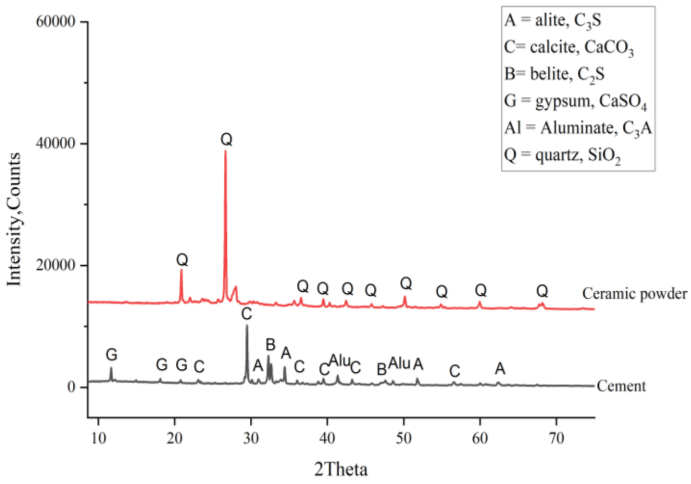

Fig. 3. XRD patterns for cement and ceramic waste. Source: own study

2.2. Mix proposition

Mortar mixes were prepared following EN 196-1 [20], with a composition ratio of three samples comprising (450 ± 2) g cement) (1350 ± 5) g sand, and (225 ± 1) g water for the reference mortar (N). Two mixes were prepared incorporating 10% and 20% ceramic waste powders (designated C10 and C20, respectively). Two other mixes were prepared by partially replacing sand with plastic waste at the same rates of 10% and 20% (P10 and P20). Finally, two mixtures combining both types of waste in the same proportions were produced, designated as M10 and M20. Table 2 outlines the detailed composition of all mortar mixtures used in this study.

Table 2. The composition of mortar mixtures. Source: own study

Mortar mix	Cement	Sand	Water	CWP	LDPE	W/C
	(g)	(g)	(g)	(g)	(g)	
N	450	1350	225	/	/	0.5
C10	405	1350	225	45	/	0.5
C20	360	1350	225	90	/	0.5
P10	450	1215	225	/	135	0.5
P20	450	1080	225	/	270	0.5
M10	405	1215	225	45	135	0.5
M20	360	1080	225	90	270	0.5

2.3. Methods

2.3.1. The XRD, DSC-TGA, FTIR and SEM analysis

The XRD, DSC-TGA, and FTIR samples were sieved and ground to a particle size of less than 63 µm. Thermal analysis DSC-TGA was performed with an SDT Q600 V20.9 Build 20 instrument from 17ºC to 900ºC at 10ºC/min heating rate in a nitrogen environment at a purge flow of 100 mL/min. XRD was scanned from 8° to 75° (2θ) at 0.02°/s. FTIR spectra were recorded at room temperature between 450 cm^{-1} and 4000 cm^{-1} of wavelength. SEM was performed on all the variants of interest.

2.3.2. Measurement of density in hardened mortar

The dry bulk density of the hardened mortar was determined in accordance with EN 1015-10 [21]. Three prismatic samples were prepared and subjected to specific curing conditions. The volume was determined according to Archimedes' principle, and the dry bulk density was calculated as the dry mass-to-sample volume ratio. The results are presented as the average of three measurements, rounded to the nearest 10 kg/m^3.

2.3.3. Compressive and flexural strengths test

The moulds were demolded after 24 hours, and the specimens were stored in water at 20°C ± 2°C until fracture testing. The flexural strength and axial compressive strength, following EN 196-1 [20], were measured on 40 × 40 × 160 mm^3 prismatic specimens at 7, 14, and 28 days of age (see Fig. 4). The results for all mixtures are the average of three tests.

Fig. 4. Flexural and compressive strengths testing. Source: own study

2.3.4. Ultrasonic propagation velocity test

The ultrasonic propagation velocity was calibrated for different mortar types after 28 days of hardening under EN 12504-4 [22] (see Fig. 5). This methodology encompasses the quantification of the duration required for a waveform to traverse a specified distance.

Fig. 5. Ultrasonic pulse velocity testing. Source: own study

2.3.5. Water absorption by capillarity test

The water absorption by capillarity test was performed in accordance with standard EN 1015-18 [23] on prismatic test specimens measuring 40 × 40 × 160 mm³ after 28 days of hardening. Several measurements were taken over a period of 72 hours to determine the amount of water absorbed by the different mortar formulations, with three samples per mortar type.

2.3.6. Effect of high temperatures test

To remove residual moisture, the samples were placed in an electric oven at 105°C ± 5°C for 24 hours. The samples were then heated at a constant rate of 10°C/min to temperatures of 150°C, 300°C, and 450°C, and held for 2 hours. Finally, the samples were cooled to room temperature in a closed oven according to the method of Arioz [24] (see Fig. 6). Compressive and flexural strength tests were then conducted, and mass loss was determined.

Fig. 6. Test of the effect of temperature on mortar mixes. Source: own study

3. Results and discussion

3.1. X-ray powder diffraction (XRD) analysis

Figure 7 shows the mineral characterisation of mortar mixtures, indicating that their main components are calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), portlandite ($Ca(OH)_2$) and quartz (SiO_2). In the control mortar (N), calcite appears as the main phase at 29 (2θ), dolomite at 31 (2θ), and portlandite mainly at 18 (2θ) and 34 (2θ). Gypsum is also identified at 12 (2θ). Quartz phase peaks were observed in the C10 and C20 mortar mixes. This is due to the presence of silica in the ceramic waste found in these mixtures. The Portlandite intensity in C20 is lower than that in the N control mortar, which can be explained by the consumption of Portlandite during the pozzolanic reaction, which reacts with silica from ceramic waste in the presence of water to form calcium silicate hydrate (CSH) [25].

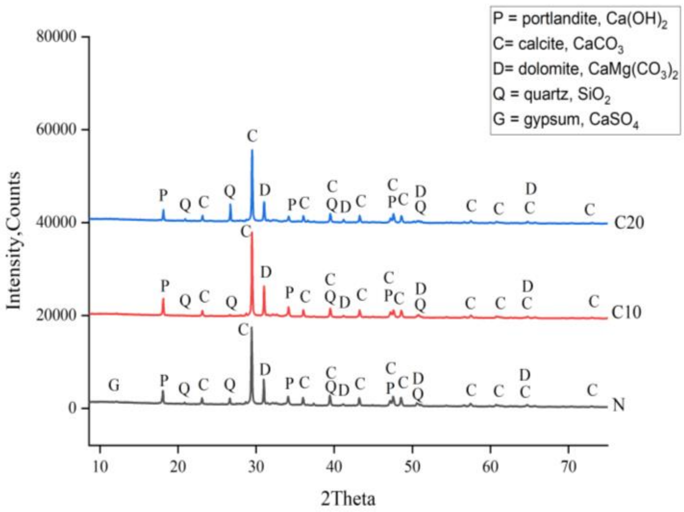

Fig. 7. X-ray diffraction analysis for N and C10, C20 mortar after 28 days of curing. Source: own study

3.2. DSC-TGA analysis

Thermogravimetric analysis (TGA) and its derivative (DSC) for the reference mortar are presented in Fig. 8. Three main mass loss regions corresponding to endothermic decomposition events are identified. The first weight loss (1.65%) occurs between 100 °C and 200 °C and is attributed to the evaporation of physically adsorbed water and interlayer water from C-S-H gel and ettringite, both typical products of cement hydration [26,27]. This phase is confirmed by a small peak on the DTG curve (blue) and a slight endothermic signal on the heat flux curve (black). The mass loss in this region remains nearly unchanged in the C10 and C20 mixtures, indicating that the ceramic powder has little to no effect on the initial water loss. The second mass loss (3.31%), observed around 400°C–500°C, corresponds to the dehydroxylation of portlandite ($CaOH_2$) [28]. As shown in Fig. 9 and Fig. 10, the replacement of cement with ceramic powder leads to a decrease in portlandite content, which can be attributed to the dilution effect of cement in mortars, where a portion of the cement is exchanged by ceramic powder. The less cement, the less amount of $CaOH_2$ in the sample. The third and most significant mass loss (23.16%) occurs between 700 °C and 750 °C and is associated with the decarbonation of calcium carbonate ($CaCO_3$), originating either from limestone aggregates or the carbonation of hydration products over time [29,30]. This process is highly endothermic. The reduction in mass loss in this region with increasing ceramic content may be explained by several factors: the initial presence of calcareous filler in the cement, the lower availability of phases prone to carbonation due to partial cement replacement, or the fact that ceramic powder contributes less to carbonate formation than the substituted cement.

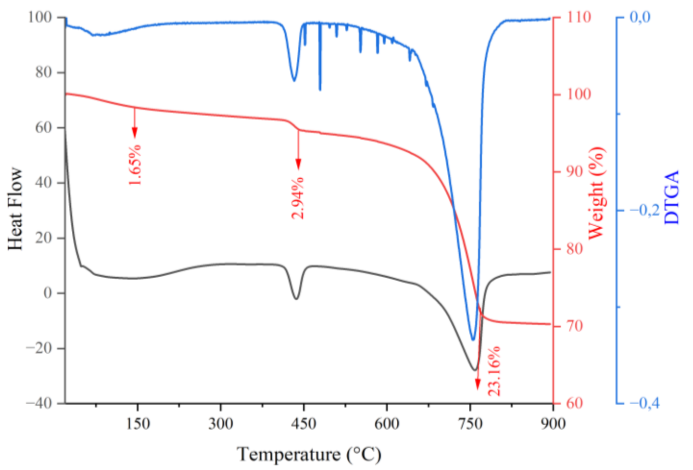

Fig. 8. TGA and DSC Curves of mortar normal (N). Source: own study

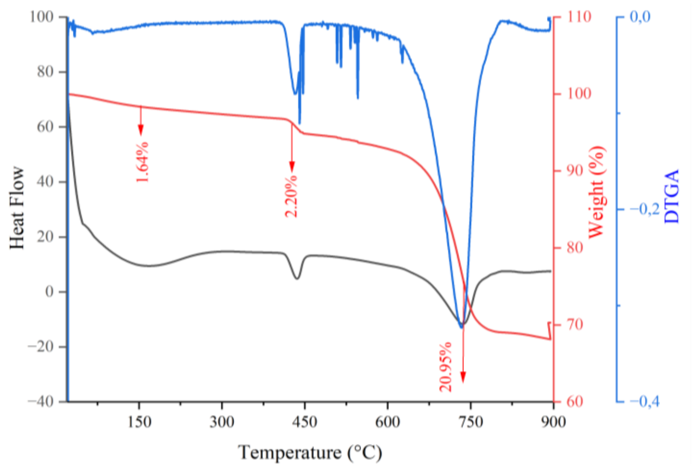

Fig. 9. TGA and DSC Curves of mortar with 10% of ceramic waste (C10). Source: own study

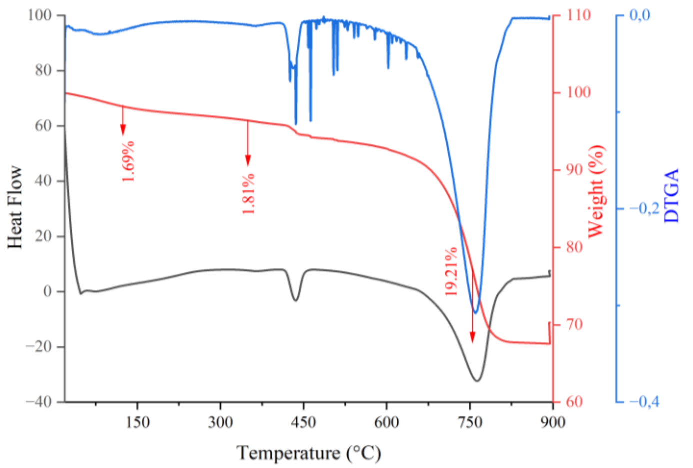

Fig. 10. TGA and DSC Curves of mortar with 20% of ceramic waste (C20). Source: own study

3.3. Fourier transform infrared (FTIR) spectroscopy

In FTIR, a single spectrum can be used to identify the chemical compounds in a sample. Each functional group of the compound absorbs specific frequencies as infrared light passes through the sample, producing a unique spectral pattern – a molecular fingerprint. The infrared spectrum is typically divided into three regions: Near, mid, and far infrared [31]. The FTIR spectra of the reference mortar (N), mortar containing 10% (C10) and 20% (C20) ceramic waste as partial cement replacements are shown in Fig. 11. The broad absorption bands at around 3400–3500 cm^{-1} in each spectrum are attributed to the stretching vibrations of hydroxyl (-OH) groups, inherent in absorbed water and calcium hydroxide, known as portlandite ($Ca(OH)_2$) [32]. An obvious peak appeared at 3640 cm^{-1} due to stretching vibrations of $Ca(OH)_2$ [33]. The intensity of this peak decreases considerably between mortars N, C10, and C20, indicating a gradual consumption of $Ca(OH)_2$ as the ceramic waste content increases [34]. This trend indicates that pozzolanic reactions are taking place, in which ceramic waste reacts with $Ca(OH)_2$, leading to the formation of more hydration products such as C-S-H gels or C-A-S-H [35]. All samples present an absorption band at around 1650 cm^{-1} that is attributed to the bending vibration of the adsorbed water molecules [36]. The strong peaks at around 1400–1500 cm^{-1} and around 870 cm^{-1} are attributed to asymmetric stretching and out-of-plane bending vibrations of carbonate groups (CO_3^{-2}) [37]. All the mortar samples for which carbonation has been confirmed had it using [38]. The 870 cm^{-1} peak is, however, somewhat depleted in C10 and C20, indicating minor differences in carbonation, although the intensity of the 1400–1500 cm^{-1} band is similar in all the spectra. The strongest band in all samples appears in the 900–1100 cm^{-1} region, attributed to the Si–O stretching bands of the silicate structures, mainly of C-S-H gel – the main hydration product of cement setting [39,40]. Any differences in the profile of this band or minor shifts of it towards lower wavenumbers between the N, C10, and C20 samples could indicate modifications in the silicate network and/or in its polymerisation degree. These transformations most likely originated from the addition of Al and Si from ceramic waste, which have a high potential to react with hydration products such as the C-(A)-S-H gel [41]. Finally, all peaks below 800 cm^{-1} are assigned to Si-O bending vibrations and metal–oxygen bonds of cement phases and added ceramic waste components. These comprise phases: quartz and mullite originated from the ceramic waste [42]. The identified deviations in this spectral region endorse the change in the mineralogical composition of mortars resulting from the addition of ceramic waste.

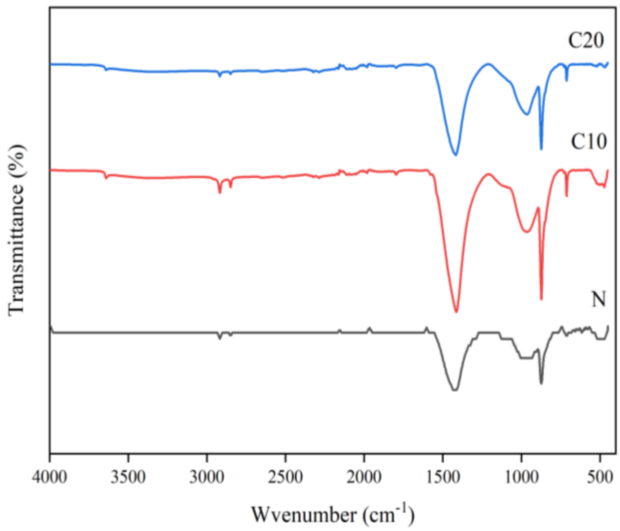

Fig. 11. FTIR spectra for samples N, C10, and C20. Source: own study

3.4. Density evaluation of hardened mortar

Figure 12 shows the density results after 28 days. The C10 mixture density was slightly higher than that of the control mortar. This is due to the use of ceramic powder as a filler that minimises porosity by filling the matrix voids. In contrast, the lower density observed when the mixtures contained waste plastic is because the density of plastic is lower than that of sand [43,44].

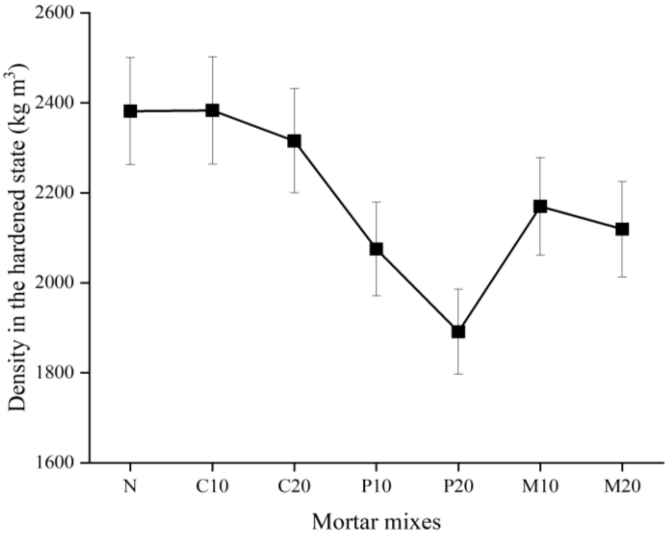

Fig. 12. Density of hardened mortar mixes at 28 days. Source: own study

3.5. Compressive strength

Figure 13 shows the compressive strength results after 28 days. A noticeable reduction in strength was observed in the plastic waste mixtures. This decline is primarily attributed to the weak interfacial bonding between the plastic particles and the cement paste, as well as the high deformability of the plastic particles, which promotes the formation of cracks and air voids [45]. Similar findings were reported by Da Silva et al. [46]. The compressive strengths of the C10 and C20 mixes reached approximately 84% and 81%, respectively, of the control mortar's strength at 28 days. This decrease may be due to the delayed pozzolanic activity of the ceramic waste at this early age. In contrast, the greater reduction in strength observed in the M10 and M20 mixes can be attributed to the lower reactivity and inferior contribution of plastic waste compared to ceramic waste.

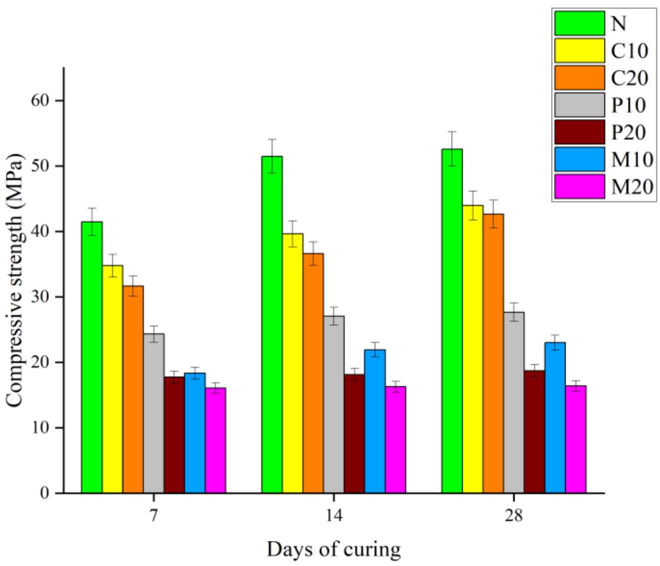

Fig. 13. Evolution of compressive strength of various mortar mixes at 7, 14, and 28 days. Source: own study

3.6. Flexural strength

Figure 14 shows the evolution of the mortar mixes' flexural strength over a given period. After 28 days, mixture C20 exhibited a flexural strength 6.10% higher than that of the control mortar. This was due to the increased pozzolanic activity of the ceramic waste, resulting in improved adhesion and densification of the matrix [47]. Li et al. [48] obtained similar results. Conversely, the incorporation of plastic waste into the mixes showed a decrease in flexural strength, which is attributed to the lack of interfacial adhesion between the plastic waste and the cement matrix [49]. The results are corroborated by the findings of Ruiz-Herrero et al. [50]. Interestingly, the M10 mix was more resistant to flexural strength than the other plastic-containing formulations, which could be attributed to the higher contribution of ceramic powder compared to plastic waste for better mechanical performance.

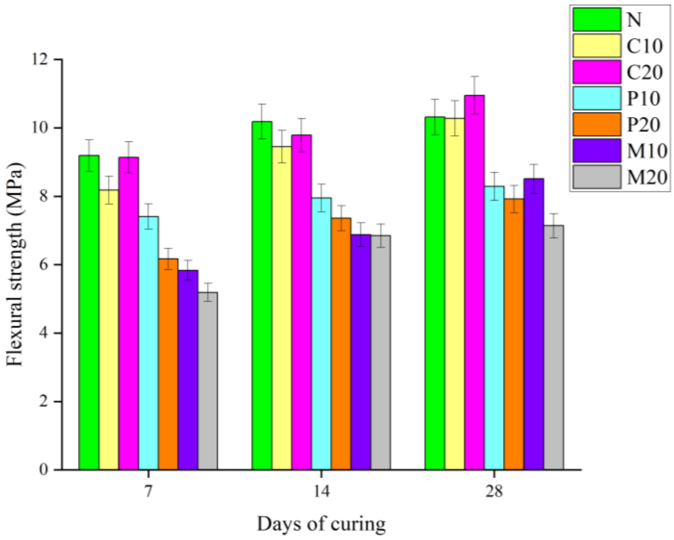

Fig. 14. Flexural strength development of mortar mixtures at 7, 14, and 28 days of curing. Source: own study

3.7. Ultrasonic pulse velocity

Ultrasonic pulse velocity (UPV) testing is a non-destructive, rapid method for evaluating the quality of cementitious materials [51]. It provides valuable information on the uniformity and relative integrity of concrete, enabling the detection of cracks and voids and the estimation of crack depth [52]. Figure 15 presents the UPV results for the mortar specimens after 28 days of curing. A slight reduction in the pulse velocity was observed in the C10 and C20 mixtures. The UPV values of these mixes exceeded 3800 m/s, classifying them as excellent quality mortars, as shown in Table 3 [53]. This performance is attributed to the densification of the microstructure and reduced pore connectivity, likely resulting from enhanced pozzolanic activity [54]. However, a reduction in compactness and overall density can explain the decrease in pulse velocity in mixtures incorporating plastic waste, as illustrated in Fig. 12 [55]. These findings are consistent with previous research [56].

Table 3. Evaluate mortar quality using typical ultrasonic pulse velocity values. Source: [55]

Mortar Quality	Excellent	Good	Poor	Very Poor
UPV (m/s)	>3800	3800–3500	3500–3200	<3200

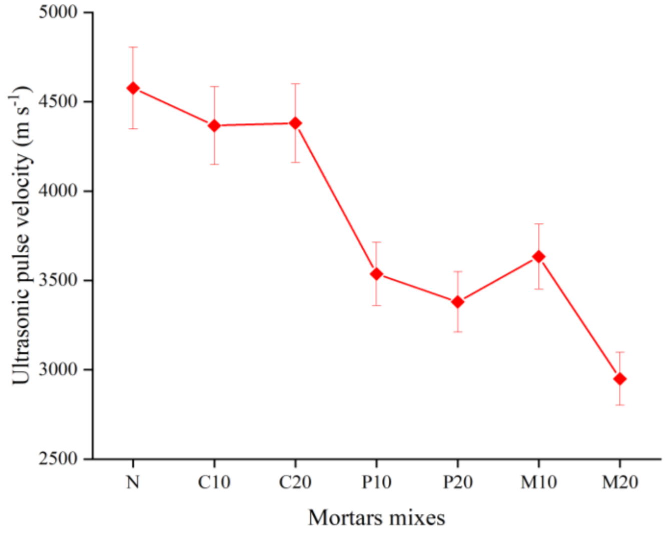

Fig. 15. Ultrasonic pulse velocity of various mortar mixtures after 28 days of curing. Source: own study

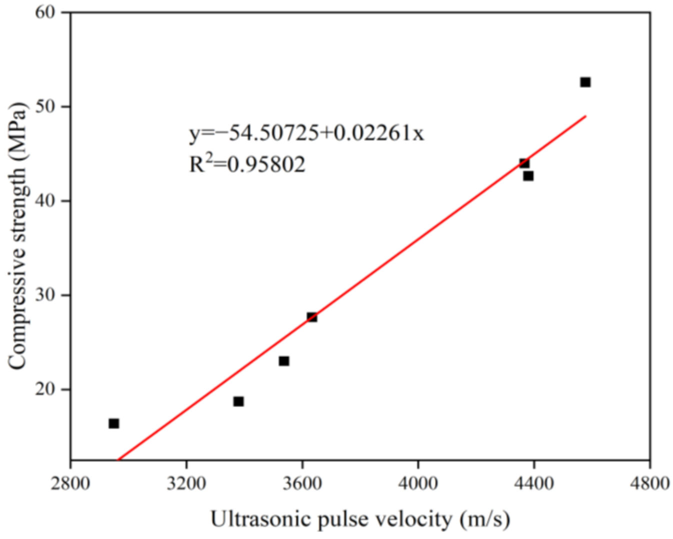

Fig. 16. Relationship between compressive strength and ultrasound velocity. Source: own study

3.8. Relationship between 28-day compressive strength and ultrasonic pulse velocity

Figure 16 shows the correlation curve established between the compressive strength of the crushing material and the corresponding ultrasonic velocities. The data points are very close to the linear regression line, demonstrating a strong correlation between the two. This is confirmed by the coefficient of determination, R^2 = 0.95802. An R^2 value near 1 (here 0.958) means that approximately 95.8% of the ultrasonic pulse velocity variance accounts for the compressive strength variance. This demonstrates an extremely strong and dependable relationship in the context of building materials. A linear regression line was fitted to the collected data points, expressed as y = -54.50725 + 0.02261x. This equation indicates that a linear model adequately explains the observed relationship across the entire range of values investigated. The graph illustrates a strong, positive linear correlation between the ultrasonic pulse velocity and the investigated mortar mixes' compressive strength. This supports the use of the ultrasonic method as a reliable measure of the mechanical strength of this material.

3.9. Water absorption by capillarity

Capillary water absorption is a key factor affecting the durability of cement-based materials, as it is strongly influenced by the pore structure [57]. The results of the capillary water absorption test are shown in Fig. 17. At the beginning of the test, all the mortar mixtures exhibited similar absorption behaviour. However, the C10 and C20 mixes demonstrated lower water absorption than the control mortar over time. This reduction can be attributed to a decrease in the average pore radius and the formation of calcium silicate hydrate (C-S-H) gels through pozzolanic reactions, which gradually fill the voids [58]. Similar findings were reported by Nayana and Rakesh [59]. The observed decrease in absorption in the P10 and P20 mixtures is due to the hydrophobic nature of the low-density polyethene (LDPE) particles, which resist water penetration and absorption. The M20 mixture exhibited the greatest reduction in water absorption, which can be attributed to the synergistic effect of combining plastic and ceramic waste powders, leading to improved pore refinement and reduced permeability.

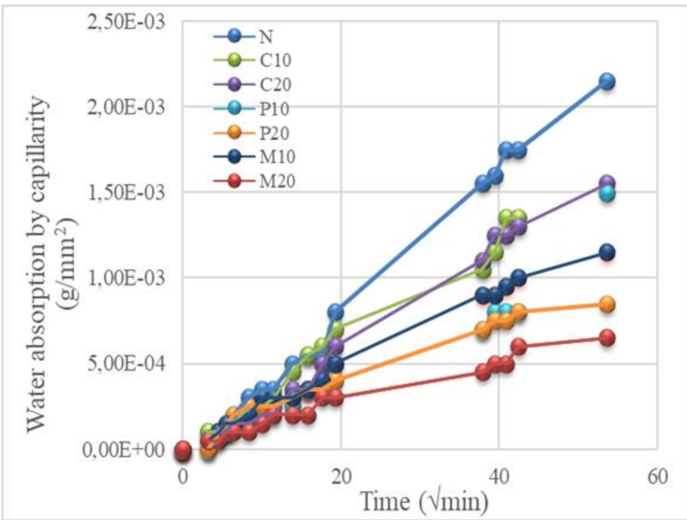

Fig. 17. Evolution of water absorption by capillary in different mortar mixes. Source: own study

3.10. The effect of high temperature on mortar mixes

3.10.1. Mass loss

The mass variations observed in the mortar samples are primarily attributed to the physical and chemical evaporation of water at elevated temperatures. Chemical water loss is particularly associated with the breakdown of hydrogen bonds within the mortar matrix [60]. Figure 18 presents the mass loss results for the mortar mixes subjected to temperatures of 150 °C, 200 °C, and 350 °C. At 350 °C, a reduction in mass loss was observed in the N, C20, and P20 mixtures. In contrast, the other mixtures exhibited increased mass loss with increasing temperature. In the P10 mix, the lowest mass loss was recorded at 150°C, while the highest mass loss was recorded at 350°C in the same mix. This is likely due to the plastic waste's thermal sensitivity, which melts at high temperatures, contributing to greater mass reduction. The mass loss up to 200 °C is primarily attributed to the evaporation of free water from the mortar samples [61]. Additionally, the decreased mass loss in the C10 and C20 mixes compared to the control mortar at 200 °C, by 27.44% and 16.16%, respectively, is associated with the pozzolanic activity of the ceramic powder, which consumes more water to form calcium silicate hydrate (CSH) [62].

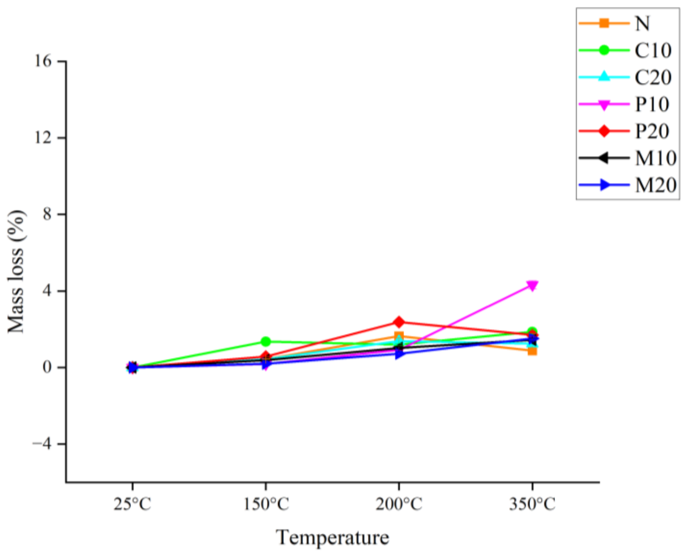

Fig. 18. Mass loss in mortar samples following thermal exposure at 150 °C, 200 °C, and 350 °C. Source: own study

3.10.2. Flexural strength

The results are shown in Fig. 19. Additionally, at 150 °C, an improvement in flexural strength was noticed in the C10 and C20 mortars compared with the control mortar by 77.55% and 65.91%, respectively. This improvement may be explained by the pozzolanic reaction between the ceramic powder and portlandite, with the production of CSH (calcium silicate hydrate), which densifies the mortar mass matrix, resulting in a higher cohesion between its elements. On the other hand, the drop in the strength of the blends with recycled plastic at 150°C, 200°C, and 350°C can be attributed to the melting and thermal degradation of the plastic, which leads to vacancies, an increase in total porosity, and the evaporation of water and CSH [63]. The reduction in flexural strength observed in the M10 and M20 mixes highlights the greater impact of plastic waste than ceramic waste in these mixes.

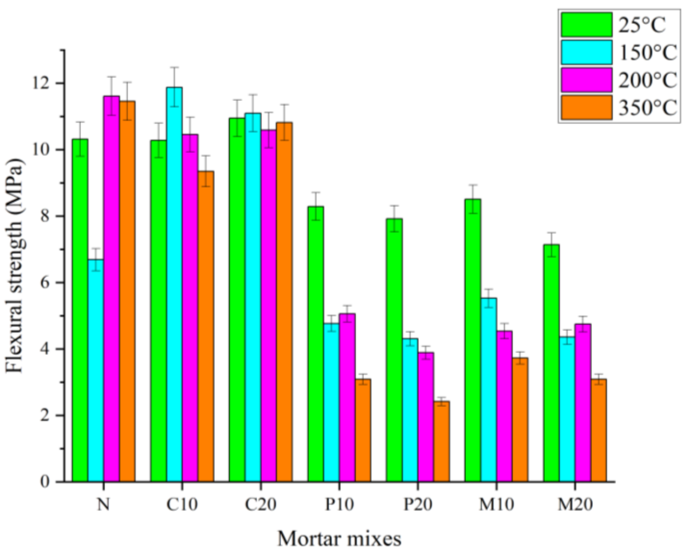

Fig. 19. Influence of elevated temperatures on the flexural strength of various mortar mixtures. Source: own study

3.10.3. Compressive strength

Figure 20 shows the results for the mortar mixes' compressive strength. At 150 °C, the C10 and C20 mixtures exhibited higher compressive strength than the control mortar by 7.26% and 3.73%, respectively. This improvement is attributed to the filler effect of the ceramic waste, which reduces the porosity, and to its pozzolanic activity, which promotes the formation of CSH. In contrast, mixtures incorporating plastic waste showed a reduction in the compressive strength at 150 °C, 200 °C, and 350 °C. This decline is mainly due to the weak bond between the plastic particles and the cement matrix, which is less effective than the natural adhesion between cement and sand [64]. The lower compressive strength observed in the M10 and M20 mixes also highlights the less favourable effect of plastic waste compared to ceramic waste under elevated temperature conditions.

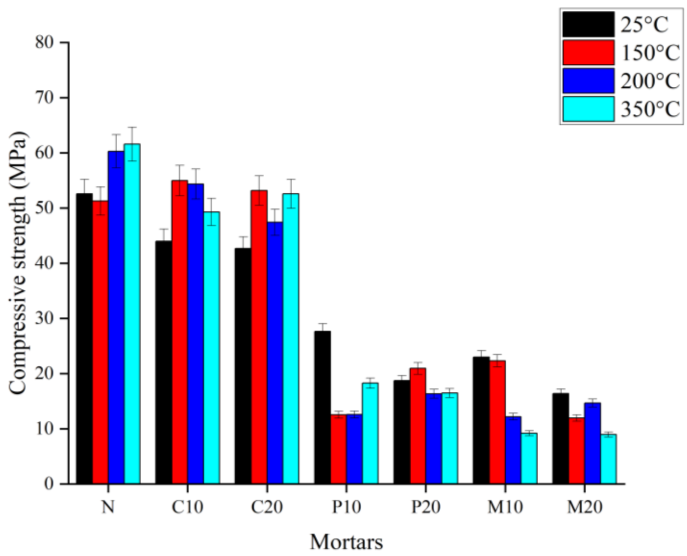

Fig. 20. Compressive strength of mortar mixes after exposure to high temperatures. Source: own study

3.11. Scanning electron microscopy (SEM) analysis

Figure 21 presents a scanning electron microscopy (SEM) micrograph of the control mortar without the ceramic waste. The microstructure is compact and dense in morphology, with the hydration products, i.e., calcium silicate hydrate (C–S–H) and perhaps portlandite crystals, being well dispersed finely. The occurrence of intergranular microcracks is likely due to thermal stresses or shrinkage effects. The absence of ceramic or plastic inclusions also reinforces the control mix homogeneity. Figure 22 shows that the mortar with 10% ceramic waste (C10) has a more irregular microstructure, and particles with angular and lamellar morphology are identifiable as the ceramic waste. These inclusions are partially embedded in the cement matrix, implying some, albeit noticeable, pozzolanic activity. The hydration products are well-formed, and the matrix is relatively dense. This is a sign that 10% replacement has good compactness and does not significantly hinder cement hydration. Figure 23 shows that the mortar containing 20% ceramic waste (C20) has a more porous and less regular microstructure. A reduction in the volume of the hydration products was observed, while the unreacted ceramic particles were far more pronounced. At this substitution level, the ceramic components are largely inert fillers, contributing to lower cohesion and higher porosity. Poorer microstructural quality leads to lower mechanical strength and long-term durability.

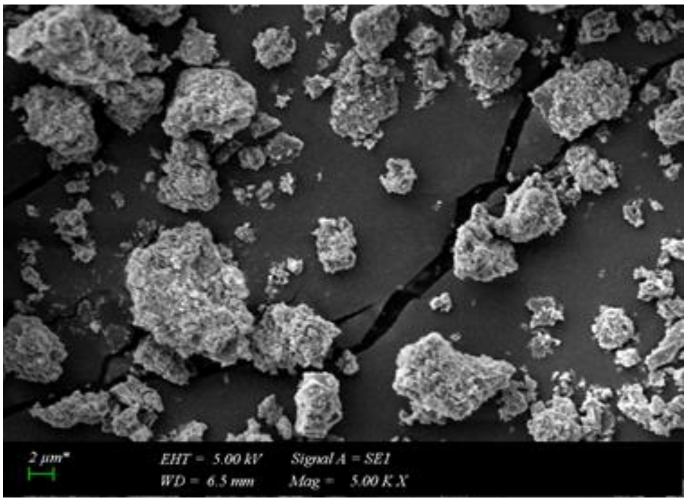

Fig. 21. Analysis SEM of the normal mortar. Source: own study

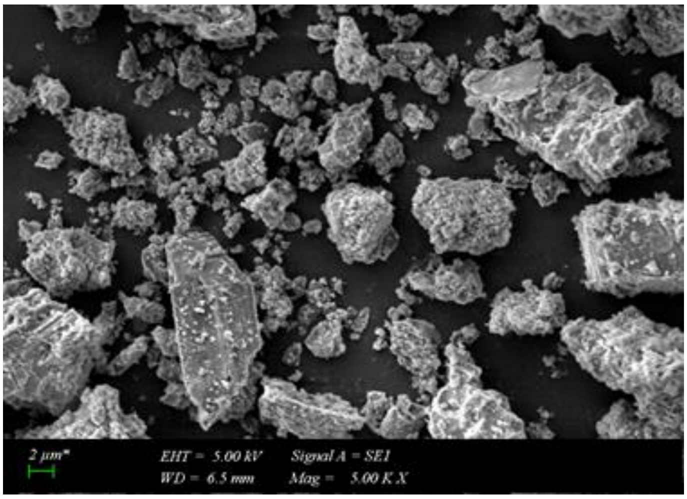

Fig. 22. Analysis SEM of the mortar C10 mix. Source: own study

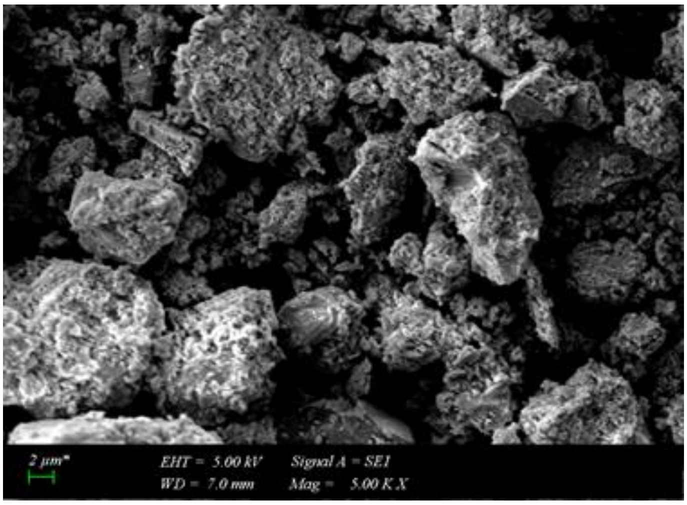

Fig. 23. Analysis SEM of the mortar C20 mix. Source: own study

4. Conclusions

This study examines the effects of incorporating ceramic and plastic waste on mortar performance. The following conclusions can be drawn:

- The XRD, TGA/DSC, and FTIR analyses clearly show the pozzolanic activity of ceramic waste, as evidenced by the decrease in portlandite, the presence of reactive phases, and the structural modification of the hydration products, which highlights its important role in the chemical and mineral development of the mortar.
- The variation in density observed after 28 days reflects the effect of substitute materials, where ceramic powder increases density by reducing porosity, whereas plastics decrease density due to their low density.
- The ceramic waste enhances both compressive and flexural strength after 28 days through its pozzolanic activity, while the plastic waste tends to weaken the mortar due to its low reactivity and poor adhesion; however, combining the two improves performance due to the effective influence of the ceramics.
- The ultrasonic wave propagation velocity results show that mixtures containing only ceramic waste are of good quality, with propagation velocities greater than 3800 m/s.
- The strong linear correlation observed between ultrasonic velocity and compressive strength confirms the reliability of the ultrasonic method as a non-destructive predictive tool for the mechanical performance of mortars.
- The incorporation of ceramic and plastic waste, especially when combined, significantly reduces capillary water absorption in mortar by improving pore structure and enhancing water penetration resistance, thereby improving its durability.
- Variations in mortar mass as a function of temperature reveal a significant influence of the nature of the additions, particularly the thermal sensitivity of waste plastics and the pozzolanic activity of ceramic powders, affecting water loss and the thermal stability of the mixes, respectively.
- The results indicate that ceramic waste improves both the flexural and compressive strength of mortar at high temperatures due to its pozzolanic and filling effects, whereas plastic waste has the opposite effect, leading to a decrease in strength due to thermal degradation and weak bonding with the cement matrix.
- SEM analysis showed that incorporating 10% ceramic waste resulted in a relatively dense and compact matrix, with advanced hydration products and no significant negative effects on mechanical performance.

The incorporation of recycled industrial waste – ceramics and plastics – serves as an effective partial replacement for conventional raw materials in mortar, with study results confirming concurrent enhancements in key performance attributes (mechanical strength, durability, thermal insulation) while maintaining quality. The environmentally friendly approach not only reduces pollution and production costs but also benefits the circular economy and greener construction processes. Academically, the research provides valuable insights into the interaction between recycled materials and binders, and opens avenues for research into other alternative industrial wastes that can be used in construction.

References

[1] AlArab A., Hamad B., Chehab G., Assaad J.J., "Use of Ceramic-Waste Powder as Value-Added Pozzolanic Material with Improved Thermal Properties", *Journal of Materials in Civil Engineering* 32(9) (2020) 1–10. https://doi.org/10.1061/(asce)mt.1943-5533.0003326

[2] Faldessai K., Lawande S.; Kelekar A.; Gurav R.; Kakodkar S., "Utilization of ceramic waste as a partial replacement for cement in concrete manufacturing", *Materials Today: Proceedings* (2023) 15–18. https://doi.org/10.1016/j.matpr.2023.06.453

[3] Taher M.J., Abed E.H., Hashim M.S., "Using ceramic waste tile powder as a sustainable and eco-friendly partial cement replacement in concrete production", *Materials Today: Proceedings* (2023). https://doi.org/10.1016/j.matpr.2023.04.060

[4] Samadi M., Huseien G.F., Mohammadhosseini H., Lee H.S., Abdul Shukor Lim N.H., Tahir M.M., Alyousef R., "Waste ceramic as low cost and eco-friendly materials in the production of sustainable mortars", *Journal of Cleaner Production* 266 (2020) 121825. https://doi.org/10.1016/j.jclepro.2020.121825

[5] Mezidi A., Merabti S., Benyamina S., Sadouki M., "Effect of Substituting White Cement with Ceramic Waste Powders (CWP) on the Performance of a Mortar Based on Crushed Sand", *Advances in Materials Science* 23(4) (2023) 123–133. https://doi.org/10.2478/adms-2023-0026

[6] Hilal N., Saleh R.D., Yakoob N.B., Banyhussan Q.S., "Utilization of ceramic waste powder in cement mortar exposed to elevated temperature", *Innovative Infrastructure Solutions* 6(1) (2021) 1–12. https://doi.org/10.1007/s41062-020-00403-x

[7] Kannan D.M., Aboubakr S.H., EL-Dieb A.S., Reda Taha M.M., "High performance concrete incorporating ceramic waste powder as large partial replacement of Portland cement", *Construction and Building Materials* 144 (2017) 35–41. https://doi.org/10.1016/j.conbuildmat.2017.03.115

[8] Ghonaim S., Morsy R., "Utilization of Ceramic Waste Material as Cement Substitution in Concrete", *Buildings* 13(8) (2023) 1–13. https://doi.org/10.3390/buildings13082067

[9] Evode N., Qamar S.A., Bilal M., Barceló D., Iqbal H.M.N., "Plastic waste and its management strategies for environmental sustainability", *Case Studies in Chemical and Environmental Engineering* 4 (2021) 100142. https://doi.org/10.1016/j.cscee.2021.100142

[10] Vivek S., Hari Krishna P., Gunneswara Rao T.D.A., "A study on the mechanical behavior of concrete made with partial replacement of fine aggregate with waste plastic (LDPE)", *Materials Today: Proceedings* (2023). https://doi.org/10.1016/j.matpr.2023.04.059

[11] Safi B., Saidi M., Aboutaleb D., Maallem M., "The use of plastic waste as fine aggregate in the self-compacting mortars: Effect on physical and mechanical properties", *Construction and Building Materials* 43 (2013) 436–442. https://doi.org/10.1016/j.conbuildmat.2013.02.049

[12] Hannawi K., Prince-Agbodjan W., "Transfer behaviour and durability of cementitious mortars containing polycarbonate plastic wastes", *European Journal of Environmental and Civil Engineering* 19(4) (2015) 467–481. https://doi.org/10.1080/19648189.2014.960100

[13] Badache A., Benosman A.S., Senhadji Y., Mouli M., "Thermo-physical and mechanical characteristics of sand-based lightweight composite mortars with recycled high-density polyethylene (HDPE)", *Construction and Building Materials* 163 (2018) 40–52. https://doi.org/10.1016/j.conbuildmat.2017.12.069

[14] Aciu C., Ilutiu-Varvara D.A., Manea D.L., Orban Y.A., Babota F., "Recycling of plastic waste materials in the composition of ecological mortars", *Procedia Manufacturing* 22 (2018) 274–279. https://doi.org/10.1016/j.promfg.2018.03.042

[15] Suwansaard A., Kongpun T., Khemkhao M., "Properties of mortar composites from plastic waste", *Journal of Applied Science and Engineering* 25(1) (2022) 59–70. https://doi.org/10.6180/jase.202202_25(1).0007

[16] *NA 442. Hydraulic binders—Common cements: Composition, specification.* Institut Algérien de Normalisation (IANOR), Algeria, 2013.

[17] *EN 197-1. Cement—Composition, specifications and conformity criteria for common cements.* European Committee for Standardization (CEN), Brussels, Belgium, 2011.

[18] Bruni S., Longoni M., De Filippi F., Calore N., Bagnasco Gianni G., "External Reflection FTIR Spectroscopy Applied to Archaeological Pottery: A Non-Invasive Investigation about Provenance and Firing Temperature", *Minerals* 13(9) (2023). https://doi.org/10.3390/min13091211

[19] Nirmala G., Viruthagiri G., "FT-IR characterization of articulated ceramic bricks with wastes from ceramic industries", *Spectrochimica Acta – Part A: Molecular and Biomolecular Spectroscopy* 126 (2014) 129–134. https://doi.org/10.1016/j.saa.2014.01.143

[20] *EN 196-1. Methods of testing cement—Part 1: Determination of strength.* European Committee for Standardization (CEN), Brussels, Belgium, 2016.

[21] *EN 1015-10. Methods of test for mortar for masonry—Part 10: Determination of dry bulk density of hardened mortar*. European Committee for Standardization (CEN), Brussels, Belgium, 199.

[22] *EN 12504-4,. Testing concrete in structures—Part 4: Determination of ultrasonic pulse velocity.* European Committee for Standardization (CEN), Brussels, Belgium, 2021.

[23] *EN 1015-18,. Methods of test for mortar for masonry – Part 18: Determination of water absorption coefficient due to capillary action of hardened mortar*. European Committee for Standardization (CEN), Brussels, Belgium, 2002.

[24] Arioz O., "Effects of elevated temperatures on properties of concrete", *Fire Safety Journal* 42(8) (2007) 516–522. https://doi.org/10.1016/j.firesaf.2007.01.003

[25] Ebrahimi M., Eslami A., Hajirasouliha I., Ramezanpour M., Pilakoutas K., "Effect of ceramic waste powder as a binder replacement on the properties of cement- and lime-based mortars", *Construction and Building Materials* 379 (2023) 131146. https://doi.org/10.1016/j.conbuildmat.2023.131146

[26] Temuujin J., Ruescher C.H., "Microstructural and thermal characterization of concretes prepared with the addition of raw and milled fly ashes", *Journal of Materials Research and Technology* 20 (2022) 1726–1735. https://doi.org/10.1016/j.jmrt.2022.07.171

[27] Kim W.K., Hong G., Kim Y.H., Kim J.M., Kim J., Han J.G., Lee J.Y., "Mechanical strength and hydration characteristics of cement mixture with highly concentrated hydrogen nanobubble water", *Materials* 14(11) (2021). https://doi.org/10.3390/ma14112735

[28] Meziani M., Chelouah N., Amiri O., Leklou N., "Blended cement hydration assessment by thermogravimetric analysis and isothermal calorimetry", *MATEC Web of Conferences* 149 (2018) 1–7. https://doi.org/10.1051/matecconf/201714901062

[29] Cunha S., Lima M., Aguiar J.B., "Influence of adding phase change materials on the physical and mechanical properties of cement mortars", *Construction and Building Materials* 127 (2016) 1–10. https://doi.org/10.1016/j.conbuildmat.2016.09.119

[30] Getachew E.M., Yifru B.W., Taffese W.Z., Yehualaw M.D., "Enhancing Mortar Properties through Thermoactivated Recycled Concrete Cement", *Buildings* 13(9) (2023) 2209. https://doi.org/10.3390/buildings13092209

[31] Witkowski H., Koniorczyk M., "New sampling method to improve the reliability of FTIR analysis for Self-Compacting Concrete", *Construction and Building Materials* 172 (2018) 196–203. https://doi.org/10.1016/j.conbuildmat.2018.03.216

[32] du Toit G., Van der Merwe E.M., Kruger R.A., McDonald J.M., Kearsley E.P., "Characterisation of the Hydration Products of a Chemically and Mechanically Activated High Coal Fly Ash Hybrid Cement", *Minerals* 12(2) (2022) 157. https://doi.org/10.3390/min12020157

[33] Dorin P., Doina P., Simona V., Maria P., Stanca C., Codruta S., Marioara M., Raluca I., Razvan E., "Properties Evolution of Some Hydraulic Mortars Incorporating Graphene Oxides", *Buildings* 12(6) (2022) 864. https://doi.org/10.3390/buildings12060864

[34] Zhang G.Y., Ahn Y.H., Lin R.S., Wang X.Y., "Effect of waste ceramic powder on properties of alkali-activated blast furnace slag paste and mortar", *Polymers* 13(16) (2021) 2817. https://doi.org/10.3390/polym13162817

[35] Reig L., Soriano L., Borrachero M.V., Monzó J.M., Payá J., "Potential use of ceramic sanitary ware waste as pozzolanic material", *Boletin de la Sociedad Espanola de Ceramica y Vidrio* 61(6) (2022) 611–621. https://doi.org/10.1016/j.bsecv.2021.05.006

[36] Soultana A., Valouma A., Bartzas G., Komnitsas K., "Properties of inorganic polymers produced from brick waste and metallurgical slag", *Minerals* 9(9) (2019) 551. https://doi.org/10.3390/min9090551

[37] Yaseen S.A., Yiseen G.A., Li Z., "Elucidation of Calcite Structure of Calcium Carbonate Formation Based on Hydrated Cement Mixed with Graphene Oxide and Reduced Graphene Oxide", *ACS Omega* 4(6) (2019) 10160–10170. https://doi.org/10.1021/acsomega.9b00042

[38] Yusuf M.O., "Bond Characterization in Cementitious Material Binders Using Fourier-Transform Infrared Spectroscopy", *Applied Sciences* 13(5) (2023) 3353. https://doi.org/10.3390/app13053353

[39] Horgnies M., Chen J.J., Bouillon C., "Overview about the use of fourier transform infrared spectroscopy to study cementitious materials", *WIT Transactions on Engineering Sciences* 77 (2013) 251–262. https://doi.org/10.2495/MC130221

[40] Bayat A., Hassani A., Yousefi A.A., "Effects of red mud on the properties of fresh and hardened alkali-activated slag paste and mortar", *Construction and Building Materials* 167 (2018) 775–790. https://doi.org/10.1016/j.conbuildmat.2018.02.105

[41] Huseien G.F., Sam A.R.M., Shah K.W., Asaad M.A., Tahir M.M., Mirza J., "Properties of ceramic tile waste based alkali-activated mortars incorporating GBFS and fly ash", *Construction and Building Materials* 214(X) (2019) 355–368. https://doi.org/10.1016/j.conbuildmat.2019.04.154

[42] Khaled B., Roula A., Hichem A., Oussama M., "Reuse of sanitary ceramic waste in the production of vitreous China bodies", *Iranian Journal of Chemistry and Chemical Engineering* 42(6) (2023) 1889–1899. https://doi.org/10.30492/ijcce.2022.559436.5494

[43] Thiam M., Fall M., "Mechanical, physical and microstructural properties of a mortar with melted plastic waste binder", *Construction and Building Materials* 302 (2021) 124190. https://doi.org/10.1016/j.conbuildmat.2021.124190

[44] Ismail Z.Z., AL-Hashmi E.A., "Use of waste plastic in concrete mixture as aggregate replacement", *Waste Management* 28(11) (2008) 2041–2047. https://doi.org/10.1016/j.wasman.2007.08.023

[45] Mustafa M.A.T., Hanafi I., Mahmoud R., Tayeh B.A., "Effect of partial replacement of sand by plastic waste on impact resistance of concrete: experiment and simulation", *Structures* 20 (2019) 519–526. https://doi.org/10.1016/j.istruc.2019.06.008

[46] Da Silva A.M., De Brito J., Veiga R., "Incorporation of fine plastic aggregates in rendering mortars", *Construction and Building Materials* 71 (2014) 226–236. https://doi.org/10.1016/j.conbuildmat.2014.08.026

[47] Bala Balaji Y., Sai Kumar Goud E., Yesuratnam G., "Study of concrete behavior by partial replacement of cement with Ceramic Waste Powder in the presence of Sisal fiber", *Materials Today: Proceedings* (2023). https://doi.org/10.1016/j.matpr.2023.05.069

[48] Li L., Liu W., You Q., Chen M., Zeng Q., Zhou C., Zhang M., "Relationships between microstructure and transport properties in mortar containing recycled ceramic powder", *Journal of Cleaner Production* 263 (2020). https://doi.org/10.1016/j.jclepro.2020.121384

[49] Basha S.I., Ali M.R., Al-Dulaijan S.U., Maslehuddin M., "Mechanical and thermal properties of lightweight recycled plastic aggregate concrete", *Journal of Building Engineering* 32 (2020) 101710. https://doi.org/10.1016/j.jobe.2020.101710

[50] Ruiz-Herrero J.L., Velasco Nieto D., López-Gil A., Arranz A., Fernández A., Lorenzana A., Merino S., De Saja J.A., Rodríguez-Pérez M.A., "Mechanical and thermal performance of concrete and mortar cellular materials containing plastic waste", *Construction and Building Materials* 104 (2016) 298–310. https://doi.org/10.1016/j.conbuildmat.2015.12.005

[51] Ali B., Hawreen A., Ben Kahla N., Talha Amir M., Azab M., Raza A., "A critical review on the utilization of coir (coconut fiber) in cementitious materials", *Construction and Building Materials* 351 (2022) 128957. https://doi.org/10.1016/j.conbuildmat.2022.128957

[52] Yap S.P., Alengaram U.J., Jumaat M.Z., "Enhancement of mechanical properties in polypropylene- and nylon-fibre reinforced oil palm shell concrete", *Materials and Design* 49 (2013) 1034–1041. https://doi.org/10.1016/j.matdes.2013.02.070

[53] Estévez E., Martín D.A., Argiz C., Sanjuán M.A., "Ultrasonic pulse velocity – compressive strength relationship for portland cement mortars cured at different conditions", *Crystals* 10(2) (2020) 133. https://doi.org/10.3390/cryst10020133

[54] Abdul A.R., Kumar D., Bakri A., Lim N.H.A.S., Awang A.Z., Loo P., "Properties of mortar containing fine industrial ceramic waste powder as cement replacement material", *Malaysian Construction Research Journal* 6(1) (2019) 46–53.

[55] Akçaözoğlu S., Akçaözoğlu K., Atiş C.D., "Thermal conductivity, compressive strength and ultrasonic wave velocity of cementitious composite containing waste PET lightweight aggregate (WPLA)", *Composites Part B: Engineering* 45(1) (2013) 721–726. https://doi.org/10.1016/j.compositesb.2012.09.012

[56] Hacini M., Benosman A.S., Kazi Tani N., Mouli M., Senhadji Y., Badache A., Latroch N., "Utilization and assessment of recycled polyethylene terephthalate strapping bands as lightweight aggregates in Eco-efficient composite mortars", *Construction and Building Materials* 270 (2021) 121427. https://doi.org/10.1016/j.conbuildmat.2020.121427

[57] Wang Y., Li L., An M., Sun Y., Yu Z., Huang H., "Factors Influencing the Capillary Water Absorption Characteristics of Concrete and Their Relationship to Pore Structure", *Applied Sciences* 12(4) (2022) 2211. https://doi.org/10.3390/app12042211

[58] Mohammadhosseini H., Lim N.H.A.S., Tahir M.M., Alyousef R., Samadi M., "Performance evaluation of green mortar comprising ceramic waste as cement and fine aggregates replacement", *SN Applied Sciences* 1(6) (2019) 1–7. https://doi.org/10.1007/s42452-019-0566-5

[59] Nayana A.M., Rakesh P., "Strength and durability study on cement mortar with ceramic waste and micro-silica", *Materials Today: Proceedings* 5(11) (2018) 24780–24791. https://doi.org/10.1016/j.matpr.2018.10.276

[60] Sedaghatdoost A., Behfarnia K., Moosaei H., Bayati M., Vaezi M.S., "Investigation on the Mechanical Properties and Microstructure of Eco-friendly Mortar Containing WGP at Elevated Temperature", *International Journal of Concrete Structures and Materials* 15(1) (2021) 1–9. https://doi.org/10.1186/s40069-020-00434-9

[61] Ashok M., Jayabalan P., Joseph J.D.R., "Thermal resistance behaviour of concrete with recycled plastic waste fine aggregates", *Innovative Infrastructure Solutions* 8(10) (2023) 1–13. https://doi.org/10.1007/s41062-023-01226-2

[62] Mohit M., Sharifi Y., "Thermal and microstructure properties of cement mortar containing ceramic waste powder as alternative cementitious materials", *Construction and Building Materials* 223 (2019) 643–656. https://doi.org/10.1016/j.conbuildmat.2019.07.029

[63] Hussein Z.M.A., Khalil W.I., Ahmed H.K., "Impact of Elevated Temperature Exposure on Some Properties of Sustainable Mortar with Plastic Bag Waste", *Engineering, Technology & Applied Science Research* 14(5) (2024) 16573–16579. https://doi.org/10.48084/etasr.8310

[64] Akçaözoğlu S., "The effect of elevated temperature on the lightweight concrete containing waste PET aggregate", *International Journal of Business & Technology* 6(3) (2018) 1–14. https://doi.org/10.33107/ijbte.2018.6.3.20