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USE OF CERAMIC WASTES TO DEVELOP LOW CARBON CEMENT FOR MADE IN ITALY INDUSTRY

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Abstract

The integration of ceramic wastes into low carbon cement is a sustainable and innovative approach to reduce the environmental impact in the construction industry. Ceramic production and generates substantial amounts of ceramic waste, posing significant environmental and disposal challenges. By recycling this waste into concrete, this study aims to reduce the carbon footprint of cement production, address waste management issues, and promote circular economy principles.

Ceramic wastes showed pozzolanic properties, which contribute to the strength and durability of concrete. The presented research explored the most significant sources of ceramic wastes available in the North of Italy and collected different samples from various origin: wastes generated at different ceramic production stages, wastes from selective construction and demolition, crushed ceramic tiles from grinding companies. The materials were analysed and treated to make them suitable as cement substitute. The cement formulation used achieves a CO_2 emission reduction of over 40% compared to ordinary Portland cement while maintain acceptable mechanical strength. The evaluation of mortar properties concerns the behaviour at the fresh state and at the hardened state, according to initial material properties like particle size distribution, specific surface area and density. The results show that ceramic waste can effectively substitute calcined clay in low-carbon mortars, reducing CO_2 emissions, admixture demand, and production costs. This strategy supports industrial application and offers scalable benefits for a more sustainable cement industry in Italy and worldwide.

Key words: ceramic waste, circular economy, low-carbon cement, recycling

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1. Introduction

Low-carbon binders formulated with waste materials present an appealing option to enhance the sustainability of cement industry. Numerous inorganic waste materials and by-products from different sources, including the ceramic industry, demonstrate suitability for such applications (Juan-Valdés et al., 2021). However, effectively leveraging these resources requires customized formulations that take into account their specific characteristics.

On one side, Limestone Calcined Clay Cement (LC^3) is a low-carbon blended cement that reduces CO_2 emissions significantly in comparison to Ordinary Portland Cement (OPC) (Scrivener et al., 2018), offering advantages such as acceptable mechanical strength (Antoni et al., 2012; Avet et al., 2019), increased durability (Ferrari et al., 2023; Jan et al., 2024a, 2024b) and reduced environmental impact (Salvi Malacarne et al., 2021), making it a sustainable and high-performance construction material.

On the other side, in Europe, tile manufacturing generates about 3 million tons of waste annually, with 65% recycled into production and 35% still sent to landfills or used as low-value fillers (García-Ten et al., 2016). Indeed, the traditional ceramic production process involves different steps that generate a certain amount of residual powder that could serve as

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potential cement substitute (Boschi et al., 2020) the scraps, the sludge, the construction and demolition waste and the exhausted lime.

In particular, these scraps consist of finished products that must be disposed of due to non-compliance with standards or lack of sales. To be repurposed as a cement substitute, they must first be crushed and ground to the desired grain size. These residues belong to two main categories: vitrified ceramics (porcelain stoneware tiles, vitreous china sanitary ware, red stoneware tiles) (Conte et al., 2024) and porous ceramics (wall tiles, clay bricks and blocks, roof tiles) (Liu et al., 2022). Vitrified ceramics, fired at 1150-1250°C, contain a predominant vitreous phase embedding residual minerals (quartz and feldspars) and new formed crystalline phases (commonly mullite). Porous ceramics, fired at 800-1100°C, consist of residual and new formed crystalline phases (e.g., plagioclase, pyroxene, melilite) dispersed in an amorphous matrix.

The sludge comes from finishing operations (lapping the surface of the tiles, grinding the edges of the tiles, cutting small tiles, etc.) and consists essentially of porcelain stoneware powder mixed with a small amount of abrasive (Molinari et al., 2024). Scraps, waste powder and sludge are increasingly recycled by the ceramic tile industry, but some excess amount can be available cyclically.

More interesting is the ceramic-rich fraction of construction and demolition waste (CDW) which is globally the most abundant residue with a limited recycling chain, at least in Italy and Europe (Marín-Cortés et al., 2023). Indeed, in Italy, it is available in large volumes, especially as "red mix" fine-grained CDW fractions, and represents a noteworthy environmental problem (Bisciotti et al., 2025).

Ultimately, another ceramic residue coming from ceramic tile production to repurpose is the exhausted lime obtained from the cleaning of kiln flue gas (Smolders and Baeyens, 2000). This waste is classified as hazardous and comprises a blend of portlandite, calcium fluoride and other compounds which might be interesting in the manufacturing of clinker (Boschi et al., 2023).

Ceramic waste materials, such as scraps, waste powder, sludge, and tile residues, have inherent properties that make them viable binders in construction materials, providing avenues to boost both performance and sustainability (Pacheco-Torgal andJalali, 2010). These ceramic waste products have found practical applications in construction, serving as recycled aggregates in concrete (Juan-Valdés et al., 2021), strengthening agents (Ogawa et al., 2020), and cement substitutes in mortar (Ferrari et al., 2025a), showcasing their pozzolanic characteristics and significant potential to enhance material attributes and promote sustainability (Dos et al., 2021; Jacoby and Pelisser, 2015; Pereira-De-Oliveira et al., 2012). Moreover, the integration of recycled ceramics into cement-based materials has shown significant potential in enhancing their resistance to aggressive environmental factors, including improved resistance to chemical attacks (Mohammadhosseini et al., 2020), reduced alkali-silica reactions (Bignozzi and Saccani, 2012; Tutkun et al., 2022), enhanced resistance to chloride penetration (Cheng et al., 2014), mitigation of carbonation (Li et al., 2021), and overall durability improvements (Alsaif, 2021).

According to Life Cycle Analysis (LCA), the use of recycled ceramics as a supplementary material in construction, such as in concrete production, not only improves the material's performance and environmental impact but also helps alleviate the landfill crisis by diverting waste from disposal sites, conserving valuable space, and minimizing associated ecological footprint (Chen et al., 2022; Zanelli et al., 2021)

While there is growing interest in using ceramic wastes as pozzolanic materials in cementitious formulations, only one recent study demonstrated the potential for incorporating ceramic waste powder into LC^3, leading to enhanced mechanical strength compared to reference cement, highlighting the innovation and industrial potential of this development (Mohit et al., 2023). However, they overlooked the significant rheological benefits that ceramic waste could provide as a substitute for calcined clay, which is a key issue given the technical challenges of calcined clay and its very high superplasticizer demand.

In this study, we collected and analysed 8 ceramic wastes coming from different industries and having the potential to be a suitable replacement of cement clinker. The CO_2 reduction achieved by LC^3 is estimated at 40%, based on calcined clay calcination at 800°C (Shah et al., 2022). Replacing calcined clay with ceramic waste could further increase this reduction, leading to even greater CO_2 savings. The ceramic wastes for this project come from collaboration with industry experts, through discussions with ceramic manufacturing companies and providers of production services for these materials.

In a first attempt, the company manufacturing ceramic products were contacted and three sources were identified and the relevant waste collected. In a second attempt, other companies generating ceramic wastes as by-products of other industrial activities were contacted. In particular, companies producing machines for ceramic production, managing demolition waste and grinding unsold ceramic tiles were contacted and additional samples were collected. The characterization of these materials is crucial to understand their behavior when mixed with other components to prepare mortar. The material characterization performed includes detection of particles' density by pycnometer method, analysis of particle size distribution by laser diffraction, measurement of the specific surface area by BET (Brunauer-Emmett-Teller) method, analysis of mineralogical composition by X-ray diffraction (XRD), and particles' morphology detection by Scanning Electron Microscopy analyses with Energy Dispersive X-ray Spectroscopy. The properties of mortar containing low-carbon cement with recycled ceramics have been evaluated and will be presented in other publications. Materials analysis is essential for developing technical solutions for end-of-life management, enabling the repurposing of ceramic waste into sustainable furniture and supporting a circular economy.

2. Experimental

2.1. Materials

The ceramic wastes used in this study are summarised in Table 1 and Fig. 1. A total of six companies were contacted as part of the study, each specializing in different aspects of the ceramic and construction industries. Atlas Concorde focuses on ceramic production and provided powder waste from ceramic tiles rectification for analysis. Cotto Possagno, another ceramic production company, contributed to the project with two types of materials: unfired ceramic powder and larger roof tile shards (5–10 cm). SACMI IMOLA S.C., industrial leader in manufacturing machinery for the ceramic industry, supplied both unfired and fired waste powders generated during machine testing. Scoreline S.r.l., which specializes in managing demolition waste, provided the finest grinding waste in the form of fine aggregates (0–4 mm). Similarly, Sinerti S.r.l. and F.A.T.A. Inerti S.r.l., both involved in grinding operations from unsold ceramic tiles, supplied fine aggregates of the same size range (0–4 mm) derived from their processes. These contributions highlight a diverse range of materials, from powders to aggregates, reflecting the various production and recycling stages in the ceramic and construction sectors.

As the aim of our project is to substitute calcined clay and use ceramic wastes as binder, some materials (RC3, RC6, RC7 and RC8) required a grinding procedure to reduce their particle size. The miniaturization was carried out in a rotary mill (Nonantola, Italy). A 300 g sample was ground for 20 minutes in ~1 L jars containing 20 ceramic spheres, each 20 mm in diameter. The obtained powder was sieved to ensure a max particle size < 300 μm to be comparable to the size of cement particles (Taylor, 1990). The resulting powders, also exhibiting different colours, are shown in Fig. 2. A commercial calcined clay was evaluated as reference material.

Table 1. Ceramic wastes collected and analysed for the study

Label	*Company*	*Address*	*Main activity*	*Material origin*	*Sample state*
RC1	ATLAS CONCORDE	Via del Canaletto, 141, 41042 Fiorano Modenese MO	Ceramic production	Rectification	Powder
RC2	Cotto Possagno	Via Molinetto, 80, 31054 Possagno TV	Ceramic production	Unfired powder	Powder
RC3	Cotto Possagno	Via Molinetto, 80, 31054 Possagno TV	Ceramic production	Roof tiles shards	Fragments (5-10 cm)
RC4	SACMI IMOLA S.C.	Via Selice, 17/A, 40026 Imola BO	Machine's production for ceramic industry	Unfired waste from machine testing	Powder
RC5	SACMI IMOLA S.C.	Via Selice, 17/A, 40026 Imola BO	Machine's production for ceramic industry	Fired waste from machine testing	Powder
RC6	Ecofelsinea S.r.l.	Via Cristoforo Colombo, 38, 40131 Bologna BO	Demolition waste's management	Finest grinding waste	Fine aggregate (0-4 mm)
RC7	Sinerti S.r.l.	Via Regina Pacis, 41049 Sassuolo MO	Grinding	Finest grinding waste	Fine aggregate (0-4 mm)
RC8	F.A.T.A. Inerti S.r.l.	Via Radici Sud, 77, 42014 Castellarano RE	Grinding	Finest grinding waste	Fine aggregate (0-4 mm)

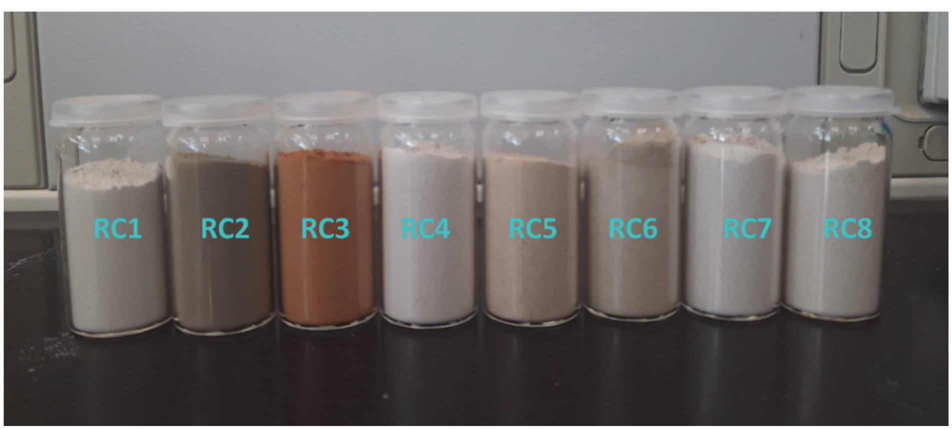

Fig. 1. Visual aspect of recycled ceramic powders collected in the project. RC3, RC6, RC7 and RC8 were milled to obtain a fine powder usable as binder

The mortars containing either calcined clay or ceramic waste were prepared following the formulation: 237 g of commercial CEM I 52.5 R (Heideleberg Materials AG), 71 g of commercial limestone (LS) (Heideleberg Materials AG), 142 g of calcined clay (Heideleberg Materials AG) or ceramic waste, 225 g of water, and 1350 g of natural crushed sand (0–2 mm), supplied by Italcementi (Bergamo, Italy). Mixing was carried out in a Hobart mixer in accordance with EN 196-1 (2016). A polycarboxylate ether-based superplasticizer (SP), with a solid content of 22 %, was supplied by the CHRYSO SAINT-GOBAIN RandD laboratory in Sermaises (France). RC2 and RC4 were not evaluated at the mortar scale as they are not expeected to exhibit pozzolanic reactivity.

2.2. Methods

A fundamental aspect of our study is the characterization of the physical and chemical properties of ceramic waste, which are essential for determining its suitability as a raw material for cementitious applications. The analysis includes advanced techniques to assess bulk density, porosity, surface texture, and chemical composition, all of which directly influence the material's behaviour in cementitious mixes. By understanding these properties, we can ensure the compatibility of ceramic waste with other materials, optimizing its incorporation into the final product.

2.2.1. Physical characterization

The physical characterization of the materials includes: density's measurement, granulometric analysis and assessment of the Specific Surface Area (SSA) and Specific Pore Volume. These properties play a crucial role in influencing the behaviour of ceramic waste when combined with a cementitious binder, affecting key aspects such as dispersion, chemical reactivity, and overall performance within the mix. Understanding these factors is essential for optimizing the material's compatibility and ensuring effective performances of the final composite.

The particles size distribution (PSD) of the recycled ceramics and CC was measured by laser diffraction in water by a Malvern Hydro 2000MU (A) according to ISO 13320:2020 requiring a maximum acceptable instrument uncertainty of 2% (ISO 13320, 2020). Materials density was measured by pycnometer method according to EN 197-6 standard (EN 197-6, 2000), ensuring an incertitude of 0.035 g/cm^3. Nitrogen adsorption was applied to quantify powder's SSA and Specific Pore Volume. A BET Analyser, Nova 800 from Anton Paar Italia S.r.l., with 4 analysis and 4 degassing stations, was used to evaluate between 0.2-0.6 g of powders. After the degassing phase (15 minutes at 150°C), the samples were exposed to N_2 adsorption isotherm. The specific surface area and specific pore volume were calculated using a DFT-based Kaomi model implemented in the Nova PC software (Landers et al., 2013).

2.2.2. Microstructural analysis

The microstructural characterization of the materials included: mineralogical analysis by X-rays diffraction and particles' morphology detection by SEM imaging. Both these properties are fundamental to understand the suitability of ceramic wastes as clinker replacement and their potential reactivity in low-carbon cements.

XRD analysis was performed on powders using a Malvern Panalytical Empyrean X-ray diffractometer (Cu tube with Kα radiation λ = 1.5406 Å, 40 kV and 30 mA, 2θ range = 4–60°, step size = 0.026°, time per step = 67 s). The dry powder was compacted onto a 27 mm diameter sample holder using the back-loading system to ensure uniform packing. The matching of the peaks with the mineralogical structure was conducted by HighScore Plus software.

Particles' morphology was observed by using a Field Emission Gun Scanning Electron Microscope (FEG-SEM, Tescan Mira3) under high vacuum conditions, applying an accelerated voltage of 10 keV and a working distance of nearly 15 mm. Quorum 150R ES (Quorum Technologies Ltd., Judges House, Lewes, UK) was used to carbon coat specimens under vacuum. The images were acquired by backscattered electron (BSE). Elemental composition was determined by energy dispersive spectroscopy (EDS, Bruker probe). Few mg of powder were dispersed on a carbon adhesive tape fixed on a metallic stub before the coating.

2.2.3. Tests on mortar

The flow table test was used to evaluate the rheological properties of mortar. Measurements were performed following the ASTM C1437 − 20 standard (ASTM C1437, 2020) on fresh mortar samples 10 minutes after mixing. A truncated cone (60 mm height, 100 mm bottom radius, 70 mm top radius) is filled with the mixture, compacted, and subjected to jolting on a flow table. The average spread diameter was recorded after 25 drops.

The mechanical strength was evaluated after 28 days of curing following the standard procedure for cement (EN 196-1, 2016)

3. Results and discussion

3.1. Particle characteristics of ceramic wastes

Density values and granulometric assessment are reported in Table 2. A calcined clay produced by calcination at 800°C in a flash calciner (label as CC) is reported for comparison. Raw clay contained kaolinite as the main clay mineral and around 30% of quartz. The densities range from 2.50 g/cm³ (RC8) to 2.82 g/cm³ (RC2 and RC6), showing moderate variation likely influenced by material composition and origin.

Table 2. Density and granulometry of powders, where d(0.1), d(0.5) and d(0.9) are the diameters corresponding to 10 vol%, 50 vol% and 90 vol% of the material, respectively

Material	*Density (g/cm³)*	*d(0.1) µm*	*d(0.5) µm*	*d(0.9) µm*
CC	2.70	2.4	17.1	55.1
RC1	2.61	4.2	26.6	88.9
RC2	2.82	1.2	6.3	31.3
RC3	2.75	1.5	8.3	46.1
RC4	2.58	2.5	9.1	33.7
RC5	2.65	2.7	13.6	107.4
RC6	2.82	2.9	24.4	107.2
RC7	2.53	3.1	20.5	91.9
RC8	2.50	3.5	28.9	132.3

The highest density is exhibited by RC2 and RC6, equal to 2.82 g/cm³ for both, indicating materials with higher metal content (as acceptable for construction and demolition material) or more compact microstructures (as it could be for the unfired ceramic). The lowest densities were found for RC7 (2.53 g/cm³) and RC8 (2.50 g/cm³), possibly due to the presence of lighter components or porosity in the samples. Most materials show a similar granulometry, although their median particle sizes (d(0.5) values) and distribution widths vary. Some key observations make evidence on the fact that RC1 and RC5-RC8 appear to have larger particle sizes, as their d(0.9) values are above 80 µm while CC, RC2, RC3 and RC4 maximum d(0.9) is 55.1 µm. The differences in particle size distributions could significantly influence the material properties, such as packing density, rheology, or reactivity, depending on the application. The results of BET analysis are displayed in Fig. 2. SSA and specific pore volume of recycled materials and CC.

Concerning SSA, CC shows the highest value (~48 m²/g), indicating a material with fine particles and potentially a high degree of porosity. RC2 shows a moderately high SSA (20 m²/g), suggesting some similarity with CC in terms of particle porosity. All the other materials (RC1, RC3, RC4 to RC8) exhibit very low SSA values, close to zero. Concerning the pore volume, it follows a trend similar to SSA, with CC showing the highest value (~0.10 cm³/g), indicating significant porosity. RC2 and RC4 also have a noticeable pore volume (~0.04 cm³/g), consistent with its relatively higher SSA and their unfired nature. Indeed, the clay present in the raw material retained its lamellar structure, creating a high volume of voids within the particles. The other materials (RC1, RC3, RC5 to RC8) exhibit minimal pore volumes (~0.01 cm³/g or less), suggesting less porous structures.

It was anticipated that vitrified ceramics, fired at temperatures between 1150-1250°C, would primarily consist of a dominant vitreous phase encapsulating residual minerals such as quartz and feldspars. Therefore, it results in a very low specific surface area (SSA) and specific pore volume as during the firing process the melting of some compounds reduces internal porosity. This is not the case of CC that was calcined at 800°C thus not reaching a vitreous phase, and for RC2 and RC4, that are unfired wastes. The high specific pore volume directly affects the material's properties, particularly its water absorption when mixed with other cement components.

This leads to significant negative impacts on the rheological properties, which are crucial for the shaping stage of mortar and concrete production. As a result, the ceramic wastes examined in this study demonstrate significant potential to enhance the workability of mortar formulations, particularly when used as a substitute for calcined clay. By incorporating these ceramic wastes, the mix's ease of handling and flowability can be improved, which could lead to better consistency and application during construction processes. This substitution not only supports the development of more efficient and user-friendly building materials but also contributes to the sustainable reuse of industrial waste.

3.2. Reactivity potential of ceramic waste

The diffractogram of the analysed materials are displayed in Fig. 3. The XRD analysis revealed the presence of quartzitic silica in all samples. In calcined clay, this occurs as a natural impurity, whereas in ceramic waste, it originates from the raw materials used in the mix design during ceramic production. The unfired waste (Fig. 4a) exhibited a more diverse composition due to the natural variability of its raw materials. In contrast, the fired ceramic waste (Fig. 4b) demonstrated a more uniform mineralogical composition, as some of its compounds formed an amorphous microstructure undetectable by XRD.

While XRD patterns identify crystalline phases, only qualitative information on the amorphous fraction, which largely governs pozzolanic reactivity can be inferred from the baseline hump. The RC6 sample, derived from construction and demolition waste, showed a distinct composition, including ettringite and calcium carbonate, compounds typically found in cementitious materials.

These differences underscore the importance of preliminary chemical and mineralogical screening to identify suitable waste streams. Standardized characterization protocols for the reliable use of ceramic waste in low-carbon cements should also incorporate an evaluation of pozzolanic reactivity, to prevent performance issues arising from variations in chemical composition.

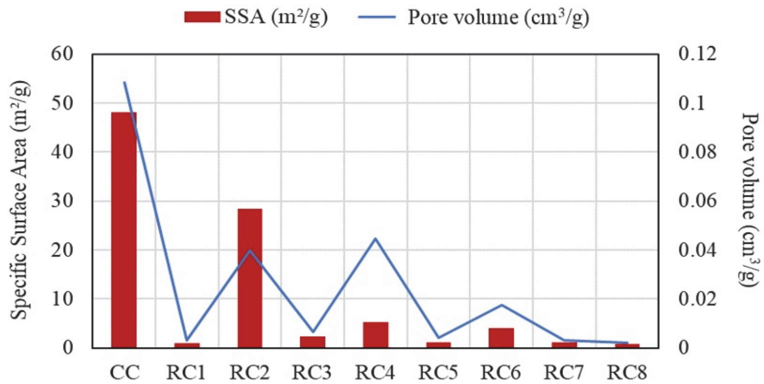

Fig. 2. SSA and specific pore volume of recycled materials and CC

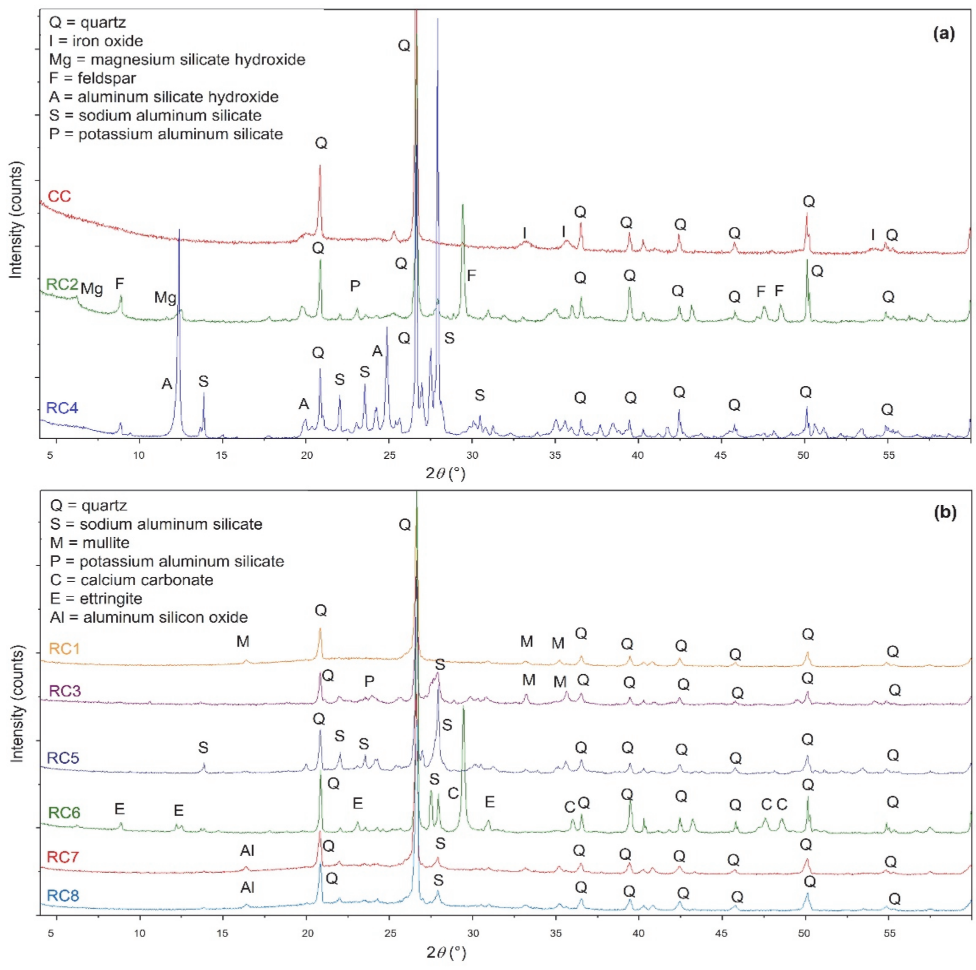

Fig. 3. Diffractograms of the ceramic wastes: (a) CC and unfired wastes, (b) fired wastes

Particle morphology analyzed by SEM is displayed in Fig. 4. The images are intended to illustrate the qualitative morphology of the particles rather than provide quantitative or elemental analysis, which would not be statistically relevant. Although the samples contain coarse particles in varying amounts, their shape and possibly even their distribution appear to be fairly comparable. Most materials display a mix of angular and irregular particles with varying degrees of compaction. This suggests that the materials have undergone similar processing or originate from related sources, resulting in comparable shape features. In summary, the powders of these materials are largely uniform, with only subtle variations that are unlikely to significantly differentiate their behaviour in most applications.

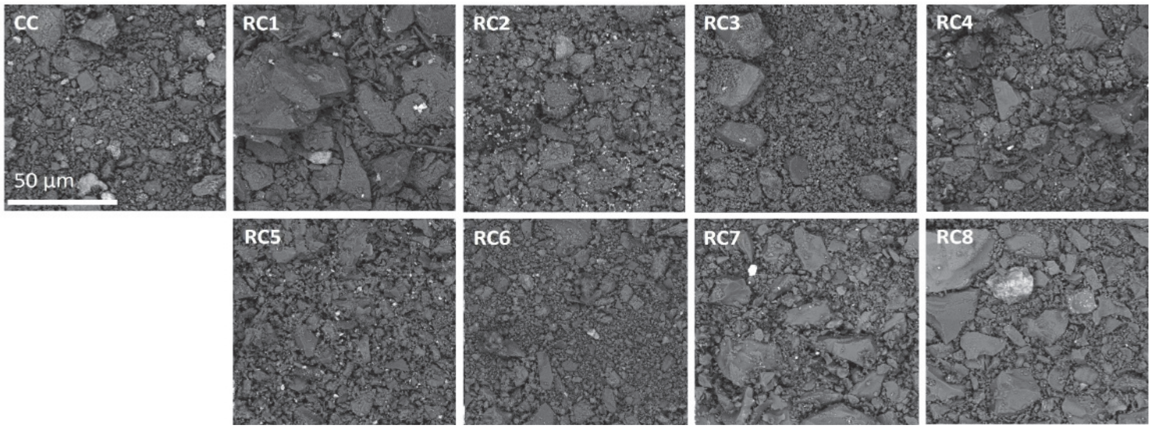

Fig. 4. Particles' morphology, BSE images (same magnification for all the samples)

However, it is not strictly necessary for them to be comparable, as the aim is to represent a variety of characteristics.

3.3. Performances and implication for industrial application

The results of the mortar spread obtained with the flow table test and 28-day compressive strength of LC^3 mixtures with different ceramic waste substitutions, highlighting both workability and mechanical performance relative to the reference LC3-CC, are displayed in Table 3. The results show that the reference LC3-CC mixture required a relatively high superplasticizer dosage (1.8%) to achieve a spread diameter of 18.7 cm and reached a compressive strength of 48.1 MPa at 28 days.

In contrast, all LC3-RCs mixtures achieved adequate workability with a much lower superplasticizer content (0.5%). SSA was shown to be a primary factor in consuming free water and impacting workability of mortar and paste (Ferrari et al., 2023; Ferrari et al., 2025b), explaining this substantial difference in SP dosage to achieve sufficient spread diameter at the flow table test.

Among the RC-based mixtures, LC3-RC3 and LC3-RC7 exhibited the highest mortar spread diameters (22.3 cm and 22.0 cm, respectively), indicating enhanced flow ability compared to the reference.

The compressive strengths of the RC mixtures ranged from 29.5 to 35.8 MPa. Importantly, most ceramic waste-based mixtures exceeded 32.5 MPa, which is the minimum strength required by the EN 197-1 standard for cement classification (EN 197-1, 2019).

The results indicate that partial replacement of calcined clay with ceramic waste can maintain adequate mechanical performance while improving workability and significantly reducing superplasticizer demand. For example, some mixtures (e.g., LC3-RC3 and LC3-RC7) achieved comparable or higher spread diameters with only 0.5% SP, compared to 1.8% SP in the reference LC3-CC, representing a reduction of approximately 70 % in admixture dosage. This reduction can directly translate into lower material costs and a smaller environmental footprint.

Moreover, the use of ceramic waste simplifies the production process by eliminating the need for clay calcination, thereby preserving natural high-grade clay for other applications. However, industrial adoption may face barriers such as variability in waste quality, the need for pre-processing, and the absence of standardized certifications to guarantee performance. Economic feasibility will therefore depend on balancing material savings, processing costs, and implementation scale, emphasizing the importance of pilot-scale trials and further collaboration with industry partners.

Table 3. Mortar performances at the fresh and hardened state

Material	*SP (%)*	*Mortar spread diameter (cm)*	*Compressive strength at 28 days (MPa)*
LC3-CC	1.8	18.7	48.13 ± 1.76
LC3-RC1	0.5	16.3	35.75 ± 0.63
LC3-RC3	0.5	22.3	35.13 ± 1.12
LC3-RC5	0.5	16.7	30.04 ± 0.34
LC3-RC6	0.5	16.3	29.49 ± 0.68
LC3-RC7	0.5	22.0	34.09 ± 3.09
LC3-RC8	0.5	20.8	33.97 ± 1.14

4. Conclusions

The present research explores the possibility to use waste materials from the ceramic industry for the design and creation of new sustainable and circular cementitious materials. Through ceramic wastes identification and characterization, this research serves as platform in developing solutions that, starting from waste, combines technological innovation with industrial application.

Eight types of recycled ceramic were characterized and analyzed in respect to a reference material with pozzolanic properties, i.e. calcined clay. The results analyse the fresh and hardened mortar's properties that are driven by the granulometry of the powders: the finer the powder, the greater its negative impact on workability but the higher the pozzolanic reactivity.

Mortar tests demonstrated that several recycled ceramic-based mixtures achieved comparable or even improved workability relative to the reference LC3-CC, while maintaining satisfactory 28-day compressive strengths above the minimum standard. Notably, these mixtures required significantly less superplasticizer, around 0.5 % compared to 1.8 % in the reference reducing both material costs and chemical usage.

In addition, the replacement of calcined clay with ceramic waste contributes to over 40 % reduction in CO_2 emissions, in comparison to ordinary Portland cement, by reducing clinker content, eliminating energy-intensive clay calcination and lowering admixture demand. Together, these results indicate that the use of ceramic waste not only enhances mortar performance but also delivers clear environmental and economic benefits, supporting the sustainable and circular use of industrial by-products in construction materials worldwide.

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