

Research paper

Clay-gypsum mortars: The influence of binder and sand ratios

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ABSTRACT

Prefabricating building elements minimizes material waste and enhances quality control. This study proposes a new formulation of clay-based mortars foreseen to produce prefabricated coating panels. The effect of the binder: sand ratio (1:2, 1:3 and 1:4, in volume) and clay replacement by gypsum (5 %, 10 % and 20 %, in volume) is assessed. The investigation focused on key properties, including workability, flow table consistence, setting time of the fresh mortars, linear shrinkage, bulk density, and flexural and compressive strengths of the hardened mortars. The clay content demonstrates a proportional impact on dimensional variation, with linear shrinkage exceeding 2 % in mortars with high clay content. Gypsum partial substitution has a small effect on fresh mortar properties, but it significantly reduces setting time and enhances mechanical performance. In mortars with different sand contents, replacing clay by 20 % gypsum increases compressive strength by 320 % and flexural strength by 685 %. Therefore, these optimized clay-gypsum mortars seem to have the potential for producing environmentally friendly prefabricated coating panels.

1. Introduction

The inefficient utilization of finite natural resources contributes significantly to waste generation due to unsustainable and ineffective processes. The European Union (EU) annually produces approximately 800 million tons of construction and demolition waste (CDW), which represents around 32 % of the total waste generated in the EU [45]. The main proportion of these CDW comprises bricks, tiles, concrete, cement-based mortars, glass and metal [81]. To reduce the consumption of natural resources and CDW generation, the implementation of optimal designs and advanced technologies are essential to minimize material waste at construction sites. Enhancing construction techniques and selecting environmentally friendly materials can reduce the environmental impact of the building industry. Furthermore, prefabricated manufactured solutions can help reducing waste production and ensure standardized products [10].

The utilization of reusable materials in construction is still a matter of ongoing debate. A lack of standardized practices and insufficient government investment continues to drive the generation of more CDW. The European List of Residues [44] classifies excavation earth, such as that produced during the construction of underground floors, as a waste product. However, this material has a high degree of versatility and, just by grinding and eventual sieving, can be used for a wide range of

purposes in the building process [71]. In fact, earth, excavated from soil, composed by different types and fractions of clay, silt, sand and coarser aggregates, is a readily available and locally sourced material that requires minimal transportation and treatment. Used without calcination allows direct reuse or repurposing at the end of its life. This circular use is only possible when no chemically reactive additions are applied [47].

From a sustainability perspective, an ideal building material or product should have low embodied energy and be capable of continuous recycling or repurposing at the end of its life [65]. To minimize the environmental impact of the construction industry, it is crucial to prioritize the use of sustainable materials and optimize their application. Circular economy (CE) proposes a closed-loop system aiming at minimizing waste of material by strategically managing the “supply chain,” optimizing “materials,” refining “design and production,” and implementing effective “management and policy-making” [53]. The supply chain is a complex management process, beginning with raw material source, navigating into the transformation, and ending in the distribution or disposal. Regarding design and production, adopting prefabricated solutions can minimize waste while enabling quality control. Moreover, the design and production of standard solutions not only reduce waste but also foster cleaner and more efficient workspaces. Finally, within the scope of management and policymaking, emphasis should be placed on ensuring low carbon dioxide (CO₂) emissions and

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prioritizing the sustainable sourcing of materials. Such measures align with CE principles, demonstrating a strong interest in environmentally responsible and resource-efficient practices in construction.

Compared to cement-based mortars, clay-based mortars may offer adequate durability when applied as indoor coatings, and plastering for dry areas. The repairs on clay-based plasters are easily performed, just by using a humid sponge [46]. However, clay mortars are also used for outdoor coatings, as renders. Many examples of ancient buildings, such as Ait Benhaddou in Morocco, the Great Mosque of Djenné in Mali, and Bam Citadel in Iran, feature clay renders that meet requirements [9]. Some clay-based mortars used for rendering have bio-based additions, such as animal dung [64], or chemically reactive additions, such as air lime or gypsum-based binders, to increase durability against rain. Mortars with these binders are no longer reusable but remain recyclable.

Clay mortars are eco-efficient building products with the potential to reduce environmental impact due to their low embodied energy [75]. Applied as indoor coatings, such as plasters, they further improve indoor comfort by functioning as moisture buffers, effectively regulating relative humidity levels [78]. In addition, they offer significant environmental benefits by capturing CO₂ [1,80] and ozone [68]. Sand is widely used as a complementary aggregate in clay-based mortars [47,66], particularly when the earth's sand content is relatively low. It helps to control shrinkage by forming a skeleton [52] similar to that found in mortars produced with other binders. However, clay-based mortars typically exhibit relatively low mechanical strength and susceptibility to water damage, which can be limiting for some applications, although these challenges can be overcome. One critical aspect of clay-based mortars as a building product is the curing time, as without chemically reactive additions, they harden and develop mechanical strength only through water evaporation. This process can take hours or even days, depending on factors such as mortar formulation, substrate in contact with the mortar, application technique and environmental conditions. To improve performance, natural or chemical stabilizers, such as fibers [50,56,76], tannins [49,84], gypsum [55,79], cement [48, 50] and hydrated lime [50], can be incorporated into clay mortar formulations.

One of the primary objectives of industrial manufacturing building elements is to ensure continuous production, where time plays a crucial role in maximizing efficiency and profitability. Consequently, the production of clay-based solutions may require additions that facilitate the rapid development of mechanical properties. However, unlike cement and lime with hydraulic properties, these additives should not significantly contribute to raising the environmental impact. Calcium sulfate hemihydrate (from now on called gypsum for simplification) is a fast-setting material, with rapid crystal formation occurring shortly after hydration, leading to a swift increase in mechanical strength [87]. Additionally, gypsum is a non-hazardous, recyclable material with a positive life cycle [15]. Compared to cement, which requires thermal treatment at approximately 1450 °C and significant energy for milling, or air lime, which is produced at around 900 °C and needs water for hydration, gypsum, produced at approximately 150 °C, stands out as an eco-friendly binder with lower greenhouse gas emissions [61]. In addition to its fast-setting properties, the literature reports that the incorporation of gypsum into clay mortar formulations can improve mechanical strength, provide some hydrophobic properties [55,59,60, 70] and decrease the liquid water absorption [70] without drastically reducing the adsorption capacity or moist buffer capacity [55]. Notably, clay-gypsum plastering is an ancient technique that is still being used in some countries and presents good durability conditions [73].

Table 1 summarizes the literature on clay-based mortars without fibers or gypsum addition, along with their characterization results. Some studies use earth, which can already include fractions of silt and sand, along with clay, while others concentrate solely on the clay fraction. The most referenced clays in the literature are non-swelling, particularly illitic and kaolinitic. To mitigate drying shrinkage, aggregate ratios greater than 1:2 are frequently used. The specific tests chosen

Table 1

Synthesis of research on clayish earth-based mortars without additions, arranged in chronological order.

Reference	Mortars analyzed	Tests	Results
[72]	Earth mortars not specified	Shrinkage (non-specified) CStr (non-specified) Ed (non-specified)	up to 2.5 % 1–3 N/mm ² 0.45–3.0 N/mm ²
[11]	Five earth mortars: two pre-mixed mortars and three formulated; four mortars with montmorillonite and illite and one with kaolinite; water content of 17–20 %	Consistence [25] WD (non-specified) LS [12] DBD [12] FStr [20] CStr [20] AStr [23]	160.0–185.0 mm 2.0–2.1 kg/dm ³ (cylindrical container and compacted) 1.5–2.5 % 1.7–1.8 kg/dm ³ 0.49–0.69 N/mm ² 1.3–2.1 N/mm ² 0.006–0.084 N/mm ² 0.11–0.14 N/mm ² (*) 0–27 %
[17]	Eighteen earth mortars with two illitic-kaolinitic clays, beside the reference mortar, different earth:sand proportions and kneading water content	VS (non-specified) CStr [37]	2.2–4.2 N/mm ² (water content variation); 1.6–9.6 N/mm ² (temperature variation)
[55]	Illitic earth-based mortars formulated with a volumetric proportion earth:sand 1:3, using a reference sand granulometry along with two alternative granulometries	Consistence [25] WD [29] LS [12] DBD [19] FStr [20] CStr [20] AStr [24] DAR [12] DynAdsDes [12] TC (ISOMET Heat Transfer)	173.2 mm 2018.8–2130.7 kg/m ³ 0–0.8 % (Prismatic samples) 1770–1910 kg/m ³ 0.20–0.25 N/mm ² 0.63–0.88 N/mm ² 0.02–0.07 N/mm ² 1.02–4.42 g up to 60.0 g/m ² 1.18–1.46 W/(m.K)
[56,57]	Illitic earth-based mortars with different volumetric proportions earth:sand (1:2, 1:2.5, 1:3 and 1:4) with water content of 18–20 % in proportional amounts relative to the total volume of clayish earth and sand	Consistence [25] WD [29] LS [12] DBD [12,19] FStr [20] CStr [20] AStr [23]	162.3–173.2 mm 2.10–2.13 kg/dm ³ 0.34–1.43 % 1.84–1.95 kg/dm ³ 0.22–0.27 N/mm ² 0.53–0.99 N/mm ² 0.07 N/mm ²
[67]	Kaolinitic clay:fine sand: coarse sand (mass ratio of 17 % kaolin, 23 % fine sand and 60 % coarse sand); cob earth from Saint-Sulpice La-Forêt	CStr [86]	0.75–1.8 N/mm ²
[77]	Six earth-mortars (earth: fine sand:coarse sand) formulated in the laboratory with different volumetric ratio	LS (specimens of 200 mm x 237.5 mm x 15 mm in metallic molds) Ed [31] AStr [12,24] DAR [12] TC (ISOMET Heat Transfer)	0–3 % 1000–1650 m/s (on tile) ≥ 0.14 N/mm ² 0.3–1.3 g (on tile) 1.00–1.35 W/(m.K) (on tile)
[48]	Three earth mortars using material from non-deteriorated parts of	Consistence [25]	170–177 mm

(continued on next page)

Table 1 (continued)

Reference	Mortars analyzed	Tests	Results		
[58]	unstabilized rammed earth walls and one commercial mortar	WD [29]	1872–2001 kg/m ³ (cylindrical container and compacted)		
		LS (Alcock test [54,85])	0.1–1.2 %		
		DBD [19]	1666–1915 kg/m ³		
		FStr [20]	0.17–0.38 N/mm ²		
		CStr [20]	0.51–0.98 N/mm ²		
		Ed [32]	1065–5860 N/mm ²		
		WAULP [35]	64–2254 s (4 ml)		
		WAC [33]	0.03–0.14 kg/(m ² . s ^{1/2})		
		DB [36]	0.08–0.13 kg/(m ² . h)		
		TC (ISOMET Heat Transfer)	0.90–1.35 W/(m.K)		
		Consistence [25]	165.2–173.2 mm		
		WD [29]	1957.8–2130.7 kg/m ³		
		LS [12]	0.85–3.30 % (Prismatic samples)		
		DBD [19]	1.74–1.91 kg/m ³		
		FStr [20]	0.18–0.25 N/mm ²		
CStr [20]	0.45–0.88 N/mm ²				
Ed [32]	1.38–4.35 N/mm ²				
AStr [23]	0.02–0.07 N/mm ²				
DAB [12]	1.1–8.8 g				
DynAdsDes [12]	35–110 g/m ²				
WAC [33]	0.15–2.01 kg/m ² /min ^{1/2}				
DB [36]	0.15–0.17 kg/m ² /h				
WED [62]	289.6–343.2 m ² - 7.5–12.7 mm				
TC (ISOMET Heat Transfer)	0.97–1.35 W/(m.K)				
(Santos et al., 2021b)	Four earth mortars with illitic clayish earth with different ratios of fine and coarse sand	Consistence [26,25]	119.0–168.0 mm		
		WD [29,28]	2040–2060 kg/m ³		
		LS [13]	0–4 % (Prismatic samples)		
		DBD [19,18]	1.77–1.79 kg/m ³		
		FStr [21,20]	0.17–0.22 N/mm ²		
		CStr [21,20]	0.39–0.58 N/mm ²		
		Ed [32]	2093–3933 N/mm ²		
		AStr [23]	0–0.03 N/mm ²		
		DAR [13]	1.4–2.6 g		
		Consistence (non-specified)	160–190 mm		
[66]	Five earth mortars varying sand ratios	WD [29,28]	1607–1787 kg/m ³		
		LS [12]	0.42–6.53 %		
		DBD [19,18]	1691–1775 kg/m ³		
		FStr [21]	0.58–1.5 N/mm ²		
		CStr [21]	1.22–4.2 N/mm ²		
		DBD [41]	1990 kg/m ³		
		LS [2]	6.2 %		
		CStr [42]	6.6 N/mm ²		
		DynAdsDes [51]	141.1 g/m ²		
		WED [62]	0.5 mm		
[83]	One mortars with illitic clayish earth from Palemono, Lithuania	Consistence [26,25]	120 mm		
		Consistence [27]	11 mm		
		WD [29,28]	1998.5 kg/m ³		
		Air content [30]	4.4 %		
		Water retention [40]	93.8 %		
		DBD [19,18]	1787.6 ± 22.5 kg/m ³		
		Total pore volume (by MIP)	0.14 cm ³ /g		
		[7,8]	One reference clay mortar mainly kaolinite and glauconite, minor illite and smectite. Volumetric proportion clay:sand, 1:4	Consistence [26,25]	11 mm
				WD [29,28]	1998.5 kg/m ³
				Air content [30]	4.4 %
Water retention [40]	93.8 %				
DBD [19,18]	1787.6 ± 22.5 kg/m ³				
Total pore volume (by MIP)	0.14 cm ³ /g				

Table 1 (continued)

Reference	Mortars analyzed	Tests	Results
[6]	One mortar composed by red clay and sand with mass ratio 1:5; earth from Szkucin, Poland	Autopore IV 9500	
		LS (non-specified)	2.9 %
		RCW (non-specified)	44.3 % weight loss after 1 min
		FStr [21,20]	0.43 N/mm ²
		CStr [21,20]	1.26 N/mm ²
		Ed [32]	91.7 N/mm ²
		Consistence [26,25]	130 mm
		Consistence [27]	11 mm
		WD [29,28]	2059.5 kg/m ³
		Air content [30]	7.4 %
		Water retention [40]	94.2 %
		DBD [20,22]	1950 kg/m ³
		Total pore volume (by MIP)	0.13 cm ³ /g
		Autopore IV 9500	
		LS (non-specified)	0.9 %
RCW (non-specified)	75 % weight loss after 1 min		
FStr [21,20]	0.88 N/mm ²		
CStr [21,20]	2.06 N/mm ²		
Ed [32]	361 N/mm ²		

Notes: AStr – adhesive strength; CStr – compression strength; Consistence – flow table consistence or plunger penetration; DAR – Dry abrasion resistance; DB – Drying behavior; DBD – dry bulk density; DynAdsDes – Dynamic vapour adsorption and desorption; Ed – dynamic modulus of elasticity; FStr – flexural strength; LS – linear shrinkage; MIP - Mercury Intrusion Porosimetry; RCW - Resistance to contact with liquid water; TC – Thermal conductivity; VS – volumetric shrinkage; WAC – Water absorption by capillarity action; WAULP – Water absorption under low pressure; WED – Water erosion by dripping action; WD – wet density; "no specified" – standard or test procedure is referred; (*)the application of a clay grout before the application of clayish earth plaster was analyzed.

for characterizing these mortars depend on the intended application and the environmental conditions to which the mortars will be exposed.

Table 2 presents a synthesis of the literature on clay-based mortars without fibers, incorporating gypsum, along with their characterization results. The gypsum additions cited in the literature typically range from 2 % to 20 % of the total weight of the earth and sand. Researchers have predominantly explored the impact of gypsum on water durability and vapor permeability.

Compared to previous studies on earth mortars, only a limited number of studies have explored the use of clay with the incorporation of gypsum as summarized in Table 2. Previous studies have primarily focused on the characterization of mortars with high gypsum content, typically added based on the total weight of the earth (comprising fractions of clay, silt, and sand). The influence of the binder:sand ratio and the effect of small substitution of clay by gypsum, and the investigation of new applications and technologies for clay-gypsum mortars continues to be a gap in the literature. The present study aims to address this gap by contributing to a deeper understanding of the potential of clay-gypsum mortars and their potential viability to produce manufactured panels for indoor applications. For that, the effects of varying binder:sand ratios (1:2, 1:3, and 1:4, by volume) and small replacements of clay by gypsum (5 %, 10 %, and 20 %, by volume of the clay) on both fresh and hardened properties were evaluated. For the fresh properties, flow table consistence, mini-slump test and setting time were performed. For the hardened properties, flexural and compressive strength tests were performed.

Table 2
Synthesis of research on clayish earth-based mortars with gypsum addition, arranged in chronological order.

Reference	Mortars analyzed	Tests	Results
(Mattone et al., 2011)	Earth-based mortars with gypsum addition (20 % wt). Earth from La Joya, Veracruz, Mexico	WES [62]	0.05 mm/min
[59]	Two-layer coating system with illitic earth-based mortar with and without (non-specified) gypsum (20 % wt). Earth from Douar Oulad, Mezzoug, Marrakesh, Morocco	WAULP [62]	10 cm ³ (15 min)
[55]	Illitic earth-based mortars formulated with a volumetric proportion earth:sand 1:3. The reference mortar compared with mortars with hemihydrate gypsum additions in varying proportions (2–8 % wt)	WED [62]	0–13 mm
		WES [62]	0.4–15 mm/min
		WAULP [35]	10–16 cm ³ (15 min)
		Sbond (non-specified)	16–19.5 kPa
		Per [34]	Comparison in percentage
		Colorimetric test (spectrophotometer)	L* = 50.92 ± 0.24
		Consistence [25]	164.0–174.3 mm
		WD [29]	2018.8–2130.7 kg/m ³
		LS [12]	0–0.8 % (Prismatic samples)
		DBD [19]	1770–1910 kg/m ³
FStr [20]	0.25–0.89 N/mm ²		
CStr [20]	0.88–2.27 N/mm ²		
AStr [24]	0.06–0.07 N/mm ²		
DAR [12]	0.02–1.05 g		
DynAdsDes [12]	up to 60.0 g/m ²		
TC (ISOMET Heat Transfer)	1.18–1.54 W/(m.K)		
[70]	Two-layer coating system with illitic earth-based mortar with and without addition hemihydrate gypsum (5 % and 20 % wt) Earth from Santena, Turin, Piedmont, Italy, with clay fraction of kaolinite, illite, and smectite-montmorillonite	WED [62]	0–9.6 ± 2 mm
		WES [62]	0.12–20 mm/min
		WAULP [35]	16–40 cm ³ (5 min)
		Per [34]	8.0–9.2 ± 2 (Two-layer sample)
[79]	Illitic earth-based mortars formulated with a volumetric proportion earth:siliceous sand 1:3. The reference mortar compared with mortars with additions: 1–6 % wt raw gypsum; 1–4 % wt unheated and thermal treated gypsum plasterboard waste	DR (non-specified)	1.40–2.66 mm
		Colorimetric test (spectrophotometer)	ΔE* > 3
		Durability accelerated aging thermo-hygrometric cycles	0.24–0.29 % weight loss
		Consistency [25]	129.0–175.0 mm
		WD [29,28]	1820–1970 kg/m ³
		LS [13]	0.7–5.6 % (prismatic samples)
		DBD [19,18]	1.70–1.74 kg/m ³
		Ed [32]	2679–5129 N/mm ²
		FStr [21]	0.52–0.81 N/mm ²
		CStr [21]	1.63–2.60 N/mm ²
DAR [13]	0.11–0.51 g		
DynAdsDes [13]	123.1–128.2 g/m ²		
RCW (non-specified)	degraded 1 min to undegraded		
TC (ISOMET Heat Transfer)	0.66–0.93 W/(m.K)		

Notes: AStr – adhesive strength; CStr – compression strength; Consistence – flow table consistence; DAR – Dry abrasion resistance; DBD – dry bulk density; DR – Drilling Resistance; DynAdsDes – Dynamic vapor adsorption and desorption; Ed – dynamic modulus of elasticity; FStr – flexural strength; LS – linear shrinkage; Per – Water vapor permeability test; RCW – Resistance to contact with liquid water; SBond – Shear test to evaluate the bond of the plasters to the wall; TC – Thermal conductivity; WAULP – Water absorption under low pressure; WED –

Water erosion by dripping action; WES – Water erosion spray test; WD – wet density; "no specified" – standard procedure is not referred.

2. Materials and methods

2.1. Materials

The reference mortars in this study are composed of clay, CEN standardized sand and water. The clay originated from Germany and was supplied by Silex, NL. The mineralogical composition of the raw material, determined by X-ray diffraction analysis (XRD), is presented in Fig. 1a). The chemical composition of the clay was evaluated by X-ray fluorescence spectroscopy (XRF), and the results are summarized in Table 3. The clay presents kaolinite, quartz, and illite traces (K). The particle size distribution of the clay were assessed using a Morphologi G3 particle characterization instrument from Malvern Instruments Limited. Clay samples, prepared as dry powders, were analyzed in triplicate using an automated dispersion system. The samples were dispersed onto a glass plate under the following conditions: sample volume of 13 mm³, injection pressure of 4 bars, injection time of 40 ms, and setting time of 120 s. Over 30,000 particles were analyzed in total. The largest and smallest clay grain sizes were approximately 10 μm and 0.2 μm, respectively (Fig. 1b)). The Atterberg limits of the clay and the plasticity index were measured following the ASTM D4318 [3] standard. The plasticity index of the clay was 16, with a liquid limit of 21 % and a plastic limit of 5 %. The sand (S) used was a CEN standardized sand [38], commercialized product by Normensand GmbH, consisting of several different sieving sand fractions with a granulometry inferior to 2 mm. The particle size distribution of the sand was assessed in accordance with EN 196–1 [38], and depicted in Fig. 2. Calcium sulfate hemihydrate, designated by gypsum (G), was supplied by Formula, Saint-Gobain, BE. It is a fine material with a minimum purity of 95 %, and <6 % (wt) is retained on the 100 μm sieve. Material densities were measured using a gas pycnometer, Micromeritics AccuPyc II 1340, with the results detailed in Table 3.

2.2. Mortar design

A total of 12 mortars with different compositions were tested. The compositions were prepared with three different binder:sand ratios: 1:2; 1:3, and 1:4, in volume. Two matching studies were conducted focused on the influence of the clay:sand ratio (reference mortars K33, K25 and K20 on Table 4) and the effect of partially substituting clay by small quantities of gypsum (all the other mortars in Table 4). Gypsum partial substitution was set at 5 %, 10 % and 20 % of the clay volume (e.g., K16-G4, where G4 is 20 % of the total binder volume). The mortars were designated based on their volumetric binder (clay and gypsum) ratio. The sand's volume was not mentioned. Although, it corresponds to the difference of combined clay and gypsum volume and the total volume, for example, K20-G5 = 20 units of clay, 5 units of gypsum and 75 units of sand, by volume. Mortars without gypsum substitutions are designated only by two characters (e.g., K20). The water ratio was kept constant across all compositions at 0.8 (by mass of the binder, K + G), ensuring uniform water content to isolate the effects of varying dry material proportions. Table 4 provides a detailed overview of the mortar compositions. The weight proportion was determined by multiplying the bulk density of each material by its corresponding volumetric proportion.

2.3. Mortars production and methodology

All fresh mortars were prepared using a 10-liter capacity Hobart mixer. Initially, the dry components were homogenized for 60 s. After homogenization, water was added over the next 30 s, followed by an additional 90 s of mixing. Subsequently, the mixer was paused for 30 s to scrape the bowl and ensure no unmixed material remained adhered to its

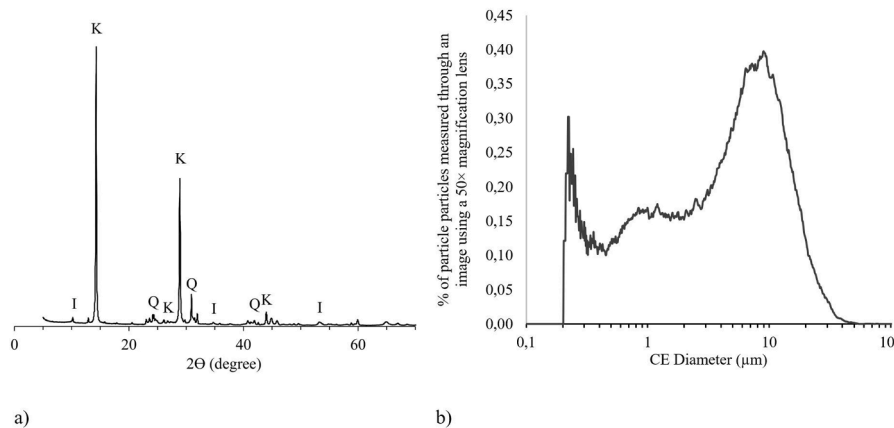


Fig. 1. Kaolinitic clay: a) XRD diffractogram (K-kaolinite, Q-quartz, I-illite); b) Particle size distribution.

Table 3
Chemical composition of the kaolinitic clay evaluated by X-ray fluorescence spectroscopy and density of all materials by gas pycnometer.

Chemical compound	wt (%)
SiO ₂	58.20
TiO ₂	0.53
Al ₂ O ₃	37.90
Fe ₂ O ₃	0.38
CaO	0.08
MgO	0.10
K ₂ O	2.80
Na ₂ O	0.01
Material	Density [kg/m ³]
Kaolinitic clay	2406
Gypsum	2960
Sand	2646

Table 4
Mortars composition in volume and mass proportions.

Mortars ID	Vol. Ratio		Mass Ratio (K:G:S)	water/ (K + G) [kg/kg]	water/ (K + G + S) [kg/kg]
	(binders: S)	(K:G:S)			
K33	1:2	1:0:2	1:0:2.20	0.80	0.25
K32-G1	1:2	1:0.05:2.1	1:0.06:2.32	0.80	0.25
K30-G3	1:2	1:0.1:2.2	1:0.14:2.44	0.80	0.25
K27-G6	1:2	1:0.25:2.5	1:0.31:2.75	0.80	0.25
K25	1:3	1:0:3	1:0:3.30	0.80	0.19
K24-G1	1:3	1:0.05:3.15	1:0.06:3.47	0.80	0.19
K23-G2	1:3	1:0.1:3.3	1:0.14:3.67	0.80	0.19
K20-G5	1:3	1:0.25:3.75	1:0.31:4.12	0.80	0.19
K20	1:4	1:0:4	1:0:4.40	0.80	0.15
K19-G1	1:4	1:0.05:4.2	1:0.06:4.63	0.80	0.15
K18-G2	1:4	1:0.1:4.4	1:0.14:4.89	0.80	0.15
K16-G4	1:4	1:0.25:5	1:0.31:5.50	0.80	0.15

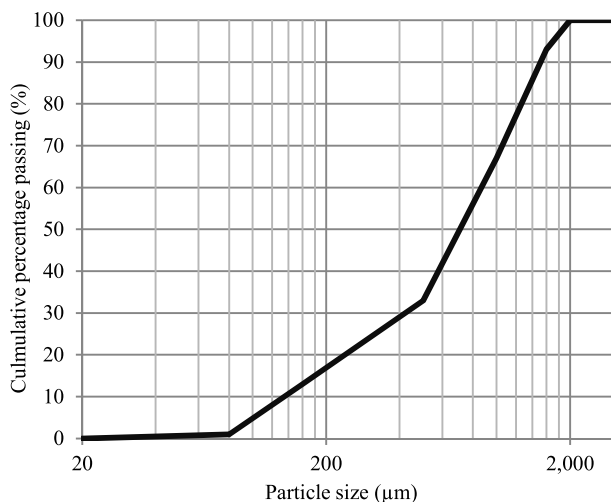


Fig. 2. Sand particle size distribution.

walls. Mixing then resumed for a final 30 s. The mixing procedure comprised a total of 240 s at a low-velocity mixing. In this study, time zero ($t = 0$ min) was defined as the time when water was first mixed with the dry materials. In Fig. 3a, flowchart is presented to summarize the experimental steps. The fresh state performance was assessed

immediately after mortar production: the mini-slump, flow table consistence, and setting time were performed simultaneously. After the fresh state tests, specimen preparation was carried out. The molded specimens were cured and linear shrinkage was assessed. Before the mechanical tests, the bulk density of the specimens was measured. The intact specimens were used for the flexural test, and one of the two halves of each broken specimen was used to perform the compressive test.

2.3.1. Manual workability, flow table consistence, mini slump test and setting time

All mortars were characterized in the fresh state. Workability was assessed when handling the mortar during the mixing and used to produce the samples. Flow table consistence was evaluated following the EN 1015-3 [26] standard. The test involved filling in two half heights a conical mold ring with internal dimensions of 60 mm height, 100 mm in diameter at the base, and 70 mm in diameter at the top, each half rammed with a metallic stick ten times to eliminate air, and the remaining excess material was scraped. The flow table consistence mold was removed. The initial height (H) and the average diameter (Ds) were measured and recorded as mini-slump values. Subsequently, the table was dropped 15 times within 15 s, the final diameter was measured in two perpendicular directions. The flow table consistence was calculated as the average of these two diameters.

The influence of gypsum substitution on the workable life of the mortars was assessed using the Vicat apparatus following the EN 196-3 [39]. The initial setting time (IST) was recorded when the needle freely penetrated the mortar, within a distance of 4 ± 1 mm from the bottom of

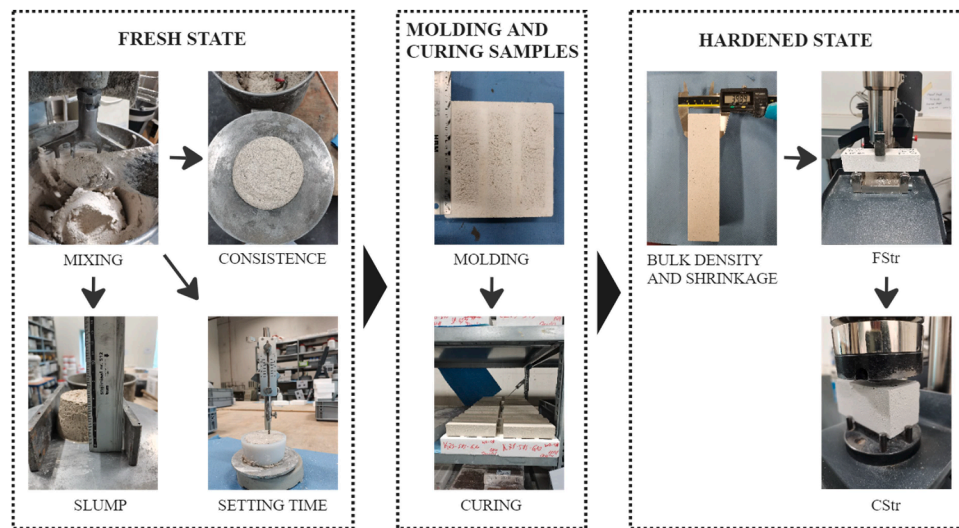


Fig. 3. Experimental synthesis and sequence; FStr - flexural strength test, CStr - compressive strength test.

the mold. After determining the IST, the sample mold was inverted to test the final setting time (FST), defined as the time when penetration into the samples was 0.5 mm using the needle for the final test. The Vicat mold was filled right after the mixing protocol and positioned for the initial setting time measurements. Time zero is considered the time when the water was first added to the mixing. The measurements were conducted at intervals of 1 min, with a maximum testing time of 480 min.

2.3.2. Mortar samples preparation

The testing methodology takes into consideration the foreseen pre-fabrication of modular indoor coating panels. The guidance outlined in EN 998-1 [43] involved selective assessment of specific hardened properties, namely bulk density (BD), flexural (FStr) and compressive (CStr) strength. Additionally, linear shrinkage (LS) was measured. Following the mixing procedure, mortar samples were cast into molds measuring $40 \times 40 \times 160 \text{ mm}^3$ for hardened state properties testing. The molds were filled in two layers, each layer compacted mechanically using a jolting table and leveled with a metal knife. The number of jolts (10+10) was chosen to prevent the migration of fine material and minimize water segregation. The samples were kept in room condition ($20 \pm 2 \text{ }^\circ\text{C}$ at $40 \pm 10 \text{ \% RH}$), de-molded after four days and cured under the same conditions. Hardened state tests were performed in triplicate, and results are presented as the corresponding averages and standard deviations.

2.3.3. Bulk density, linear shrinkage, flexural and compressive strength testing

The hardened properties were evaluated after 90 days. The BD was determined by measuring the sample volume with a digital caliper and the mass of the sample at room temperature, with an accuracy of 0.01 %. Due to the presence of gypsum, that can undergo chemical changes under relatively low temperature, and the extended curing time, the samples were not subjected to heat to obtain a dry mass but were assessed after reaching equilibrium in room conditions. For consistency, samples without gypsum followed similar conditioning to obtain the mass. LS was measured according to DIN 18947 [14] by comparing the difference in the length of the mortar between the fresh state (size of the molds) and the hardened state after 90 days. FStr and CStr were assessed following EN 1015-11 [21], using a Controls Automax 5 hydraulic testing machine equipped with a 25 kN load cell for flexural and a 300 kN load cell for compression. The load was applied to the sample at the rate of 10 N/s for FStr and 50 N/s for CStr.

3. Results and discussion

3.1. Workability when handling the mortar, flow table consistence and the mini slump results

The workability of mortars will significantly influence the industrial manufacturing coating panels, as more fluid mortars reduce the need for compaction within molds. However, increasing the water content during mortar preparation can also lead to greater shrinkage. While the water/binder mass ratio ($w/(K + G)$) are constant for all mortars in relation to the total dry materials ($K + G + S$), the water/dry material mass ratio varies. Specifically, for the three different binder:sand volume ratios (1:2, 1:3, and 1:4), the water/dry material ratios are 0.25, 0.19, and 0.15, respectively (Table 4).

When handling the mortars during the mixing and preparation of the samples, it is observed that mortars without gypsum became more fluid as the binder content increases, decreasing the sand content. This fluidity can be directly associated with the ratio of water/dry material content. During the preparation of the hardened samples, after compacting mechanically, a thin layer of water ($<1 \text{ mm}$) appears before the leveling. The samples exhibit low segregation, confirming the suitability of the preparation protocol for these mortars. No weeping is observed during the curing. Notably, during the mixing of the mortars with gypsum it is possible to observe a clear decrease in fluidity: the mortars were initially more fluid but, by the end of the mixing, the workability is similar to the mortars without gypsum.

Test results of the flow table consistence and mini-slump test are depicted in Fig. 4. Mortars with binder:sand ratios of 1:3 and 1:4 with and without gypsum, display similar flow behavior when comparing before and after the drops. The flow of these mortars is $160 \pm 12 \text{ mm}$. When compared to other earth mortars [48,56,57] (Table 1), the reference mortars binder:sand ratio of 1:3 and 1:4 (without gypsum) exhibit lower flow. Although the earth mortars from the literature were formulated with higher water ratios, which may have significantly increased their flowability. On the other hand, mortars with a 1:2 binder:sand volumetric proportion show a significantly higher flow, with an increase of 145 % compared to those with a 1:3 proportion both without gypsum substitutions. Despite a higher concentration of fine particles, which may necessitate an increased water content to ensure proper hydration. Nevertheless, this adjustment has been observed to enhance the flow of the mortars. This indicates that the balance between binder and sand can significantly impact the workability of the mortar.

Regarding the gypsum content, a substitution of 5 % in all mortars (G1) reduces the flow, while the opposite effect is observed for a 20 %

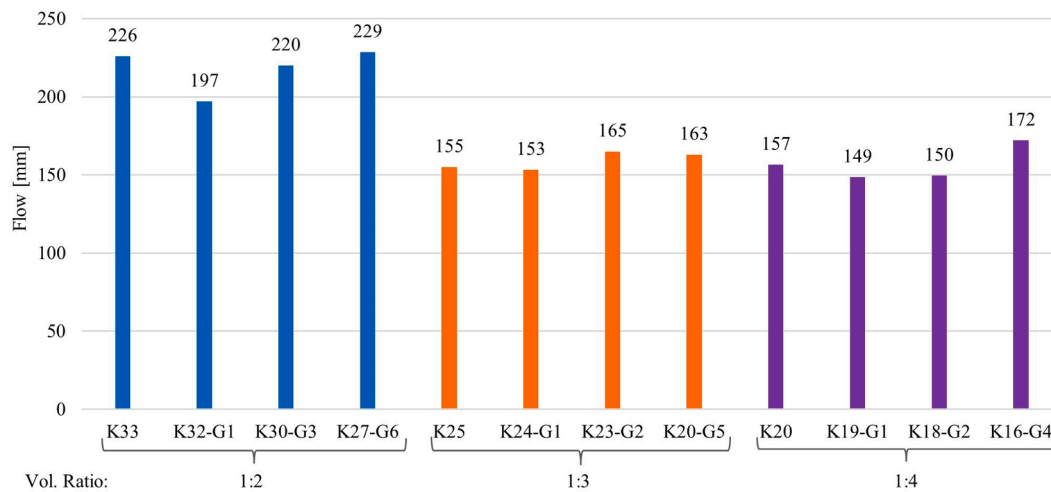


Fig. 4. Flow of clay and clay-gypsum mortars with 1:2, 1:3 and 1:4 binder:sand (vol.) proportions.

substitution (G6, G5 or G4, respectively for 1:2, 1:3 and 1:4 mortars). Overall, the gypsum substitutions led to minor variation in flow (<10 % compared to the reference mortars). This behavior is similar to the findings of Lima et al. [55] and Santos et al. [79], who observed that consistence decreased with addition of gypsum, while higher spreads were obtained with 6–8 % (wt) of gypsum additions.

According to DIN 18947 [14], the flow table consistence for non-binder-stabilized clay plastering mortars should be around 175±5 mm. Among the tested mortars, only the mortar K16-G4 falls within this standard range, as less fluid but workable mortars were deliberately designed in the present study to minimize shrinkage. Nonetheless, since all the mortars exhibit good workability and absence of weeping or segregation, this indicates that the water content was suitable for fabricating modular panels, most probably allowing to reduce the compaction energy associated with the production.

The mini-slump test results vary based on the binder:sand ratio, with both diameter and height providing valuable indicators of fresh mortar workability. Fig. 5 presents the mini-slump results for the mortars. Mortars with 1:3 and 1:4 binder:sand ratios exhibit minimal variation in diameter after the removal of the mold, with a maximum flow increase of 7.5 %. In these mortars, the addition of gypsum does not significantly affect the flow. Conversely, mortars with a 1:2 ratio demonstrate greater susceptibility to variations in gypsum content. A small gypsum substitution reduces flow by 10 %, while higher gypsum substitution increases flow by 10 %. Compared to the flow consistence test, the mini-slump

flow results exhibit similar trends.

For all mortars, regardless of the binder:sand ratio, the slump height increases proportionally with the gypsum substitution. However, mortars with a 1:3 ratio exhibit a more pronounced increase in slump, whereas those with a 1:2 ratio show only a slight variation in slump as the gypsum content increases. No slump is observed in the reference mortars with 1:3 and 1:4 ratios. These results can probably be attributed to particle packing, where the presence of finer materials (binders) and the calibrated granulometry of the sand influence the material’s workability. The incorporation of fine clay may reduce workability due to increased plasticity. On the other hand, a higher water content decreases particle friction, affecting the material’s self-supporting ability.

3.2. Setting time

All mortars without gypsum exceed the testing time (>480 min), as shown in Table 5. In the absence of gypsum, clay-based mortars rely exclusively on water evaporation. This is because «clay minerals are small particles formed by flat layered structures that retain water for long periods» [5]. In general, the use of gypsum has proven effective in reducing the setting time for all binder:sand ratios. Across all binder ratios, mortars with 5 % gypsum substitutions (K32-G1, K24-G1 and K19-G1) exhibit an initial setting time above 40 min and a final setting time below 60 min. Compared with the initial setting time of the gypsum plaster provided by the producer (17 min) [74], the workable time of 1:3

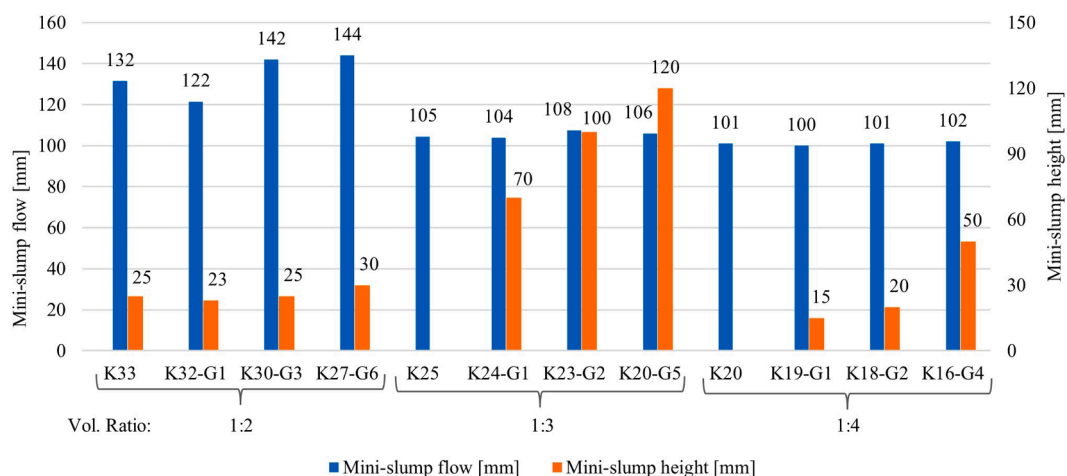


Fig. 5. Mini-slump of clay and clay-gypsum mortars with 1:2, 1:3 and 1:4 binder:sand (vol.) proportions.

Table 5
Setting time test results.

Mortars ID	IST [min]	FST [min]
K33	>480	>480
K32-G1	40	48
K30-G3	10	12
K27-G6	9	11
K25	>480	>480
K24-G1	44	58
K23-G2	11	14
K20-G5	9	11
K20	>480	>480
K19-G1	45	60
K18-G2	11	15
K16-G4	10	11

Notes: IST – Initial setting time; FST – Final setting time.

ratio clay mortars with 5 % gypsum (K24-G1) are approximately 250 % longer. Moreover, the combination of clay and aggregates, along with the low gypsum content, interferes with crystal growth and interlocking, causing the gypsum crystals to become more dispersed [4]. On the other hand, both 10 % and 20 % of gypsum substitutions reduce the setting time by approximately 80 % compared to 5 % gypsum substitutions. Both 10 % (K30-G3, K24-G2 and K19-G2) and 20 % (K27-G6, K20-G5 and K16-G4) of gypsum substitutions exhibit similar initial setting times. In this case, the higher gypsum content may have reduced the effectiveness of the aggregates and clay in dispersing the crystals and shortening the distance between dehydrated particles. As a result, gypsum may have achieved better interlock, facilitating the formation of gypsum crystals. The difference between the initial and final setting times becomes less pronounced with increasing gypsum content.

3.3. Linear shrinkage and bulk density

Linear shrinkage inside the molds is observed before de-molding the samples: difference between the length of the molds and the length of the samples. Visually, no cracks are evident in any of the samples. Fig. 6 provides insight into the relationship between the clay:sand ratio and shrinkage. The reference mortars (without gypsum) exhibit higher linear shrinkage (LS) as the clay content increases, from 1:4 to 1:2 ratio mortars. A reduction of 80 % in shrinkage is observed when the binder ratio decreases from 1:2 to 1:4 (K33 to K20), while a 20 % reduction is observed when the binder ratio decreases from 1:2 to 1:3 (K33 to K25). An increase of the clay binder needs a higher water demand to ensure adequate hydration of the fine particles, which maintains the

workability of the mortar. In the other hand, the increase of water content also intensifies water evaporation, contributing to higher shrinkage. As expected, these findings confirm that the clay content has a significant impact on the shrinkage of the mortars. The literature also support this observation, indicating that for various non-swelling clays, shrinkage is highly dependent on the sand ratio. In a study conducted by Emiroğlu et al. [17], an almost linear relation was established between volumetric shrinkage and clay:sand ratio, using different clays (yellow clay containing 72 % illite and 28 % kaolinite; red clay containing 71 % illite and 29 % kaolinite) and the ratio of 35 % water/binder was adopted for all formulations. Lima et al. [57] reported similar findings, demonstrating that a higher ratio of illitic earth in the mortar resulted in higher shrinkage. Compared to the results reported in Lima's study, the reference mortars K33 and K25 exhibit a 170 % higher LS. It is important to note that shrinkage is also influenced by the type of clay minerals [17, 56]. Non-swelling clays exhibit lower linear shrinkage due to their reduced capacity for water absorption. The laminar structure of clay minerals contributes to the water retention and dimensional variations [69].

The particle size distribution and source of the aggregates also plays a role. Shrinkage can be controlled by optimizing particle packing. The studies conducted by Santos et al. [76] and Lima et al. [55] reported that, with the same binder:sand ratio but varying the sand grading, it was possible to reduce dimensional variation. Lima et al. [58] reported a low linear dimensional variation of just 0.38 % in a mortar made with kaolinitic clay. However, the use of siliceous unwashed sand, which may contain fine material, could have influenced the shrinkage.

The addition of gypsum negatively impacts on dimensional variation. This may be attributed to the rapid drying process induced by the gypsum's presence. In the initial hours, the mortar lacks the capacity to effectively withstand volume changes. For the 1:2 and 1:4 ratios, a 20 % gypsum content appears to have a similar or even reduced effect on shrinkage compared to the 5 % and 10 % gypsum partial substitution. Santos et al. [79] reported a linear shrinkage proportional to the gypsum additions. However, it is important to note that, in that study, the gypsum was addition in proportion to the total volume of dry materials (earth and sand), leading to a significantly higher gypsum content. When comparing mortars with similar volumetric proportions, the mortar studied by Santos et al. [79] with a 20 % gypsum additions exhibits a linear shrinkage 10 % lower than the same 1:3 mortar with a 20 % gypsum substitution (K20-G5).

On average, only the mortar K30-G3 exhibited shrinkage higher than 3 %. The recommended shrinkage limit according to the standard NZS 4298 [63] is below 3 %, while standard DIN 18947 [14] suggests a limit below 2 %. The first criterion is typically used for plasters applied on a

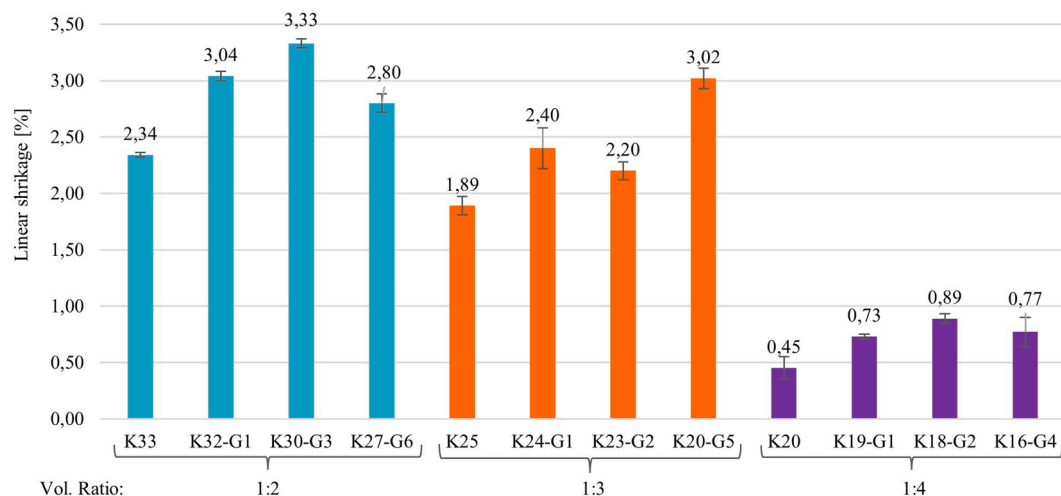


Fig. 6. Linear shrinkage of clay and clay-gypsum mortars with 1:2, 1:3 and 1:4 binder:sand (vol.) proportions.

substrate, while the second applies to non-chemically stabilized clay plastering mortars in cast in metallic molds. Mortars with a 1:4 ratio, both with and without gypsum, exhibited the best results in terms of shrinkage. Shrinkage properties are less critical for modular panel production. Nevertheless, high shrinkage may induce micro-cracks, which can lead to reduced mechanical performance [82].

The bulk density (BD), measured after 90 days under room conditions, shows a slight but non-proportional variation relative to the binder content (Fig. 7). The reference mortar K25 with 1:3 ratio has a BD that is 3 % and 5 % higher than K20 and K33 with 1:4 and 1:2 ratios, respectively. Lima et al. [57] and Pedernana and Elias-Ozkan [66] established a linear relation between the binder:sand ratio and the BD, reporting that an increase of sand volume slightly reduced the BD. However, this reduction was not significant (<5 %). Santos et al. [76] suggested that variations in the fraction of fine and coarse sand have a minor impact on the BD but contribute to enhancing the mechanical performance. According to the literature, the BD of mortars without additives (Table 1) typically ranges from 1.6 to 1.9 kg/dm³, while mortars with gypsum additions (Table 2) fall within the range of 1.7 to 1.9 kg/dm³. In the present study, when gypsum is introduced, the BD of the mortars slightly decreases as the gypsum contents increases. Mortars with 20 % gypsum exhibit lower BD compared to those with the same ratio but without gypsum substitution. Compared to the reference mortar, high gypsum substitutions reduce the BD by 7 %, 6 %, and 5 % for the 1:2, 1:3, and 1:4 ratios, respectively. Lima et al. [55] reported a 5 % reduction of the BD when 20 % of gypsum (by weight of earth) was added to an earth-based mortar, which is consistent with the range observed in the present study. According to DIN 18947 [14], these mortars can be classified as class 1.8 (reference values of 1.6 kg/dm³ to 1.8 kg/dm³).

3.4. Flexural and compressive strength

Fig. 8 presents the mechanical results of the mortars. It can be concluded that the binder ratio has a minor influence on the flexural strength (FStr) of the mortars, both with and without gypsum. Mortars without gypsum exhibit an average FStr of 0.06 MPa. The low plasticity of the kaolin clay may have contributed to the reduced FStr. However, clay-based mortars generally exhibit low FStr (Table 1). The FStr of mortar K25 is 66 % lower compared to a kaolin-based mortar with a similar ratio studied by Lima et al. [58]. This difference may be attributed to variations in the mineral composition of the kaolinitic clay used in the two studies. Furthermore, the siliceous unwashed sand used in Lima et al. [58] most likely contains more fine material (d₅₀=500 μm), which may have also influenced the final FStr. Several studies [57,67,

76] suggest that sand particle size granulometry has a direct impact on the mechanical strength of clay-based mortars.

Gypsum proportionally enhances the FStr of mortars. Mortars with 5 % gypsum substitutions exhibit a maximum FStr increase of 333 % (K32-G1), while mortars with 10 % gypsum substitutions show a maximum increase of 466 % (K30-G3). Notably, 20 % gypsum substitution exhibits a significant increase in FStr exceeding 685 % compared to the reference mortar. Mortars with a binder ratio of 1:4 and 1:3 show similar performance, suggesting that the improvement in FStr is primarily attributed to the content of gypsum. As reported by Doleželová et al. [16], the FStr of gypsum mortars was, on average, 2400 % higher than clay-based mortars, as the gypsum dihydrate crystal demonstrates a better mechanical performance.

There is no clear relationship between linear shrinkage and mechanical strength. Mortars with higher shrinkage, both with and without gypsum, exhibit similar or even better mechanical performance.

Regarding compressive strength (CStr), comparable results were observed for the 1:3 and 1:4 ratios, both with and without gypsum. Without gypsum, the clay ratio has minimal influence on CStr. The mortars exhibiting the highest mechanical strength are K27-G6, K20-G5, and K16-G4, in that order. The use of 5 % and 10 % of gypsum impacts on CStr, particularly as the clay ratio increases. However, these low gypsum substitutions contribute only an additional 0.1–0.3 MPa to CStr. The highest CStr is achieved with a 20 % gypsum substitution, resulting in an increase of over 320 % compared to mortars without gypsum. Similar findings were reported by Lima et al. [55] and Santos et al. [79] regarding an increase in compressive strength with the addition of gypsum. However, the same studies noted a small decrease in moisture adsorption as gypsum content increased. Controlling the moisture buffer capacity of clay-based mortars is essential to maintaining their overall performance. The formulated earth-based mortars by Lima et al. [55] presented a 260 % higher CStr when 20 % gypsum was added to the mortar. Similarly, in the present study, a 20 % gypsum substitution in mortars with binder:sand ratios of 1:1, 1:2, and 1:4 resulted in CStr increases of 400 %, 320 %, and 360 %, respectively. These findings collectively highlight the potential of gypsum as a sustainable stabilizer for clay-based mortars.

The EN 998–1 [43] uses only CStr for classifying rendering and plastering mortars. The lowest classification, CS-I, corresponds to a strength range between 0.4 to 2.5 MPa. According to the DIN 18947 [14], only the mortars with the best results can be classified as S-I, requiring an FStr higher than 0.3 MPa and CStr higher than 1.0 MPa. In the literature, the CStr for clay-based mortars typically ranges from 0.6 to 3 MPa [67,72]. Considering the more demanding standard for earthen rendering and plastering mortars [14] only mortars with a 20 % gypsum

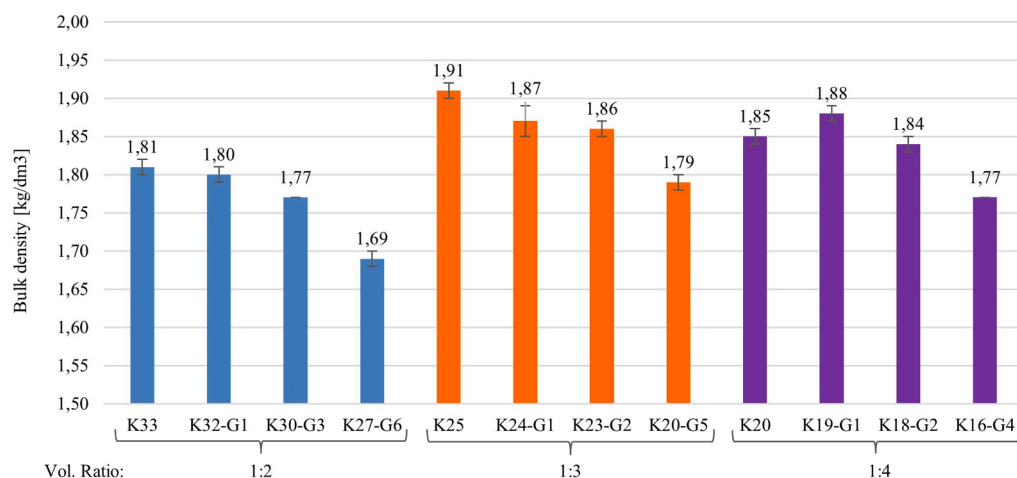


Fig. 7. Bulk density of clay and clay-gypsum mortars with 1:2, 1:3 and 1:4 binder:sand (vol.) proportions.

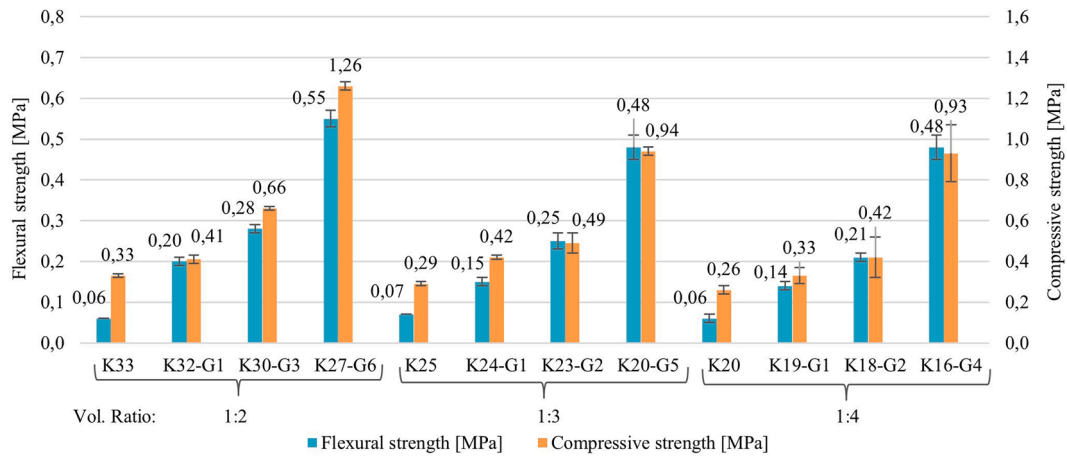


Fig. 8. Flexural and compressive strengths of clay and clay-gypsum mortars with 1:2, 1:3 and 1:4 binder:sand (vol.) proportions.

partial substitution (K27-G6, K20-G5, K16-G4) meet the minimum FStr requirement.

There is a strong correlation between the two mechanical strengths, demonstrating an improvement in performance with the incorporation of gypsum into the mortar (Fig. 9). Mortars without gypsum addition deviate further from the linear regression, although their values are more easily represented as a single point. The use of 5 % and 10 % gypsum exhibits a greater range of correlation between the mechanical strengths. However, mortars with 20 % gypsum show higher variability in mechanical performance. This linear increase in mechanical strength indicates that partial substitution with gypsum can effectively stabilize clay-based mortars.

4. Conclusions

The characteristics of clay-based mortars must align with the specific requirements for their intended applications to ensure optimal performance. A total of 12 clay-based mortars with varying binder:sand (1:2, 1:3 and 1:4, in vol.) and calcium sulfate hemihydrate proportions (5 %, 10 %, and 20 %, by volume of the clay) were tested to assess their fresh and hardened properties. Calcium sulfate hemihydrate, referred to as

gypsum for simplification, was used as a partial replacement for clay. The key findings from the study are summarized below:

- The clay ratio had a minor impact on workability and mechanical strength. However, a notable disadvantage of increasing the clay ratio was the occurrence of higher linear shrinkage. Additionally, for the same binder:sand ratio, mortars with gypsum partially replacing clay exhibited higher shrinkage than those without gypsum. Notably, mortars with 20 % gypsum content and 1:2 and 1:4 ratios showed similar or slightly reduced shrinkage compared to mortars with 5 % or 10 % gypsum.
- Gypsum substitutions caused minimal variations in workability, with less than 10 % difference from reference mortars. A 5 % gypsum substitution reduced flow, whereas a 20 % substitution increased it.
- Based on their consistence and lack of segregation, the clay-gypsum-based mortars were deemed suitable for modular panel fabrication, thereby reducing the compaction energy requirements associated with production.
- The bulk density exhibited a small variation, ranging from 3 % to 5 % for the pure clay mortars and from 5 % to 7 % for mortars with partial gypsum substitution.

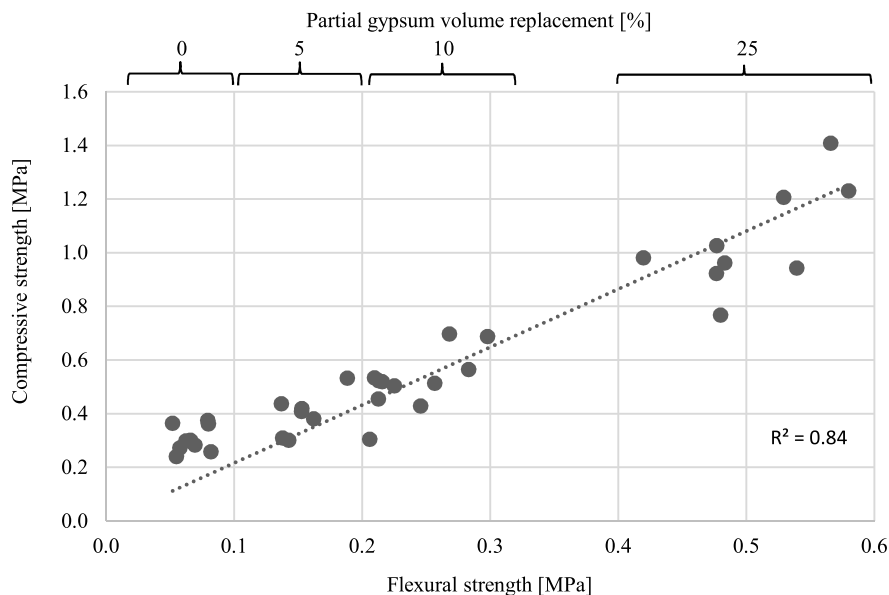


Fig. 9. Correlation of flexural and compressive strength of clay and clay-gypsum mortars.

- The clay ratio had minimal influence on the compressive strength (CStr) and flexural strength (FStr) of mortars without gypsum. However, gypsum substitution proportionally enhanced both properties. Mortars with 5 % gypsum substitution exhibited a maximum FStr increase of 333 %, while those with 20 % gypsum substitution showed a maximum increase of 685 %. Low gypsum substitutions contribute up to a 200 % increase in CStr, with the highest CStr was achieved with a 20 % gypsum substitution, resulting in an increase of over 320 % compared to mortars without gypsum.
- Combining the results of mechanical strength and shrinkage, mortar with the lowest binder ratio and the highest gypsum substitution, with a volumetric proportion of 1:0.25:5 clay:gypsum:sand (vol.), was identified as the most suitable formulation for the foreseen application to producing prefabricated coating panels.
- However, considering the setting time results, the workable life of mortars with gypsum is limited. Therefore, exploring the use of retarders to delay the setting time presents an opportunity for future development.
- Complementary studies on the microstructure of the mortars and its effect on the hardened properties would provide valuable insights for future research. Further developments could include the analysis of the hygroscopic and thermal capacity of the formulated mortars.

Overall, it was possible to develop an optimized clay-gypsum mortar that seems suitable for the production of manufactured indoor coating panels. The design approach can be adapted to various clays with different mineralogies, making these findings relevant across diverse geographies and contexts in which on-site or excavated earthen materials are available.

Achieving eco-efficient stabilization of clay-based mortars remains a challenge due to the limited availability of materials that are both sustainable and non-hazardous. The use of non-contaminated excavation earth, resulting from construction works, could contribute to reducing sand consumption as aggregate, as some silt and sand are already present in the excavated earth.

Incorporating sustainable materials alongside innovative approaches and eco-friendly construction methods has immense potential for creating solutions competitive with modern construction products. Therefore, further research should focus on eco-efficient indoor coating panels, with a particular emphasis on their capacity to passively control indoor room' relative humidity, namely by moisture buffering.

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CRedit authorship contribution statement

Douglas Rocha: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paulina Faria:** Writing – review & editing, Supervision, Conceptualization. **Sandra S. Lucas:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Douglas Rocha reports financial support was provided by Foundation for Science and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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