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THESEUS

Hub4Circularity

A First of a kind Hub for circularity demonstrator for Attica and peripheral regions

Grant Agreement No 101178059

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Publishable summary

Concrete waste and mixed C&DW additions modify brick properties through changes in mineral composition, particle size and interactions during firing. Most waste types reduce density and compressive strength while increasing porosity and water absorption, although glass powder can improve strength and lower water uptake due to its fluxing behaviour. Furthermore, marble dust is being tested as a component in the binder for concrete based on the LC3 principle, where clinker is partially replaced by calcined clay and carbonate-rich materials. This approach aims to valorise marble dust in a low-carbon binder system while maintaining suitable mechanical performance.

Reported optimal replacement rates range from 5 to 35 wt.%, depending on waste type and firing temperature. Mixed C&DW remains challenging due to its heterogeneity, but studies show acceptable performance at 15–25 wt.% when conditions are controlled. Environmental assessments are limited, yet available studies indicate that firing immobilizes many contaminants. In conclusion, moderate waste incorporation is technically feasible when waste fraction and firing temperature are carefully balanced.

Results achieved so far show that marble dust can function as a carbonate-rich component in low-carbon LC3-type binders for concrete. Mineralogical analysis confirmed that the marble dust consists predominantly of calcite with a minor dolomite fraction, making it suitable for use as a reactive carbonate source. A key practical challenge was the strong agglomeration of the powder, and laboratory trials showed that sieving was necessary to break up flocs and enable effective use in binder systems. Based on this, marble dust calcined clay cement (MC3) formulations were developed with clinker contents ranging from 50 wt.% to 15 wt.% while maintaining a calcined clay-to-marble dust ratio of 2:1. Flow-table testing showed that all MC3 mixes achieved acceptable workability, although workability decreased as the proportion of calcined clay and marble dust increased. Compressive-strength testing at 3, 10 and 28 days demonstrated a clear strength ranking from MC3-15 to MC3-50, reflecting the decreasing clinker content. Importantly, the 28-day target strengths of 30, 40 and 50 MPa were achieved for MC3-25, MC3-35 and MC3-50, respectively, demonstrating the technical potential of marble dust in LC3-based concrete binders.

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Abbreviations

Abbreviations	Full name
ASTM	American Society for Testing and Materials
C&DW	Construction and demolition waste
CSPCs	Chemical Species of Potential Concern
LC3	Limestone Calcined Clay Cement
MC3	Marble dust calcined clay cement
MIP	Mercury intrusion porosimetry
SEM	Scanning electron microscopy
TGA	Thermogravimetric analysis
XRD	X-ray diffraction

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1 Introduction

The global demand for building floor area is projected to double between 2015 and 2050, with fired clay brick production expected to increase by 50%, contributing approximately 0.68–0.89 Gt CO_2e in greenhouse gas emissions by mid-century [1]. At the same time, the generation of construction and demolition waste (C&DW), which accounts for more than one-third of total waste generated in the EU[2] and over 25% of global solid waste, has emerged as a significant environmental challenge[3]. This has intensified the need of sustainable waste management solutions within the construction industry. In response, the Waste Framework Directive [4] set a target to increase the preparation for re-use, recycling, and other material recovery of non-hazardous C&DW to a minimum of 70% by weight by 2020. One strategy to support this goal is the partial substitution of natural clay in brick production with various waste materials.

Traditionally, bricks are manufactured using clay, marl, or clay-shale mixtures[5], while cement-based bricks are also common. Both production methods are energy-intensive and contribute significantly to greenhouse gas emissions and the depletion of natural resources[6]. One strategy to reduce the environmental impact of brick production is the partial substitution of clay with various waste materials, thereby lowering the carbon footprint and incorporating recycled content into higher-value products.

A wide range of organic and inorganic waste materials has been investigated for this purpose. This document focuses on inorganic wastes such as fly ash, waste marble powder, concrete, glass, limestone, ceramic and C&DW. Despite increasing interest in local waste valorisation, research on the use of mixed C&DW remains limited. This may be attributed to the highly heterogeneous nature of C&DW, which includes both inert and non-inert components, making it difficult to establish a universal definition [7,8]. Rayhan and Bhuiyan [8] recently proposed the following definition of C&D waste: "…the unwanted hazardous and non-hazardous material arising in the construction and demolition sites in the form of inert and non-inert materials and it is considered as temporal losses of construction and demolition activities." The complex and variable composition of C&DW, combined with limited data, complicates the evaluation and comparison of results across studies and introduces uncertainty regarding the performance of bricks incorporating such waste [9].

This review examines recent literature (2015–2025) on the incorporation of inorganic waste and C&DW in fired clay bricks, focusing on: i) common practices (waste types, particle size, firing temperatures, replacement rates, and measured parameters), ii) the effects of different inorganic waste types on technological and mechanical properties, and iii) recommended replacement rates for optimal performance based on intended brick applications.

Furthermore, concrete is widely recognised as one of the most impactful construction materials in terms of global CO_2 emissions, mainly due to the cement clinker content in the commercial cements used world-wide. Today the replacement levels of clinker are usually up to 35%. At the same time, marble processing generates large volumes of fine marble dust, particularly in countries such as Greece with significant marble extraction and cutting activities. This by-product is often rich in calcium carbonate and therefore has potential for valorisation as a component in low-carbon concrete binders. In particular, marble dust may be used in systems based on the LC3 principle, where carbonate-rich materials act together with calcined clay to reduce clinker demand while maintaining suitable performance. This creates an opportunity to address both waste generation and cement-related emissions through a circular construction-materials approach.

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1.1 Purpose of the deliverable

This deliverable supports THESEUS WP5 (Task 5.3) by synthesizing recent literature (2015–2025) on using inorganic wastes and construction and demolition waste (C&DW) as partial replacements in fired clay bricks. It summarises waste types, processing routes, firing conditions and their effects on key properties (e.g., density, strength, porosity and water absorption), and compiles reported replacement-rate ranges and practical limits. It also frames next-step valorisation pathways in cementitious materials, notably the use of waste marble dust as a supplementary component in concrete production. This pathway is considered in light of the LC3 principle, i.e., reducing clinker demand through synergistic use of limestone (and other fillers) with reactive aluminosilicate sources. Together, these outputs provide an evidence base for selecting materials and parameters for follow-on lab work and scalable circular construction solutions.

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2 Fired clay brick production

2.1 Production volumes

According to an IBISWorld report, Greece's "Clay Building Materials Manufacturing" industry—which includes clay bricks, ceramic tiles, clay roof tiles, and other products—had a market size of approximately €90.8 million in 2024, with 52 businesses operating and moderate growth trends. In a 2023 breakdown of European production share for bricks, tiles, and similar construction products, Greece accounted for about 3.52% of the total units produced.

It is, however, difficult to find exact figures of the production volume in Greece. KEBE is the largest brick and roof tile manufacture and produces approximately 2000 tons of clay blocks and 1000 tons of roof tiles per day at their plant in Nea Santa of Kilkis.

2.2 Production process

The production process begins in the stock yard, where raw clay is crushed and reduced in size. Material smaller than approximately 3 mm is transferred to the silo, with an average moisture content of around 15%, which can vary depending on weather conditions. During storage in the silo, additional moisture may be added to compensate for evaporation, and the clay is typically held for about one week.

Prior to extrusion, the moisture content of the clay from the silo is averaged to 18–20%. Up to 1% petcoke may be incorporated to enhance combustion efficiency, provide additional energy, and induce porosity in the final product. In addition to petcoke, fired brick producers may use a range of alternative additives and fuels to improve combustion efficiency and porosity in the final product. Common options include biomass residues such as sawdust, rice husk, or olive husk, which are renewable and locally available; coal or lignite fines, which have traditionally been used but generate higher emissions; and industrial by-products or waste-derived fuels such as paper sludge, plastics, or sewage sludge, which help reduce waste disposal while supplying energy. Carbonate minerals like chalk or dolomite can also be added to create porosity through gas release during firing. These alternatives are increasingly relevant as the industry seeks to reduce reliance on petcoke and lower carbon and sulphur emissions.

Moisture adjustments are carried out depending on the extrusion pressure required and the type of product being manufactured. Temperature control may not be applied during this stage, and the extruded material is promptly transferred to the drying section. Drying occurs at 40–90 °C over 12–16 hours, with the relative humidity initially set at 90% and gradually decreasing to achieve a final clay moisture content of 5–7%.

Kiln firing is typically conducted with natural gas, though older plants may use fuel oil, coal, or biomass. A prekiln stage at 40 °C for two hours may be applied but is sometimes omitted in summer months. The main firing process takes place at 930 °C for 18 hours, starting with a pre-firing at 300 °C, followed by firing at 930 °C and rapid cooling to 400 °C. Temperature is controlled by burners located along 20–50% of the kiln length.

After firing, bricks and tiles undergo a controlled water addition, creating a thermal shock that deactivates calcium minerals. This stabilizes the products, which are then ready for packaging and can be dispatched directly without additional storage. Alternative approaches used by other producers include slow or staged cooling instead of quenching, or the incorporation of chemical additives into the clay before firing, such as

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phosphates or silicates, to immobilize calcium and reduce post-firing reactions. Partial water misting during cooling is another method to achieve similar effects while minimizing thermal stress.

2.3 Material fractions used and composition of clay

The primary raw material for fired clay bricks is natural clay, which provides the plasticity and mineral content necessary for forming and firing. In some industrial processes, additional components may be incorporated to optimize performance. For example, quartz or sand is often added to reduce shrinkage and cracking during drying and firing, feldspars and other fluxes can improve sintering and mechanical strength, and carbonates may be used to adjust firing behaviour or create controlled porosity. Organic materials or waste additives, such as sawdust or paper sludge [10], can also be included to enhance porosity and reduce weight. While some producers rely solely on clay (with petcoke added as a combustible additive), these additional components are commonly used elsewhere to improve the stability, strength, and overall performance of the final product. The mineralogical and chemical composition of typical clay is summarised in Table 1.

Table 1 Composition of the clay used in fired brick and roof tile production[9,11–13]

Element (expressed as oxide)	Content (%)	Function in fired bricks	Main mineral source
SiO_2	45–60	Reduces water demand, reflects non-plastic character, reduces shrinkage during drying and firing, but increases shrinkage during cooling due to higher porosity	Quartz, sand, feldspars
Al_2O_3	10–20	Reacts during firing to form mullite, which increases chemical and mechanical resistance	Kaolinite, illite, feldspars
Fe_2O_3	10–25	High content can cause discoloration/efflorescence; in low-oxygen firing forms FeO which reacts with silica, trapping gases and causing bloating (“black core”)	Hematite, magnetite, pyrite, marcasite
CaO	1–8	Reacts with silica to form wollastonite or pseudo-wollastonite ($CaSiO_3$), improving mechanical resistance and reducing firing shrinkage; >8% calcareous clay increases porosity and lowers density	Calcite, dolomite, limestone
MgO	1–4	Provides stability during firing	Dolomite, magnesite
Na_2O/K_2O	1–3	Fluxing agents, reduce firing temperature	Feldspars, micas, alkali-bearing minerals

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A list of studies conducted with different material fractions intermixed in fired clay production is shown in Table 2. The studies were conducted at lab scale and included waste types as concrete, glass, ceramic tiles, marble waste powders etc.

Table 2 Conditions for fired brick production used in referenced studies

Waste type	Particle size	Replacement rate (wt.%)	Firing temperature (°C)	Firing duration (h)	Author
Concrete, glass and ceramic	<100µm	15	1000	2	[5]
Concrete	<100µm	Up to 15 (7 treatments with 2.5 wt.% increments)	1000; 1100	2	[14]
Limestone	1 –100 µm	Up to 15 (4 treatments with 5 wt.% increments)	900	2	[12]
Marble waste powder	<100µm	Up to 35 (7 treatments with 5 wt.% increments)	950; 1050	2	[15]
Mixed construction waste	<0,6mm	5–45% (5 wt.% Increments)	700, 850, 900	5	[7]
Mixed construction waste	≤0,125mm; 0,6–0,125mm	15%	900, 940, 950	n.a.	[16]
Construction and demolition waste (roof tiles)	<0,6mm	5–45% (5 wt.% Increments)	700, 850, 900	n.a.	[17]

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2.4 Factory production control

2.4.1 Routine test of products in the production line

The routine testing of products in a brick manufacturing plant is a critical stage for ensuring quality, compliance with applicable standards, and meeting market requirements. The process is systematically applied at all stages of production, from raw materials to the final product.

2.4.1.1 Raw Material Inspection

Before the start of production, sampling inspections of raw materials are carried out. The inspections include:

- Percentage of sand, clay and silt
- Moisture content and particle size distribution
- Plasticity, homogeneity and foreign inclusions

The results are recorded and evaluated before feeding the materials into the production line.

2.4.1.2 In-Process Production Control

During the production process, samples are taken at regular intervals to check:

- Dimensions and geometric accuracy of green (unfired) bricks
- Moisture content prior to drying
- Surface quality and presence of cracks

In the event of deviations, immediate corrective actions are taken through equipment adjustments.

2.4.1.3 Post-Drying Inspection

After the drying stage, inspections are carried out for:

- Any moisture on the inside and outside of the products
- Cracks or deformations
- Dimensional uniformity
- Weight loss

Defective products are removed before firing.

2.4.1.4 Post-Firing Inspection

At the final stage, fired bricks are subjected to laboratory and visual tests, such as:

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- Compressive strength
- Water absorption
- Dimensional accuracy
- Visual inspection of color and surface defects

All tests are conducted in accordance with applicable European standards (e.g. EN).

2.4.2 Procedure for preparation and testing of laboratory specimens

The laboratory procedure for testing the flexural strength of a specimen begins with preparing the test specimens, while compressive strength is determined on the final product. First, 6 kg of raw material is dried at 120 °C for one day, and the moisture content is calculated. Next, the Pfefferkorn test is performed: 100 g of dried material is mixed with 16 g of water, and additional water is gradually added to achieve the desired plasticity, ensuring that the ratio of final height to starting height falls within 0.73–0.78. Based on the results, for example, 4 kg of material is mixed with the calculated percentage of water.

The prepared mix is then inserted into the extruder, leaving approximately 2.5 kg in the machine. This generates around 180 g per specimen, producing roughly 8–10 test specimens. The extrusion process lasts about 30 minutes, during which the temperature rises due to the mechanical work. Experience indicates that a temperature of around 40 °C at the extruder neck produces successful samples.

After extrusion, the specimens are cut with a knife, weighed individually, and two holes are made in each specimen. The distance between the holes is measured, and changes are recorded after drying and firing (shrinkage). The drying procedure consists of three stages: first, specimens are dried at 45–50 °C for 5 hours while wrapped in moisture-retaining cloths; next, the temperature is increased to 60–70 °C over 3–4 hours with a ramp of 15–20 minutes; finally, the temperature is raised to 90 °C for 10 hours with a similar ramp period. After drying, the weight and hole distances are recorded.

The specimens are then subjected to firing at 930 °C for a specified duration, followed by natural cooling in the oven for several hours, completing the total burning process. After firing, the weight and hole distances are measured again. Finally, the specimens are tested for flexural strength, along with any other required mechanical properties.

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3 Technical properties

Fired clay bricks are widely used in construction, serving both as components of the building envelope and as structural elements in load-bearing applications such as walls and columns.

Consequently, water absorption (especially for facing clay blocks), compressive strength and thermal conductivity are considered critical performance parameters, as they directly influence the durability, mechanical stability and energy efficiency of the bricks [7,9].

The durability of clay bricks, in particular, is strongly affected by their water retention capacity, since increased water penetration can reduce resistance to weathering and compromise long-term performance [18]. These properties are often influenced by the bulk density of the bricks and the proportion of waste materials used as partial replacements in the clay matrix [9].

Commonly reported parameters in the characterization of fired clay bricks include compressive strength, bulk density, water absorption and porosity. In addition, several studies also document properties such as loss on ignition, thermal conductivity, efflorescence, firing linear shrinkage and flexural strength. Table 3 provides an overview of the parameters reported across different studies.

The selection of which properties to measure is typically guided by the intended application of the bricks. For instance, parameters related to thermal insulation, structural load-bearing capacity, or weight reduction are prioritized depending on the functional requirements of the final product.

Table 3 Key performance indicators measured in referenced studies

Author	Density	Water absorption	Loss on ignition	Thermal conductivity	Compressive strength	Flexural strength	Porosity	Efflorescence
5	x	x	x			x		x
14	x	x	x		x		x	x
12	x						x	
15	x	x		x	x		x	
7	x	x	x		x			x
16	x	x				x	x	x
17	x	x	x		x			

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3.1 Effect of inorganic waste additions

The incorporation of various types of inorganic waste into clay brick formulations results in products with differing characteristics and quality, and there is an uncertainty concerning expectable properties of fired clay bricks depending on the type of waste added as well as the amount [7,14]. These variations are primarily attributed to differences in metal and mineral content of the waste materials, its particle size distribution and their interactions with the clay minerals during firing [5,9,14,16]. Muñoz et al. [9] report that the existing literature lacks sufficient data to enable reliable predictions of brick properties based on the type and quantity of waste added. Raini et al. [5] further emphasize in their study the significant influence of the composition of the raw clay materials on the final quality of the bricks, while Zanelli et al. [16] did not observe an evident variation caused by the different clay types used in their study when adding C&DW residues.

According to the literature, in many cases, the addition of inorganic residues often results in a proportional relationship between bulk density and other key properties such as compressive strength, water absorption and thermal conductivity [9,15]. Dubale et al. [17] further observed a correlation between the addition of roof tile waste and increased shrinkage in clay fired bricks.

The structure and chemical composition of specific waste types, such as concrete waste, significantly affect porosity, which in turn influences water absorption capacity, thermal performance, porosity and compressive strength [14]. Generally, higher additions of inorganic waste tend to reduce bulk density and compressive strength, while increasing porosity and water absorption (Figure 1). This trend is evident for waste types including concrete [5,14], marble waste powder [15] and mixed construction waste [7]. For instance, marble waste additions reduced the bulk density of bricks by 2.9–20.6%, due to CO_2 release during carbonate decomposition [15], indicating a change in texture and microstructure due to increased pore volume generated during the combustion of the waste (Figure 2). Compressive strength decreased by 26% at temperatures of 1000 °C and by 19,5% at 1100 °C with waste additions of 15 wt.%. Furthermore, bulk densities resulting from the addition of roof tile waste (Figure 4) were higher compared to those from mixed C&DW in the same soils types (Figure 3), highlighting the importance of accounting for compositional differences within C&DW [17].

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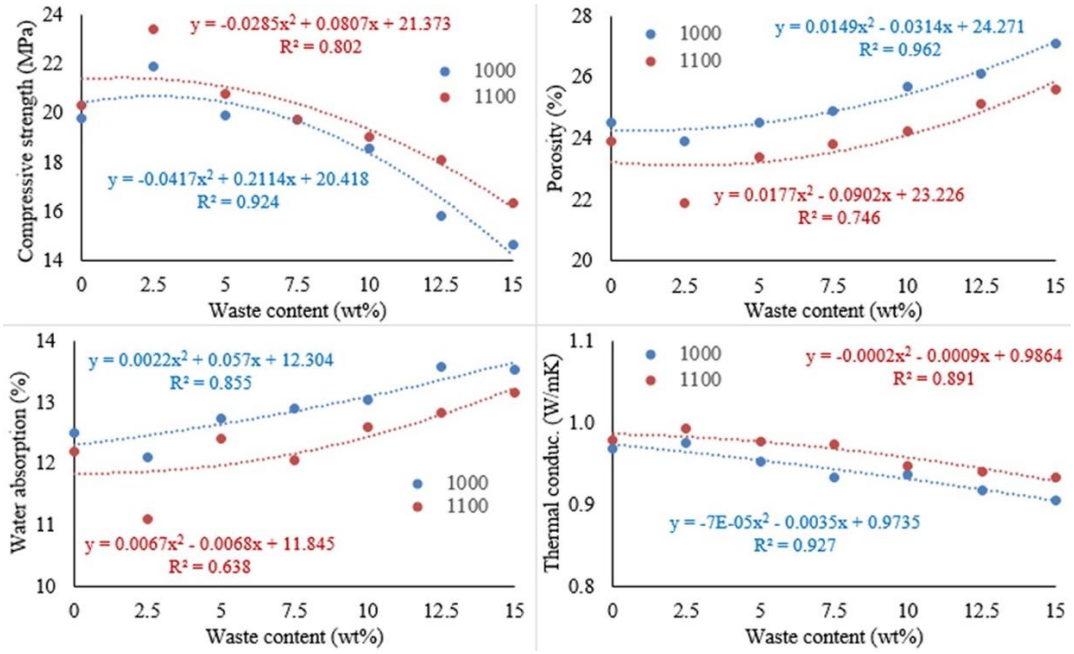


Figure 1 From [14]: Correlations between brick properties and waste content for bricks fired at two different temperatures, 1000 °C and 1100 °C.

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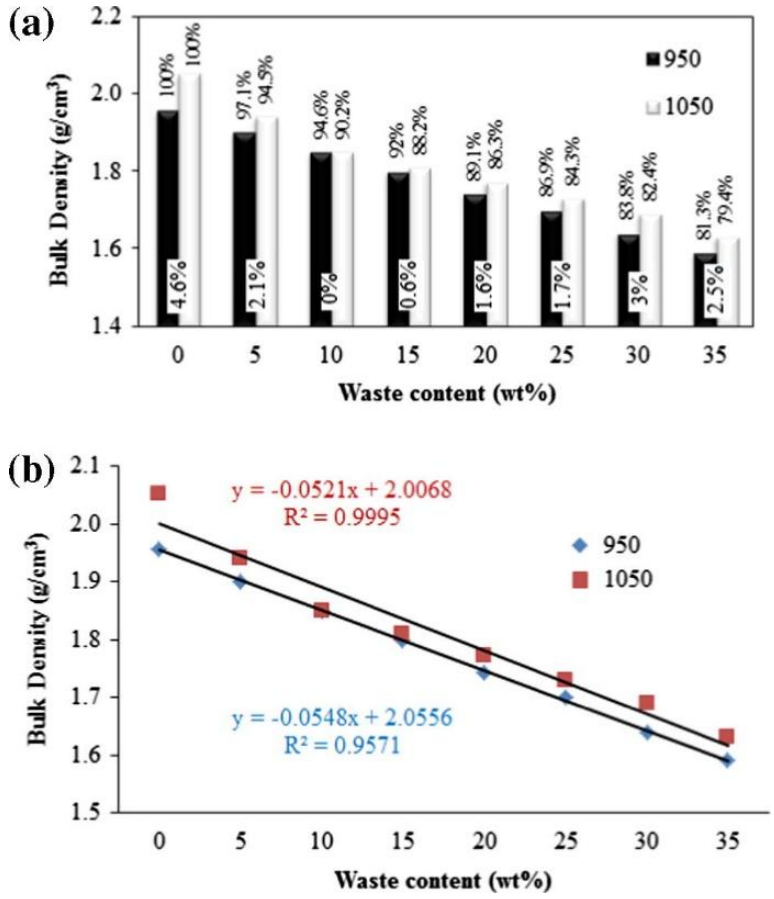
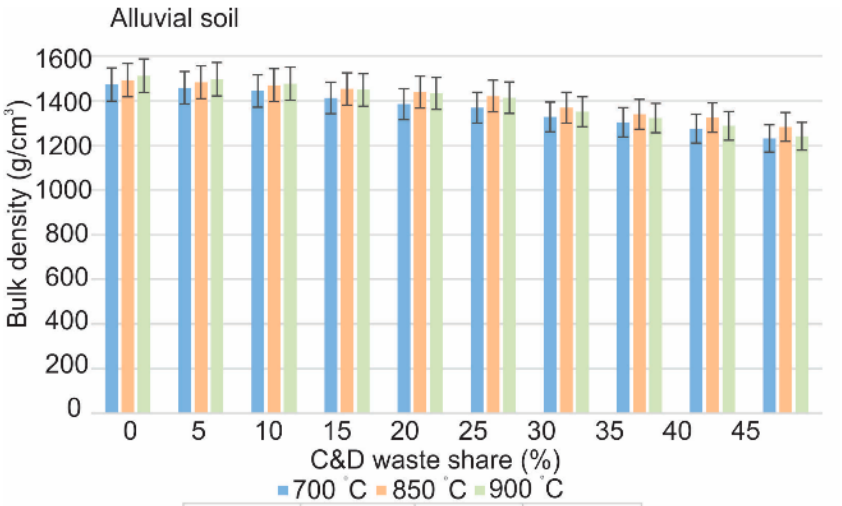


Figure 2 From [15]: (a) reported bulk density values of bricks, (b) linear fits proportion to waste marble percentage for bulk density at two different temperatures (950 °C and 1050 °C).

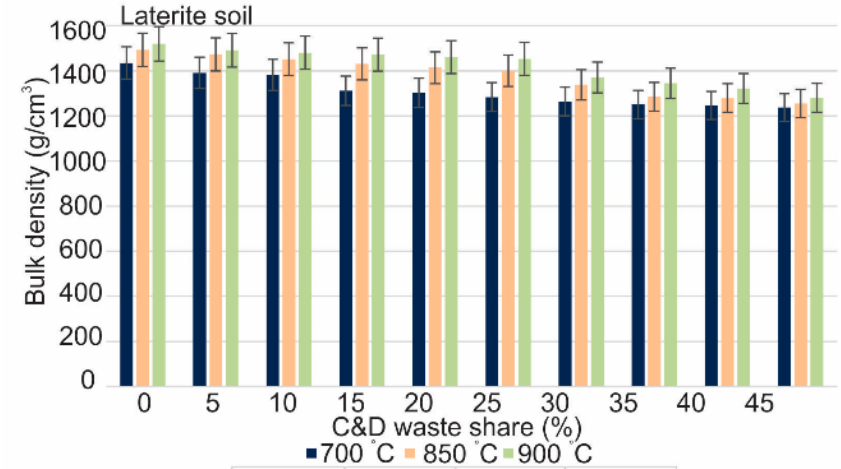
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Covariance	*AS (700 °C)*	AS (850 °C)	AS (900 °C)
AS (700 °C)	6024.09		
AS (850 °C)	5366.26	4850.64	
AS (900 °C)	6808.24	6122.86	7754.44

a)



Covariance	*LS (700 °C)*	LS (850 °C)	LS (900 °C)
LS (700 °C)	4330.49		
LS (850 °C)	4927.29	6737.09	
LS (900 °C)	4465.05	6355.35	6134.25

b)

Figure 3: From [7]: Bulk density of fired clay bricks with increasing additions of mixed C&D waste in alluvial (top) and laterite soils (bottom).

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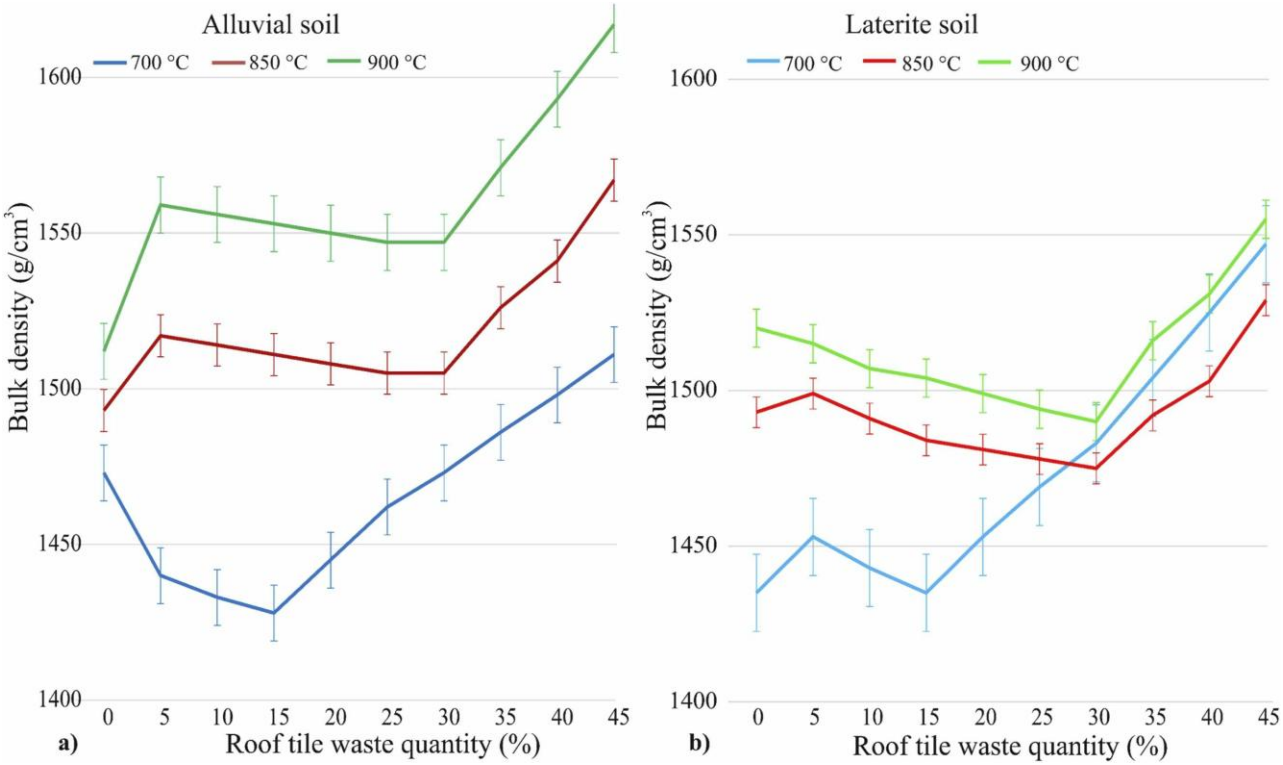


Figure 4: From [17]: Bulk density of fired clay bricks with increasing additions of roof tile waste in alluvial (left) and laterite soils (right).

In contrast, the use of glass powder has been shown to have the opposite effect. Raini et al. [5] reported that increasing the proportion of glass powder resulted in bricks with higher density, greater flexural strength and lower water absorption, potentially due to the presence of fluxing agents, which facilitate the fusion with clay particles.

Increased porosity is generally associated with higher water absorption, which can negatively impact the durability and overall quality of the bricks [12,14,15]. However, certain materials, such as waste marble powder and limestone can be intentionally used as pore-forming agents to tailor porosity [12,15], whereas concrete powder is not recommended for this purpose [14].

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3.2 Influence of firing temperature on brick performance

The density of a brick depends on the volume and density of the ingredients, the proportion of ingredients and firing temperatures. Several studies have demonstrated that increasing firing temperature affects the mechanical and physical properties of bricks [14,15,17].

Sutcu et al. [15] observed that the compressive strength of bricks containing marble waste powder increased only slightly with higher firing temperatures. In the case of concrete waste additions, Gencel et al. [14] reported that the effect of temperature on bulk density was insignificant with an increase of only 1.5%, when the temperature was raised from 1000 °C to 1100 °C (Figure 5). They also noted that other brick properties investigated in their study were not significantly affected by the temperature change. Figure 1 illustrates the impact of firing temperature on water absorption, compressive strength, porosity and thermal conductivity. In contrast, Dubale et al. [17] found that increasing the firing temperature led to greater shrinkage, higher loss on ignition and increased bulk density, while water absorption decreased.

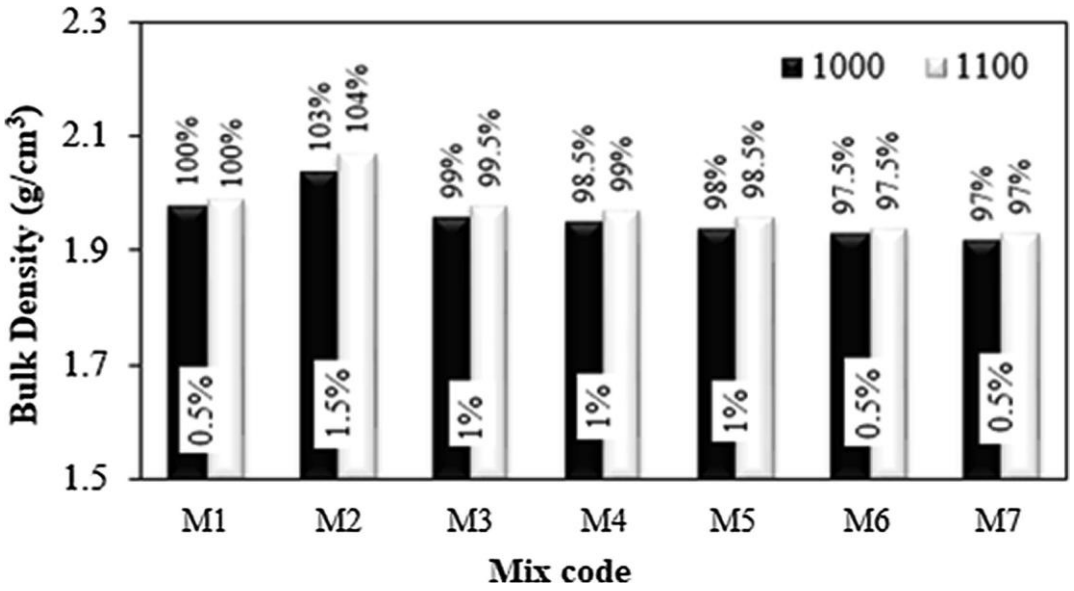


Figure 5: From [14]: Bulk density variation of bricks fired at 1000 °C and 1100 °C, respectively. Mix code M1-7 refers to bricks with a concrete waste content in wt. % of 0 (M1), 2,5 (M2), 5 (M3), 7,5 (M4), 10 (M5), 12,5 (M6) and 15 (M7).

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4 Recommended replacement rates for inorganic waste in fired clay bricks

Due to a variability in waste composition and limited long-term performance data, many studies refrain from recommending specific replacement rates. However, among those that do, suggested rates generally range from 5 to 35 wt.% depending on the type of waste added and chosen firing temperatures [7,12,14,15,17]. The following section lists replacement rates used in different studies for different types of wastes and their implications for brick properties.

4.1 Concrete waste

Although lower waste addition levels generally result in bricks with better performance for strength, porosity, water absorption and thermal conductivity, Gencel et al. [14] found that additions up to 15 wt.% do not compromise essential quality standards. In contrast, Raini et al. [5], observed a 7.3 MPa reduction in flexural strength at the same replacement rate, accompanied by decreased density and increased capillary water absorption, highlighting the need for strict control of addition rates.

4.2 Limestone

Additions increase porosity and thermal conductivity of bricks but reduce mechanical strength and contribute to higher CO_2 emissions at elevated replacement rates. Thalmaier et al. [12] recommend a maximum of 5 wt.%. Bricks with 15 wt.% limestone exhibit high porosity and lower mechanical properties, making them only suitable for dry indoor environments [12].

4.3 Glass and ceramic waste

Additions of 15 wt.% have been shown to improve brick quality by increasing both density and flexural strength [5].

4.4 Waste marble powder

Although waste marble powder additions have a significant effect on the compressive strength of bricks, replacement rates up to 30 wt.% still yielded bricks suitable for structural applications [15].

4.5 Mixed C&DW

Specific recommendations are scarce. However, Zanelli et al. [16] demonstrated that 15 wt.% C&DW additions yielded acceptable values for working moisture, bulk density, and water absorption in bricks commonly used in industrial practice. Dubale et al. [7] proposed temperature-dependent replacement rates recommending 10 wt.% at 700 °C and 25 wt.% at 850 and 900 °C, in accordance with Indian standards.

4.6 Roof tile waste

Roof tile waste, which often constitutes a significant fraction of construction and demolition waste, can be incorporated into fired clay bricks at rates of up to 30 wt.% when produced at 900 °C to meet ASTM 3rd class

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standards. Additionally, up to 35 wt% can be used at firing temperatures of 850 °C and 900 °C to satisfy 2nd class requirements according to Indian standards. These formulations result in bricks with a water absorption of 19% and compressive strengths ranging from 6–9 MPa [17].

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5 Environmental impact and possibilities

5.1 Assessment of the release to soil and groundwater

To form a sound and safe basis for the evaluation of the environmental impact from cement-based products, the potential waterborne release of Chemical Species of Potential Concern (CSPCs) needs to be determined by leaching characterisation. Thus, the leaching characteristic is a material property that in combination with scenario-based assessment determines the direct impact on the recipients (e.g., surface water body, groundwater). Hence, leaching can be defined as the transfer of a chemical species from the solid to the aqueous phase. In granular condition (e.g., as recycled fine aggregates) leaching is controlled by the species solubility in the aqueous phase and by diffusion in monolithic state (e.g., submerged concrete bridge pier). Many studies have reported the leaching from concrete and mortar materials (e.g., [19,20]. The released quantity of chemical species from cement-based products is dependent on several factors like water contact time, temperature, aggressiveness of exposure conditions, concrete quality, shape of concrete and the type of binder used. The latter is important, since this is the material part that is most chemically active in concrete produced with good quality natural aggregates. Hence, most of the metal release is derived from the hydrated cement paste in mortar and concrete.

Leaching tests in laboratory are normally carried out under conditions that are controlled and with certain fixed test parameters. In the pH dependence test (EN 14429, EPA 1313), the aim is to study the equilibrium-based aqueous concentrations and release from the test material at different pH values. This type of leaching behaviour has been addressed for a range of inorganic materials (e.g., [21–25] . In contrast, in leaching tests where whole pieces of products or compacted granular materials are exposed (e.g., CEN/TS 16637-2:2014, EN 15863, EPA 1315), the leaching becomes controlled by diffusion and dissolution rates.

When water infiltrates voids and pores, the pH of an alkaline material (e.g., a granular or cracked cement-based product) gradually decreases due to carbonation, which may alter the leached concentrations and release rates of the substances of interest. In addition, external field conditions, such as exposure to slow-moving groundwater or direct rainfall, may further influence leaching because of differences in pH, buffering capacity, geochemistry, water contact, and degree of saturation [26]. Consequently, the release of substances may vary under different external pH conditions. This behaviour can be qualitatively predicted from laboratory leaching characterisation (EN 14429, CEN/TS 16637-3, EN14405, EPA 1314) and further assessed by geochemical speciation-based modelling, although chemical equilibrium is generally not reached under field conditions.

5.2 Potential negative environmental impacts of waste additions in fired clay bricks

It follows from the methodology of release assessment that the impact on soil and ground water from fired bricks depends on the alternative materials used and in which scenario the brick will be used. Hence, fired bricks produced with e.g. slight polluted C&DW may not increase the risk for leaching to soil and groundwater in its primary service life, i.e. used in the monolithic form as whole pieces of products. In the recycling stage it may be used in unbound use as filling materials etc. and will therefore require the relevant test regime (e.g. tests on crushed products).

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Only a limited number of the reviewed studies assessed the potential environmental impacts of incorporating waste into fired clay bricks by including leaching tests in their methodologies. Gencel et al. [14] reported that leaching tests did not reveal significant concentrations of heavy metals, indicating that these elements can be effectively immobilized within the brick matrix during firing. In contrast, Dubale et al. [17] evaluated the leaching potential of the raw waste powder prior to its incorporation into clay. Their results showed that cadmium concentrations in the leachate exceeded the limits set by the US EPA. Nevertheless, the authors concluded that using roof tile waste as a partial replacement in brick production yields an environmentally safe product [17]

5.3 Potential environmental benefits of waste additions in fired clay bricks

Environmental benefits, such as resource conservation and emission reduction are generally mentioned in different studies, but no detailed quantitative emissions or life cycle assessment data was included in any of the reviewed studies. Emission reduction strategies can follow two distinct paths. Lowering the firing temperature leads to reduced energy use and direct emissions but might influence key performance indicators such as compressive strength and porosity. In contrast, maximising waste additions diverts waste material from landfill, but might require higher firing temperatures, offsetting energy savings.

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6 The use of Marble dust in concrete production

6.1 Introduction of LC3 principle

Limestone Calcined Clay Cement (LC3) is a low-carbon binder concept in which a substantial share of Portland cement clinker is replaced by a combination of finely ground limestone ($CaCO_3$) and reactive calcined clay (often metakaolin derived from kaolinite-rich clays). A commonly cited reference composition for LC3-50 is approximately 50% clinker, 30% calcined clay, 15% limestone and 5% gypsum (as sulphate carrier), although the optimal proportions depend on locally available raw materials and targeted performance (https://lc3.ch). The underlying principle is to reduce CO_2 emissions by lowering the clinker factor (and the associated process and fuel emissions) while maintaining mechanical performance and durability through favourable hydration chemistry and microstructural development.

In concrete, LC3 behaves as a ternary system where (i) clinker hydration produces C–S–H and portlandite ($Ca(OH)_2$), (ii) the calcined clay reacts with portlandite and supplies reactive Al_2O_3 and SiO_2, promoting the formation of additional C-(A)-S-H (i.e., aluminium-substituted C–S–H), and (iii) limestone contributes both as a filler (packing/nucleation effects) and as a reactant in synergy with aluminates released from the clay. This synergy enables an "alumino-carbonate" reaction in which carbonate from $CaCO_3$ and reactive aluminates form stable carboaluminate hydrates (e.g., hemi- and monocarboaluminate) [27]. Such hydrates can precipitate within available pore space and contribute to a denser microstructure, often resulting in reduced permeability and improved transport resistance (e.g., to chloride ingress) at comparable strength levels relative to plain Portland cement systems. At the same time, sulphate balance (gypsum content) and fineness/particle-size distribution must be managed, as LC3 systems typically exhibit higher sulphate demand and may show increased water demand when the clay is very fine or has a high specific surface area [28,29].

From a materials engineering perspective, LC3 can therefore be described as a "reactive filler" concept: while limestone on its own is largely an inert or weakly reactive filler in cement, combining it with an alumina-rich supplementary cementitious material (calcined clay) shifts the hydrate assemblage towards more carboaluminates and more C-(A)-S-H. Concurrently, the reduced clinker content lowers portlandite availability and can refine the pore structure. In practice, LC3-based binders can achieve comparable 28-day strength to reference Portland cement concretes, but with a lower embodied carbon footprint and, in many cases, improved durability indicators in aggressive exposure conditions [30]. Performance is, however, sensitive to raw material quality (in particular the kaolinite content and calcination degree of the clay), particle-size distribution, temperature history, and admixture selection/dosage. Consequently, LC3 mixtures should be verified and optimised through mix design iterations and application-relevant testing.

The potential of marble dust (marble powder) in concrete is primarily linked to the fact that it often consists of finely ground carbonates (mainly calcite and/or dolomite) and can therefore act similarly to limestone filler in LC3-type systems: it may improve particle packing, provide nucleation surfaces for hydration products, and serve as a carbonate source for carboaluminate formation when combined with a reactive aluminosilicate source (e.g., metakaolin). In addition, marble dust can enable the utilisation of a local waste/by-product stream and reduce demand for virgin raw materials. The overall effect is strongly dependent on fineness, mineralogy and purity (e.g., $CaCO_3$ and potential $MgCO_3$ content) as well as the presence of impurities (e.g., silicates, clays or organics). However, numerous studies have demonstrated that LC3 binders exhibit a high

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tolerance to low-grade calcite and metakaolin waste materials, presenting a promising approach for waste valorisation with advantageous functional properties [31–33].

6.2 Preliminary results with Marble dust in concrete mix at laboratory scale

The waste marble dust from THRACE MARBLE S.A. in Greece was acquired and analyzed by XRD-Rietveld to determine its mineral content. Results indicated that the dust consisted predominately of calcite (>95%) as well as dolomite (<5%), making it well-suited as a carbonate source for LC3 systems. However, a major issue with the marble dust powder was its high agglomeration, rendering it unsuitable for addition to concrete mixes, as these agglomerates could create large defects and potentially weaken mechanical properties. These agglomerates form because, during marble cutting, the tiny dust particles carry surface charges that repel one another. To improve separation, a flocculant is added to the wastewater, causing particles to form larger, heavier clumps (or flocs) that settle faster. This process allows the mixture to separate into a sludge layer at the bottom and clearer water on top, which can then be reused or safely discharged. **Figure 6 (a)** shows the images of flocks of marble dust as captured using an optical microscope.

To effectively separate them, agglomerated marble dust was manually brushed through a 125 µm sieve, which worked well for lab-scale experiments (**Figure 6 (b)**). For preliminary tests, the sieved marble dust was used to prepare a first LC3 system with 50% replacement of cement. As seen in **Figure 7,** the sieving process yielded clearly in a full utilization of the potential of the marble dust as filler and reactant in LC3 systems. However, this manual lab scale process is highly time-consuming, and more efficient automated methods are needed to break the flocs for large-scale experiments or industrial trials.

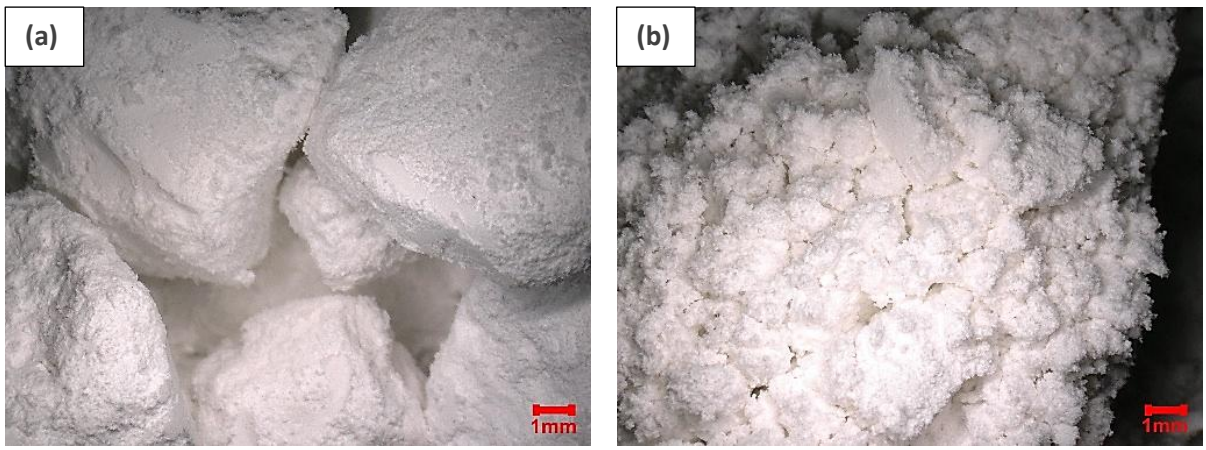


Figure 6: (a) Flocs, and (b) sieved marble dust powder

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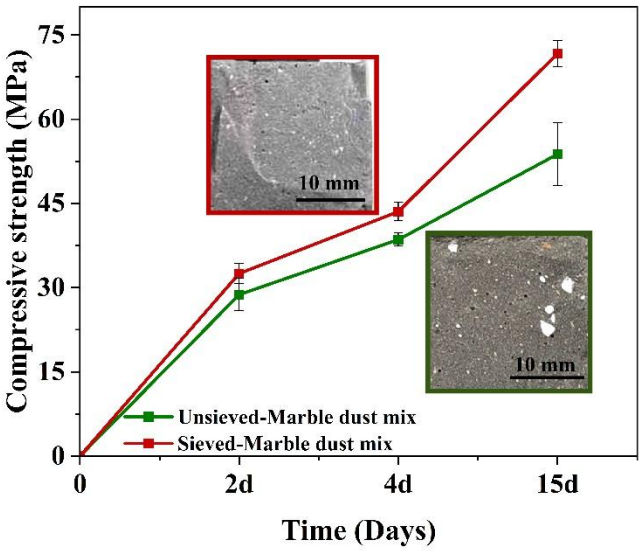


Figure 7: Compressive Strengths of marble dust calcined clay cement binders as a function of testing age. The inlets show the cross section of two representative specimens. (presented at the RILEM Spring Convention & Conference on Innovative Construction Materials and Processes for Sustainable Buildings and Infrastructure 2026, Ghent, Belgium, and to be published in Springer soon.)

To further explore the full potential of marble dust in LC3 systems, a detailed study was started. For making this study more efficient, the marble dust was sieved down semi-automated to a maximum size of 250 µm. Subsequently, various LC3 systems incorporating marble dust were developed - the designation marble dust calcined clay cement (MC3) was assigned to these systems. The clinker content was varied from 50 wt.% in MC3-50 to 15 wt.% in MC3-15. Necessary to ensure adequate sulfation gypsum content was measured by isothermal calorimetry and identified to be ~2 wt.% of the binder for MC3-50, MC3-35 and MC3-25 and 1 wt.% of the binder for MC3-15. The calcined clay-to-marble dust ratio was maintained at 2:1 across all mixtures. These developments were informed by prior research on LC3 systems [34] and aimed to achieve 28-day compressive strengths of 30, 40, and 50 MPa, as specified in the original project proposal. The detailed mineralogical composition of the raw binder components is provided in **Table 4**, based on XRD-Rietveld analysis, while **Figure 8** presents the binder formulations. All these systems were produced using a water-to-binder ratio of 0.4.

Table 4 Mineralogical composition of raw binder materials determined by XRD-Rietveld analysis. More details can be found in the references [34,35].

Portland Cement **CEM I 52.5 R (Holcim Pur 5 R), Germany**		Calcined clay Puzzo® grey, GEORG & SCHNEIDER, Germany		Marble dust THRACE MARBLE S.A., Greece		Gypsum Grüssing GmbH, Germany	
Minerals	**Wt. [%]**	**Minerals**	**Wt. [%]**	**Minerals**	**Wt. [%]**	**Minerals**	**Wt. [%]**
Alite (C3S)	54	Muscovite	7	Calcite	95	Gypsum	91

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Belite (C2S)	20	Feldspar	3	Dolomite	5	Anhydrite	6
Aluminates (C3A)	7	Quartz	25	-----	-----	Calcite	3
Ferrite (C4AF)	9	Calcite	1	-----	-----	-----	-----
Calcite	5	Anatase	1	-----	-----	-----	-----
Gypsum	2	Amorphous	63	-----	-----	-----	-----
Bassanite	3	-----	-----	-----	-----	-----	-----

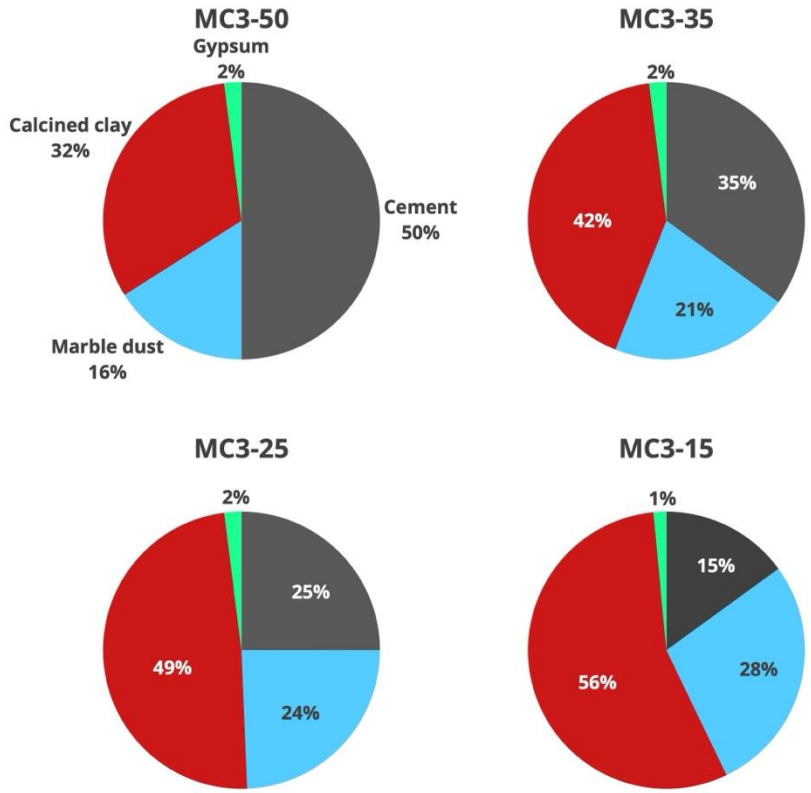


Figure 8: Marble dust calcined clay cement (MC3) binder formulations.

Table 5: MC3 mix designs

Raw ingredients	MC3-50	MC3-35	MC3-25	MC3-15
Cement	665	461	327	194
Marble dust	213	277	318	360
Calcined clay	426	553	636	721

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Gypsum	27	26	26	19
Water	532	527	522	518
Superplasticizer	6	3	4	5

The initial phase involved conducting the Hägermann flow table test to evaluate the flowability of the developed MC3 pastes. An illustration of this testing procedure with MC3-50 and MC3-15 pastes is shown in **Figure 9**. Adjusting workability, or flowability, is a critical practical consideration. Insufficient workability, characterized by a stiff paste, complicates mixing, placement, and pouring; it may fail to adequately fill voids, and the elevated yield stress can result in honeycombing, surface imperfections, and increased mechanical defects due to the material's limited capacity for rearrangement under low shear conditions. Conversely, excessive flowability, indicated by a highly fluid mix with a low yield stress, can lead to segregation, in which heavier particles settle while lighter ones rise. Additionally, it can lead to bleeding, particularly in systems containing sand or coarse particles. Overly water-rich or excessively paste-rich mixes to achieve higher flow can compromise mechanical strength, elevate shrinkage and creep, and negatively impact dimensional stability and early-age cracking resistance.

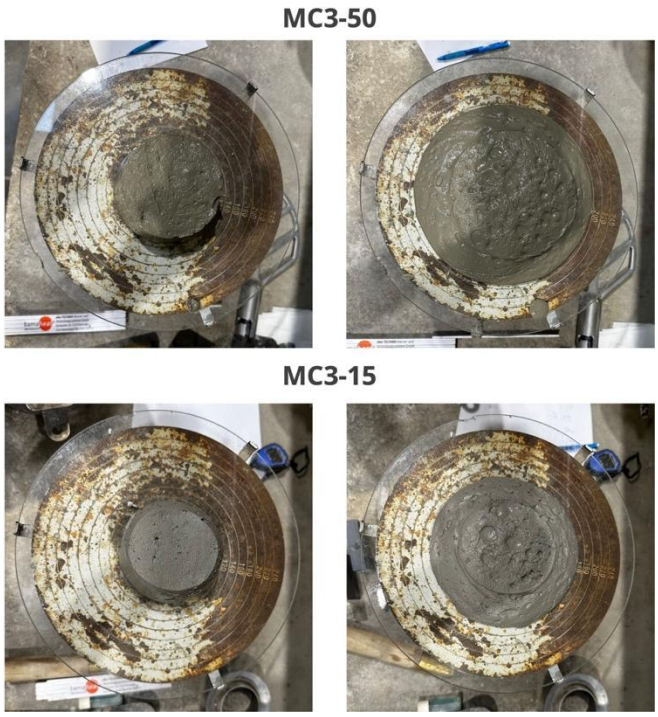


Figure 9: Spread diameter of MC3-50 and MC3-15 before (left) and after 15 strokes (right).

There is no established standard for the recommended flow diameter range; however, a range of 150-200 mm after strokes is generally considered adequate. In evaluating the various MC3 formulations developed herein, all satisfied this range criterion (see **Figure 10**). Nevertheless, a clear trend emerged: as the proportion of calcined clay and marble dust powder increases in the MC3 mixes, their workability decreases. This

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reduction is attributed to the higher water demand of the MC3 mixes, which results from the high specific surface area of calcined clay and marble dust particles[36].

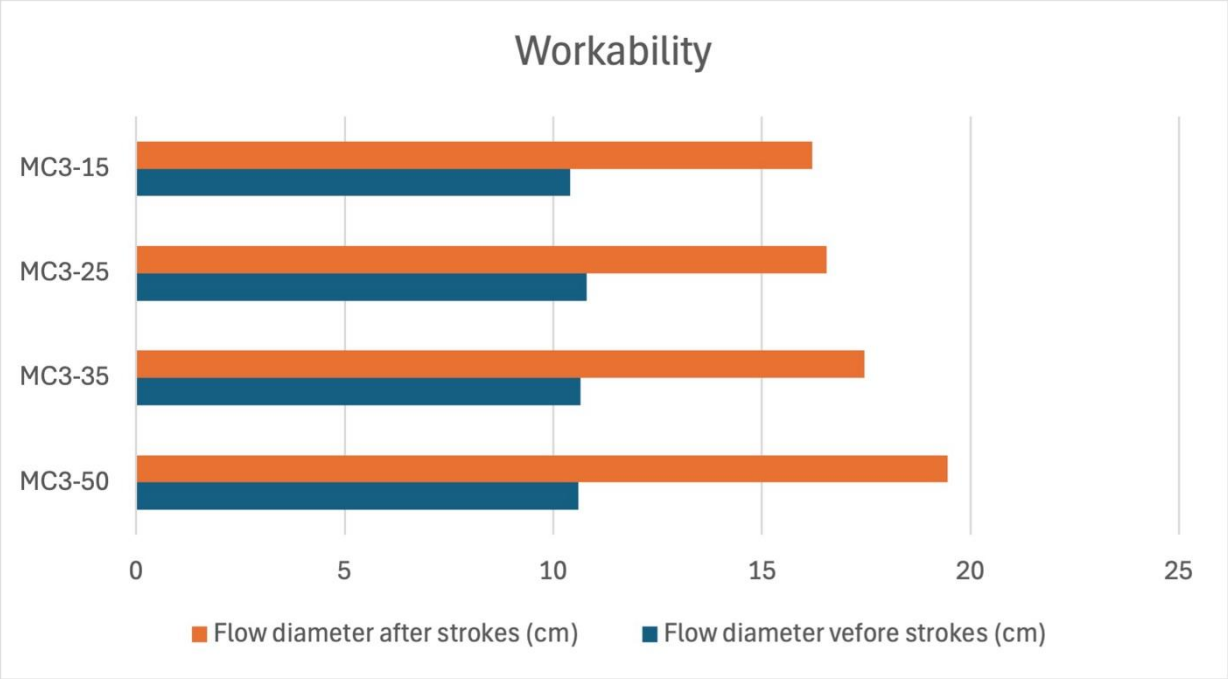


Figure 10: Quantified spread diameter of MC3 pastes.

Subsequent compressive-strength assessments were conducted at 3, 10, and 28 days after standard curing procedures. These tests complied with EN 196-1 and were performed on prismatic specimens. The results, depicted in **Figure 11**, illustrate a consistent trend across all ages examined: the specimen designated MC3-15 had the lowest compressive strength, followed by MC3-25, MC3-35, and MC3-50, which had the highest strength. This pattern correlates directly with the composition of the primary binder component, Portland cement, which is present at its minimum in MC3-15 and at its maximum in MC3-50.

More importantly, this trend persisted across all tested ages**. Notably, the strength targets set forth in the original proposal, specifically 30 MPa, 40 MPa, and 50 MPa after 28 days of hydration, were successfully achieved by the MC3-25, MC3-35, and MC3-50 mixtures, respectively**. These findings underscore the potential to incorporate waste marble into construction materials, enabling the development of tailored compositions that meet diverse mechanical property requirements at different target strengths.

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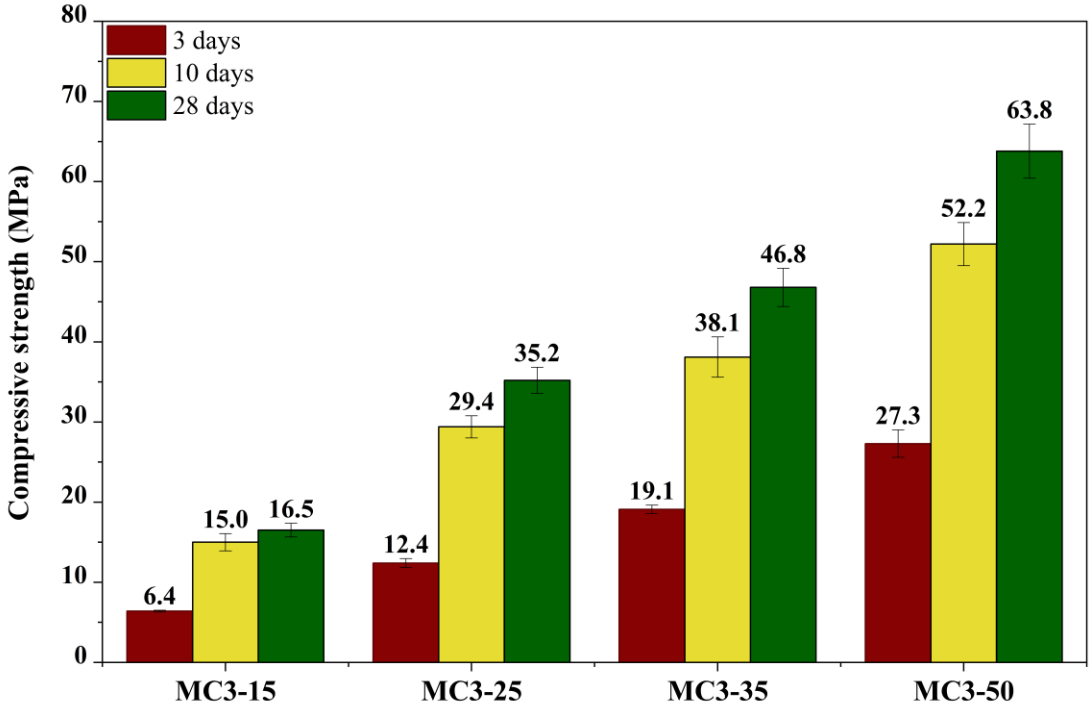


Figure 11: Compressive strengths of various MC3s after 3, 10, and 28 days of standard curing.

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7 Conclusions and next steps

7.1 Conclusions

Fired clay bricks incorporating moderate levels of inorganic waste can meet compressive strength and water absorption standards provided that waste content and firing temperature are properly balanced. Optimization of replacement rates is waste-specific and may also depend on the clay material used. For materials such as concrete, glass, ceramic, roof tile waste and mixed C&DW, additions of up to 35% are recommended in the literature at firing temperatures between 700 and 1100 °C. However, higher waste contents may reduce brick performance and limit their application range.

To achieve the dual goal of minimizing the environmental impact while meeting load-bearing and regulatory requirements, both waste additions and firing temperature must be carefully calibrated. The selected firing temperature should compensate for the effects of waste additions to maintain key performance indicators. More research is needed, particularly on mixed C&DW, to support the development of standardized production protocols that ensure consistent brick quality. Addressing the variability in C&DW composition and clarifying the influence of clay types are critical steps toward this goal. Efforts must also move beyond laboratory-scale testing to validate these approaches under industrial production conditions.

Additionally, it is necessary to perform sustainability assessments of not only the production process to assess the impact of temperature vs. the amount of waste added, but also material preparation and transport. These assessments are crucial for accurately determining the net benefit of substituting natural clay with waste materials. By addressing the full lifecycle of brick production, such evaluations can help identify optimal production conditions and support informed decision making.

Regarding the marble dust investigations, the results obtained so far demonstrate that this by-product has clear potential as a carbonate-rich component in low-carbon concrete binders based on the LC3 principle. Mineralogical characterization confirmed that the material is dominated by calcite with a minor dolomite fraction, which makes it suitable for use together with calcined clay in clinker-reduced systems. The laboratory work also showed that the main practical limitation is not the chemistry of the material itself, but its strong tendency to form agglomerates after industrial processing, making deagglomeration an essential pretreatment step. Once this issue was addressed by sieving, the marble dust could be successfully incorporated into marble dust calcined clay cement (MC3) formulations with a wide range of clinker contents. The developed binders showed acceptable workability, although the mixes became less flowable as the replacement level increased, reflecting the higher water demand of the fine carbonate and calcined clay fractions. Compressive-strength testing nevertheless confirmed a technically promising performance, and the target 28-day strengths of 30, 40 and 50 MPa were achieved for MC3-25, MC3-35 and MC3-50, respectively. Overall, these findings indicate that marble dust can be valorised as part of a circular and lower-carbon binder concept, provided that future work addresses efficient large-scale powder processing, further durability assessment and optimisation of the binder design for practical concrete applications.

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7.2 Next delivery

For the next reporting period, the focus will continue on the development of C&DW intermixes for fired brick production at laboratory scale. This work will begin with the basic characterisation of the waste raw materials, using feedstock collected from three locations in Greece (one location is already established) with different levels of pre-sorting, including one highly advanced sorting stream conducted by ICCS. Based on this characterisation and the literature review already conducted, the recipe will be optimised through small-scale laboratory testing in order to identify the most promising formulations. The best-performing mixtures will then be selected for further testing in pilot scale.

Regarding the further development of MC3 technology with marble dust, the next phase will include a more in-depth analytical investigation of the developed MC3 binders, including TGA, XRD, SEM and MIP, in order to better understand hydration processes, phase development and microstructural characteristics. In parallel, the key material-design parameters will be further optimised to improve the robustness and performance of the binder systems. The generated results will also form the basis for the preparation of a scientific article.

An assessment of the upscaling potential will also be carried out for both material pathways addressed in this deliverable. For C&D waste in fired clay bricks, the main focus will be on the availability and consistency of suitable mineral fractions, the influence of pre-sorting quality, and the compatibility of the selected waste streams with existing industrial brick-production processes. For marble dust, the upscaling assessment will focus on the feasibility of using this carbonate-rich by-product as a component in LC3-type concrete binders, with particular attention to powder handling, deagglomeration, mix design robustness and the potential for implementation in larger-scale concrete production. Together, these assessments will provide a first basis for evaluating technical feasibility, process integration and the wider circular-economy potential of both solutions.

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