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Cow Dung Biostabilized Earth Mortars: Reusability and Influence of Cow Dung Processing and Cow Diet

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Abstract: Historically, cow dung has been widely used as a biostabilizer in earth building, although the scientific research on this subject is still limited. The available research provides evidence of the positive effects of this bioaddition on earthen blocks and plasters, as it improves their physical and mechanical properties and durability in water contact. The present research does not aim to characterize biostabilized earthen mortars or to explain the interaction mechanisms between the earth and cow dung components, because this topic has already been investigated. Instead, it aims to investigate strategies to optimize the collection and processing of cow dung so as to optimize their effects when used in earth-plastering mortars, as well as considering the effects of using them fresh whole, dry whole, and dry ground (as a powder); the effects of two different volumetric proportions of cow dung addition, 20% and 40% (of the earth + added sand); the effects of 72 h (fermentation–humid curing) before molding the biostabilized mortar; the influence of the cow diet; and the potential of reusing cow dung stabilized mortars. The results show that as the freshness of the cow dung increases, the mortar's durability increases under water immersion, as well as the mechanical and adhesive strength. Collecting cow dung fresh and drying (composting) it in a plastic container is more efficient than collecting cow dung that is already dry on the pasture. The cow diet and the use of dry (composted) cow dung, whole or ground into a powder, does not result in a significant difference. A 72 h period of humid curing fermentation increases the adhesive strength and durability under water. The proportion of 40% promotes better durability under water, but 20% offers greater mechanical and adhesive strength. Finally, cow dung addition does not reduce the reusability of the earth mortar. The new mortar obtained by remixing the mortar with water presents increased properties in comparison to the original reference mortar with no cow dung addition. Therefore, the contributions of this research are innovative and important, offering technical support in the area of biostabilized earth-plastering mortars. Furthermore, it is emphasized that cow dung addition can be optimized as an efficient traditional solution to increase the mechanical resistance, but especially to increase the durability of earth mortars when in contact with water. This effect is particularly important for communities lacking financial resources, but also reveals the possibility of using eco-efficient waste instead of binders obtained at high firing temperatures.

Keywords: cattle manure; soil; biostabilization; biocementation; clay-based plasters and renders; DIN 18947; earthen building; shrinkage; cracking; performance under water; adhesion; strength

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1. Introduction

Considering the current impacts on the planet related to climate change, the development of building products and solutions that can meet the constructive demands of humanity but with lower environmental impacts in their production is fundamental and increasingly urgent [1].

Earth building is derived from ancestral knowledge and its use spans millennia. The immense collection of heritage buildings built with earth around the world highlights the potential and durability of this material. In addition, in recent decades, earth building has been increasingly investigated worldwide. These investigations aim to improve conservation techniques, but also support the use of earth in new constructions [2].

Another aspect that demonstrates the importance of earth products for construction is the building standards that have been published in several countries [3], with an emphasis on Germany [4]. Since 2013, the German Institute for Standardization has been publishing a broad set of DIN standards for earthen building products that encourage the use of biostabilization to reduce the use of irreversible, chemically active binders, such as cement, lime, and gypsum, whose production processes and disposal at the end of the life cycle compromise the advantages of earthen construction.

For earth building, earth mortars are necessary in several stages: the production of adobe and other techniques that use pasty earth-based composites, the laying of masonry and flooring, and repairs, in addition to rendering and plastering mortars to coat and protect the surfaces of the walls and ceilings. Earth mortars can be produced by mixing earth with water. Complementary aggregates can be added to control shrinkage, and, depending on the mortar requirements, other components can be added, namely stabilizers. However, especially for plastering applications in indoor environments, the additions must not compromise the advantageous hygroscopic behavior of the clay-based mortars.

The earth used to produce earth mortars is the resulting fraction of the soil after removing gravel and larger aggregates. It is composed of different types and fractions of clay, silt, and sand, with clay acting as the binder. Therefore, the composition of earth mortars varies according to the application and requirements foreseen and the earth selected for the construction.

Despite contributing significantly to the good performance of the mortar in terms of workability, mechanical resistance, and adhesion to substrates, the clay present in the earth is sensitive to water [5].

To improve earth-rendering and -plastering mortars so that they perform well when in contact with rain or water when used indoors, many additions have been historically used, such as air lime, vegetable oils, animal fats, and excrement [6], such as cow dung. To this day, in rural communities in Brazil [7] and in several other regions of the world [8], bovine excrement is traditionally used as a biostabilizer in earthen mortars and in the production of flooring, adobe, and renders (applied outdoors) and plasters (applied indoors) [9].

Cow dung has historically been used primarily for agriculture and as biomass for energy production [10], but other applications are currently being explored, such as the use of cow dung fibers for reinforced friction composites [11] and cow dung ash to replace fly ash in cement mortars and concrete [12,13].

Despite cow dung being a natural material, cattle meat production is a commercial industry that has enormous negative environmental impacts in Brazil and other countries. The majority of the animals are pasture-fed. In general, in extensive bovine monoculture in Brazil, the first step of the production process is the deforestation of the native forest. The wood is then sold illegally and grasses are planted for pasture. After a few years, this soil becomes depleted, worn out, trampled, and nutritionally poor and is then used in eucalyptus monoculture to produce wood. With this process, the ultimate outcome is the desertification of several areas that, until 30 years before, were rich and fertile [14–17].

The cows that are raised in the feedlot process are fed with a ration of cereals. However, in addition to the suffering caused to the animals due to imprisonment, the huge feedlot cattle culture also promotes deforestation, which is often illegal, while also creating conflicts with traditional and peasant communities, in addition to harming the biodiversity in Brazilian (and other countries) biomes due to the implementation of huge monocultures of soy and corn, used to produce the rations of cereals that feed these feedlot animals.

According to data from the Brazilian government [18], in 2022, Brazil had 203 million human inhabitants and around 235 million cattle (in addition to 1.6 billion chickens) for its domestic market and exportation. Of this bovine population, around 20 million animals are used for milk production, while the other 215 million are used for beef and breeding purposes. On average, each cow produces 15–45 kg of dung daily. This agro-industrial waste has high potential for potable water contamination (groundwater and rivers) due to improper (and illegal) disposal.

These problems do not occur in small-scale breeding for self-sustainment and local commerce in traditional communities, where low volumes of cow dung are left onsite to fertilize the land. In this sense, it is noteworthy that this research does not seek to stimulate the production of beef cattle in Brazil and other countries, but offers a scientific basis for earth-building techniques in traditional communities, while also recommending the proper disposal of agricultural waste collected from dairy production by incorporating it into buildings. In addition, it intends to justify and highlight the wisdom that exists in the ancestral knowledge of traditional communities and empirical solutions for vernacular architecture.

Despite the above, there are regions where cows are religiously and culturally considered sacred beings, such as India. For this reason, these animals are highly respected. Their meat is not consumed, but dairy products are highly appreciated. According to Dhama [19], cow products and excrement (dung and urine) have long been used in traditional Indian medicine; cow dung is regarded as an important antiseptic and is also added to earth mortars to produce floors and plastering.

Schmidt et al. [20] (p. 1) "did not find evidence that environmental exposure to cows contributes to growth deficiency in children in rural India, neither directly by affecting growth, nor indirectly by increasing the risk of diarrhea". The often-reported contamination in humans is related to other factors, such as structural poverty, a lack of potable water, a lack of basic sanitation, and the inappropriate disposal of human waste. Moreover, in the work by Munshi et al. [21], cow dung samples were analyzed and showed antimicrobial activity against pathogens. Raj et al. [22] also explained that, in agriculture, in addition to microbiological activities linked to increased fertility, the ecological balance promoted by the use of cow dung is capable of controlling pathogens through an antagonistic effect. The microorganisms present in cow dung are responsible for suppressing the mycelial growth of phytopathogenic fungi such as *Fusarium solani*, *F. oxysporum*, and *Sclerotinia sclerotiorum*, notable disease-causing agents, particularly in tomato plants. Furthermore, the microbiota from cow dung are effective in controlling several other pathogens, including fungal, bacterial, and nematode organisms. When added to earth mortars as a biostabilizer, cow dung may also exhibit this antiseptic action and does not pose a biohazard for humans. However, protective gear such as gloves, shoes, and glasses is of the utmost importance, as is also the case when manipulating cement, lime, or gypsum.

Therefore, in the Brazilian context, and in other countries that are major bovine producers, with proper treatment, cow dung can be a viable choice for the biostabilization of earth mortars (and earthen blocks) in new constructions, whether in traditional rural communities or modern urban settings.

The scientific investigation of cow dung addition in earth building still needs development. Despite this, there have been some interesting studies published since the 1990s that agree with or complement each other in terms of the majority of the achieved results. According to these, cow dung addition increases the workability of mortar, limits shrinkage and the occurrence of cracks, reduces water absorption, and improves the mechanical and adhesive properties, in addition to increasing the durability of earth renders and blocks, particularly when applied in contact with water [5,23–28].

According to Millogo et al. [29], when cow dung was added to kaolinitic earth mortars, its components reacted with the kaolinite ($Al_2Si_2O_5(OH)_4$) and fine quartz (SiO_2) that were present in the clayey earth, resulting in insoluble silicate amines ($SiO_4(NH_3)_4$). This substance bound the mortar's components together, resulting in water resistance and hardness. The cow dung fibers decreased the shrinkage of the mortars after drying and prevented cracks from appearing, improving their performance.

Kulshreshtha et al. [30] investigated the hydrophobic effect of cow dung addition in earth blocks. The researchers attributed this effect to the presence of small-sized microbial aggregates, SSMA (0.5–7 μm), which are rich in fatty acids, coming from the cow's digestive system and reacting with the earth mortar's components.

Rao et al. [31] published a specific investigation about the interaction of cow dung with earth mortars. A kaolinitic clay was used (wt. ratio of 1:1 kaolinite–sand) with 10% wt. powder dry cow dung addition. The effects of the cow dung were justified by the natural activity of ubiquitous microbes, which produced extracellular polymeric saccharides (EPS). The EPS extruded by the microbes were negatively charged and bound to the particles present in the earth mortar, increasing its mechanical resistance.

Rao [32] concluded that the microbial glue described by Millogo et al. [29] may correspond to the EPS-rich biofilms identified by Rao et al. [31]. This cementation provided by EPS exhibited strong adhesion due to the growth of fibrous bridges and bonds. Rao [32] (p. 79) explained that "*layers of EPS constitute protective biofilms that shield microorganisms from environmental stress (. . .). They are located on the surfaces of the microorganisms and are responsible for the cohesion of microorganisms and the adhesion of biofilms to surfaces (. . ..). Polysaccharides are bound to surfaces by the growth of fibrous bridges, filling of voids and formation of Van der Waals, hydrogen and ionic bonds (. . .)*". Therefore, according to Rao et al. [31], the cementation of EPS can improve the earth mortar's strength by filling pores and combining kaolinite aggregates into a bonded mass.

The investigative field related to the biocementation of earth, i.e., using bacteria and its metabolic pathway products to promote the agglutination of earth particles, was first developed by Whiffin [33] and Mitchell and Santamarina [34]. Since the 2000s, it has been possible to find some research in the multidisciplinary area involving geotechnical engineering, architecture, and microbiology.

Due to environmental concerns, the intention to reduce the consumption of pollutant binders, and large possibilities for application, investigations into biomineralization in civil engineering are currently gaining more prominence [35,36].

For earth building, aiming to optimize the performance in relation to rain action and the durability of coatings, new biomaterials based on bacteria have been developed for biocementation, being added in the formulation of mortars [37]. Meanwhile, others have been developed for biodeposition, applied as coating surface treatments [38].

According to Rao et al. [31], microbial activity can be used to produce inorganic biocements, such as through microbiologically induced calcite precipitation (MICP) [39,40], and organic biocements, such as through biofilm formation by exopolysaccharides (EPS) [41,42]. Based on Rao [32], in its composition, cow dung contains bacteria capable of being applied in both biocementation processes. Therefore, researchers have concluded that cow dung is an efficient natural biostabilizer for earth building, with great chemical and biological compatibility. Thus, more research is necessary to identify strategies to optimize the cow dung addition and to develop new bioproducts for building. Furthermore, the use of this biowaste may reduce the use of binders to stabilize earth mortars and, as such, prevent the release of tons of carbon dioxide into the atmosphere, namely due to lime and cement production and consumption.

To highlight the qualities of cow dung as a bioadditive for earth building, Pachamama et al. [26] compared its behavior with that of hydrated air lime. A Brazilian kaolinitic earth was used to produce the earth mortars. The cow dung, collected in the pasture, was piled up under the shade for air drying and was turned over daily to homogenize the material during a period of eighteen days. To control shrinkage, four volumes of sand were added to one volume of earth to produce the reference mortar (0% addition). Four more mortars were produced with the addition (in volumetric proportions) of 10% and 20% of cow dung, 5% of air lime, and the combined addition of 10% cow dung and 5% air lime. Unlike the air lime, the addition of the cow dung limited shrinkage and cracks and improved the physical, mechanical, and adhesive properties. The researchers explained that the low addition of air lime probably interrupted the clayish structural matrix of the earth mortar and did not produce a strong calcium carbonate structural matrix to replace it, resulting in a decrease in the mortar's compressive strength compared to the reference mortar with no addition. However, each earth has its own characteristics. Therefore, studies on the effects of cow dung on mortars produced with earth from different origins, in different proportions and under different conditions of use, are important and have been the focus of several publications.

At first, in a previous study [5], it was attested that, compared to 20%, the proportion of 10% (vol.) of cow dung addition offered greater mechanical resistance and adhesive strength. However, the 20% proportion still increased the resistance of the reference mortar and also offered greater durability in the water immersion test. For this reason, in the present study, the 20% proportion of cow dung addition was chosen to evaluate and compare the effects of different conditions and types of processing of cow dung: the effects of using it whole and fresh, whole and dry, and as a dry powder; the effects of 72 h fermentation–humid curing of the cow dung before molding the fresh stabilized mortar; the influence of the cow diet on the effects of the cow dung on the earth mortar; and the potential of reusing [43] cow dung stabilized mortars.

According to Rao et al. [31], the humid curing of earth and cow dung mixes allows the activity of aerobic and facultative anaerobic bacteria, resulting in higher biofilm production and in agglutinating the earth particles to prevent the production of EPS. Rao et al. [31] indicate that 7 days of humid curing is essential for optimum fiber–earth interactions and EPS bonding upon the addition of the cow dung. They also recommend that the fermenting mortar mix should be turned over as little as possible before application or molding, in order to avoid damaging the connections between earth, fibers, and EPS. Millogo et al. [29] subjected the biostabilized mortar to humid curing for 72 h before molding with adobe to improve the microbial activity, and an increase in the adobe's durability was registered.

By definition, fermentation occurs in the absence of oxygen. To ferment the stabilized earth mortar, it is necessary to place the mixture in a hermetic, closed recipient. However, in order to approximate to the procedures that are traditionally carried out in situ, in the present study, the stabilized earth mortar was placed in an open, plastic container, with wet burlap on top, as recommended by Rao et al. [32]. For this reason, this procedure should not be referred to as fermentation but as humid curing. Despite this, it was clear that the content under the upper external layer of the stabilized fresh mortar mixture was not in contact with oxygen. Thus, the humid curing procedure used in the present study may also allow the activity of both aerobic and facultative anaerobic bacteria, as described by Rao et al. [31].

The present research does not aim to characterize the biostabilized earthen mortars in order to explain the reaction mechanisms between the components of the mortar and cow dung, because there are three studies [29–31] that have already carried out specific tests for this. Among them, the most complete study [31] obtained its conclusions from biological characterization tests and analyses at 0, 7, 14, and 28 days, using samples from wet and pasty earthen mortars with cow dung addition, cultivated inside covered 250 mL polypropylene centrifuge bottles. However, the effects on the mortar specimens were not evaluated. Therefore, as this is an area that is still in its initial phase, the present research aims to evaluate, in earth mortar specimens, the effects exerted on the physical and mechanical properties by cow dung of different proportions, types of processing, and origins. It also aims to compare the results with the interpretations presented in the three aforementioned references, so as to verify and justify the results and conclusions obtained in the present study.

Therefore, the contributions of this research to the scientific field on earth plasters and to the characterization of traditional biostabilizers in vernacular architecture are innovative and considered important in offering technical support in the area of biostabilized earth-plastering mortars.

2. Materials and Methods

2.1. Earth

The earth used to produce the mortars was from Portugal (Mediterranean temperate climate) and its complete characterization was presented in a previous study [5]. It was collected in the metropolitan region of Lisbon, in Caparica. For this reason, it was labeled CAP earth. The earth clods were easy manually broken and sieved through a mesh with a 2.79 mm opening after being air-dried. The particle size distribution of the CAP earth was 60% of sand, 25% of silt, and 15% of clay. Mineralogical characterization showed that there was (in mass) 51.2% of quartz, 27.2% microcline, 9.6% of muscovite, and 8.2% of illite. The CAP earth's loose bulk density was 1.14 g/cm^3.

2.2. Sand

To limit shrinkage, a medium-sized (0.2 mm to 0.6 mm) washed quartzose sand, commonly used for building in Lisbon, Portugal, was used. The sand's loose bulk density was 1.40 g/cm^3.

2.3. Cow Dung

To achieve the research objectives, three samples of cow dung (CD) were used, all collected in the metropolitan area of Lisbon, south of the River Tagus, Portugal: the first one was collected dry in the pasture, the second was collected fresh in the pasture, and the third was collected fresh from the stables of feedlot cows that were fed with rations of cereals.

The dry and fresh CD produced by animals raised in free-range and pasture-fed conditions was collected on a farm located in the municipality of Moita, South Lisbon. The collected sample that was dried in the pasture (CDdrypow) was used in one way only: it was ground to a powder. The cow dung sample collected fresh on the pasture (CDfp) was used in four ways: doughy as collected (CDfp), after seven days of composting (CDfp7), after thirty days of composting (CDfp30), and after thirty days of composting but also ground to a powder (CDfp30pow).

The fresh CD produced by feedlot cows that were fed with rations of cereals was used after seven days of composting (CDfrat7). It was collected in a farm in Sobreda, South Lisbon. The animals were fed mainly with rations of cereals (nutritional base), but also received small daily portions of hay and straw (roughage food). Information about the cow dung samples is given in Table 1.

Table 1. Cow dung sample descriptions.

Cow Dung Sample	Collected	Animal Diet	Drying Time	Use
CDfp	fresh	pasture	0	whole
CDfp7	fresh	pasture	7	whole
CDfp30	fresh	pasture	30	whole
CDfp30pow	fresh	pasture	30	powder
CDdrypow	dry	pasture	-	powder
CDfrat7	fresh	ration	7	whole

2.3.1. Processing of Cow Dung Samples

The CD collected fresh from the pasture (Figure 1a) had a doughy consistency and part of it was added fresh and doughy to the mortar (CDfp). The rest of the material was composted (dry curing) in the same way as is traditionally performed in rural areas in Brazil, i.e., leaving it to air-dry under the shade and turning over the material daily. According to Bamogo et al. [8], this process releases heat, water, methane, carbon dioxide, and ammonia. Due to the high temperatures (around 55–60 °C), composting also contributes to the killing of pathogenic microorganisms, seeds, fly eggs, and other possible contaminants [44].

(**a**) (**b**)

Figure 1. Cow dung freshly collected (**a**) and after drying in an open plastic container for 7 days (**b**).

It was decided to compost (dry curing) the CD in plastic containers (Figure 1b) to prevent any physical, chemical, or biological components (such as bacteria) from being lost/leached into the ground soil. Thus, it was assumed that there would be greater uniformity and a larger presence of these components in the final sample of dried CD after 7 and 30 days, so that they could be added to the earth mortar (sand + earth). The plastic containers were left open (covered only with mosquito nets), under the shade and exposed to the wind (air drying), and the material was turned over daily with a spatula to ensure that it was uniform.

After 7 days, the material was manually disaggregated once again and sifted through different sieve meshes, from the largest to the smallest, while always manually disaggregating the lumps that had agglomerated (Figure 2a). Then, the material was sifted through finer sieves by hand (with gloves), applying light pressure in circular movements, using a sieve mesh with an opening of 4.8 mm.

(**a**) (**b**)

Figure 2. Cow dung sieved after 7 days of drying (**a**) and after sieving (**b**).

Finally, the material was sifted in the same way through the 2.79 mm mesh, to break up the last small, wet clumps and retain the remains of fine twigs, sand, and cow hair. After being sieved, the material was quite homogeneous and rich in vegetable fibers whose lengths did not exceed 2 cm (Figure 2b); it was quite moist, with a mild odor.

After analyzing the CD daily, it was observed that if the material had been left to dry for a larger number of days before sifting, more aggregates (lumps) would have been formed and it would have become drier and harder, similarly to when the material was collected dry on the pasture. For this reason, it was decided to allow the material to dry (composting) for 7 days, which made it possible to pass it easily through the finest sieves, and weigh the "solid" material, without being too pasty or too dry. It was still quite moist, soaked in its own liquid and likely rich in microorganisms, their metabolites, and other organic compounds, such as fatty acids and amines [29–31].

After this process, part of the material was used immediately for the production of earth mortars and was labeled CDfp7, because it was left to dry (composting) for 7 days.

To verify the differences in the effects on the earth mortar of the addition of fresher or drier CD, after separating CDfp7, the rest of the material was left to dry (composting) for a further 23 days in the same uncovered plastic container. This sample was labeled CDfp30, because it was left to dry for 30 days.

Moreover, among the studies published about the effects of CD addition as a biostabilizer on earthen materials, some used fresh and whole CD, and others used dry and ground powder CD. For this reason, in the present research, part of the material that was dried (composted) for 30 days (CDfp30) was passed through an electric mill to be ground into a powder. This sample was labeled CDfp30pow.

An attempt was also made to grind a sample of CDfp7 and other samples with different moisture content, but, due to the high humidity that still existed in these samples, the mill was unable to grind them.

Finally, the samples were collected on the pasture after drying in contact with the soil. Naturally, the CD fragments were already hard (Figure 3a), as the compounds in liquid form were transferred to the soil, but it was possible to manually break them into smaller pieces to be ground in the electric mill (Figure 3b). These samples were labeled CDdrypow.

(**a**) (**b**)

Figure 3. Cow dung dried on pasture after being collected (**a**) and after manually broken before passing through the electric mill to produce CDdrypow (**b**).

The CD produced by the cows fed with rations of cereals was also collected fresh, from a feedlot cow stable, and had a doughy consistency. After seven days of drying (composting) in the same way as previously described, the sample labeled CDfrat7 was obtained. This CDfrat7 had a stronger odor of fermented starch when compared to the other pasture-fed CD. It was possible to observe visually, and without specific equipment, that CDfp7 (pasture fed) had plant fibers in its composition in larger quantities and with greater lengths compared to CDfrat7 (fed with cereal rations).

2.3.2. Complementary Characterization of Cow Dung Samples

For each moisture content measurement, three small samples of approximately 10 g of CD were collected and placed in small aluminum capsules that were left in an oven at 100 °C for 24 h. The moisture content was calculated as the percentage difference in the mass of the CD before and after the drying procedure. To determine the density, a container with a volume of 100 mL and a digital balance with 0.01 g precision were used. The container, filled with CD, was weighed; the weight of the empty container was subtracted; and the mass was divided by the volume of the container. To avoid human errors, normative procedures were followed to determine the apparent density of the materials, as outlined in EN 1097–3 [45].

Table 2 presents the density and moisture content values of all CD samples used and the amount of dry material equivalents contained in 100 mL. It is interesting to observe the relation between the moisture content and density in the evaluated CD. As expected, it is observed that, while it was drying, the CD lost water and, therefore, weight, and its density decreased. Despite being well known, this is important information to be presented in academic research when characterizing CD and comparing different samples of the same material. As the additions were calculated using the volume, this interfered with the effective quantity (by mass) of CD that was added to the earth mortars. Therefore, to be able to compare the test results with those of other research, the moisture content and density of the CD samples were recorded, specifically on the exact day that they were used to produce the earth mortars. Furthermore, the measurement unit in volumetric proportions was physically comparable with that of other additions, although the loose bulk density allowed the definition of the corresponding mass used in laboratory production. Moreover, in situ, it facilitates practical application without using equipment such as a balance.

Table 2. Moisture content and loose bulk density of all cow dung samples used and the amount of dry material contained in 100 mL.

Cow Dung Samples	Moisture Content (% mass)	Density (g/cm³)	Dry Solid Fraction Content in 100 mL (g)
CDfp	84	0.99	16
CDfp7	61	0.40	16
CDfp30	12	0.20	18
CDfp30pow	10	0.40	36
CDdrypow	10	0.40	36
CDfrat7	57	0.38	16

2.4. Mortars and Specimens

An initial experimental earth mortar using only CAP earth with no sand addition was produced and used to plaster a ceramic brick with a 20 cm × 30 cm surface and a 1.5 cm thickness. A large amount of shrinkage and many cracks were observed (Figure 4).

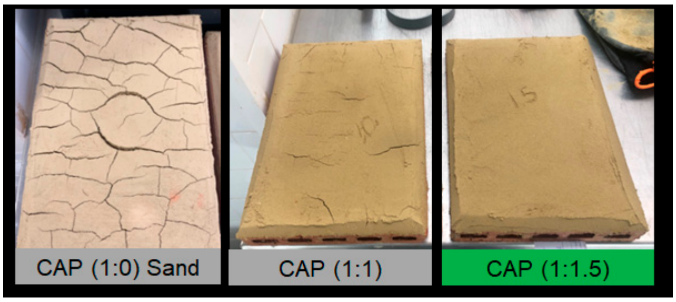


Figure 4. Preliminary shrinkage test to optimize sand addition in earth-based plasters on brick. In green, the optimized earth–sand volumetric proportion of 1:1.5 is shown.

The addition of sand, as a fine aggregate, may decrease the mechanical strength but contributes to limiting the shrinkage of earth mortars. For this reason, unless other materials are added to perform this function (such as fibers or sandy earth), balanced sand content has to be added. However, sand needs to be specifically extracted from nature, while the earth used was excavation waste from construction works. Therefore, to determine the earth–sand ratio of the mortars that minimized the utilization of additional sand, different proportions of sand were considered in the production of the mortars using the water necessary to obtain flow table consistency [46] of 170 mm. The mortars were produced with volumetric earth–sand ratios of 1:0, 1:1, and 1:1.5 and used to plaster bricks with the same thickness.

After 24 hours of air drying in laboratory conditions, the mortar that showed limited microcracks appearing on the plaster surface was chosen (Figure 4). This preliminary shrinkage test showed that it was necessary to add 1.5 volumes of sand to 1 volume of CAP.

To achieve the objectives of the present study, apart from a reference earth mortar with no addition (0% CD), nine other mortars with different CD additions were produced in volumetric proportions that were calculated based on the total volume of the dry components: earth + sand. All ten mortars were formulated with the CAP earth and are described below.

- CAP-REF—earth–sand (1:1.5) with no addition (0% CD).
- CAP+20CDfp—earth–sand (1:1.5) with addition of 20% of CD collected fresh in the pasture (CDfp).
- CAP+20CDfp7—earth–sand (1:1.5) with addition of 20% of CD collected fresh in the pasture, dried for 7 days (CDfp7), and molded immediately after mixing.
- CAP+20CDfp7FM—earth–sand (1:1.5) with 20% of CDfp7 addition, left in an opened plastic container, with a mosquito net on top, for 72 h to obtain a fermented mortar (FM); an extra 50 mL of water was added to the mortar to compensate for the evaporating water during the humid curing, to keep the mortar moldable and not too dry.
- CAP+20CDfp7rec—this mortar was produced by reusing the specimens of CAP+20CDfp7; three specimens were broken and mixed with water to produce three new recycled specimens (with no extra addition of earth, sand, or CD).
- CAP+40CDfp7—earth–sand (1:1.5) with 40% of CDfp7 addition.
- CAP+40CDfp30—earth–sand (1:1.5) with the addition of 40% of CD collected fresh in the pasture and dried for 30 days (CDfp30); the CDfp30 density was 0.20 g/cm³.
- CAP+20CDfp30pow—earth–sand (1:1.5) with the addition of 20% of CD collected fresh in the pasture, dried for 30 days and ground to a powder (CDfp30pow); the CDfp30pow density was 0.40 g/cm³; because of the difference in density after grinding, first, the volumetric proportion of 40% of CDfp30 was measured and then this volume was ground and considered equivalent to 20% of CDfp30pow.
- CAP+20Cddrypow—earth–sand (1:1.5) with the addition of 20% of CD collected dry and ground to a powder (Cddrypow).
- CAP+40Cdfrat7—earth–sand (1:1.5) with the addition of 40% of CD collected fresh from cows fed with rations and dried for 7 days (Cdfrat7).

All mortar compositions are listed in Table 3. They had a volumetric earth–sand ratio of 1:1.5, meaning that they contained 40% CAP earth and 60% additional sand.

Table 3. Added cow dung and water/dry component mass ratio necessary to reach 170 ± 5 mm flow and wet density of earth mortars.

Mortars with Volumetric Ratio (Earth–Sand) 1:1.5	CD Addition (% vol. E+S)	Water/Dry Components (%)	Wet Density (g/cm³)
CAP REF	0	20	1.45
CAP+20CDfp	20	21	1.37
CAP+20CDfp7	20	23	1.36
CAP+20CDfp7rec	20	26	1.30
CAP+20CDfp7FM	20	25	1.36
CAP+40CDfp7	40	30	1.26
CAP+40CDfp30	40	30	1.24
CAP+20CDfp30pow	20	33	1.21
CAP+20CDdrypow	20	36	1.23
CAP+40CDfrat7	40	36	1.23

A mechanical mortar mixer for the laboratory was used to prepare the mortars according to the DIN 18947 standard [47]. To guarantee good workability and low shrinkage, water was added to obtain a mortar with flow table spreading of 170 ± 5 mm [46]. The ratio of water to dry components varied, and it depended on the quantity of cow dung added to the mortar formulation and how dry the sample of cow dung was. The higher the amount of cow dung was and the dryer it was, the more water that had to be added to achieve good workability. The ratio by mass of water and dry components is given in Table 3. The fresh mortars were characterized by their wet densities, following EN 1015-6 [48]. DIN 18947 [47] requires as a parameter that all fresh mortars present a density higher than 1.2 kg/dm³.

In order to evaluate the mortars after drying, two types of specimens were produced for each mortar, namely four standard 40 mm × 40 mm × 160 mm prismatic specimens (Figure 5a), as determined in DIN 18947 [47], and three render areas, measuring 5 cm × 4 cm and 2 cm thick, applied on experimental walls (Figure 5b) for the shear stress test, according to Hamard et al.'s [49] suggestions. To achieve the verification of the adhesive potential of cow dung addition, the evaluated mortars were applied on adobe and ceramic brick masonry walls (Figure 5c). The surface of the masonry was moistened before each application of the render with sprayed water.

(**a**) (**b**) (**c**) (**d**)

Figure 5. Prismatic specimens (**a**), render/plaster specimens applied on experimental masonry walls of ceramic bricks (**b**) adobe (**c**), and being tested with handmade equipment with the addition of weight (**d**).

Three prismatic specimens were first used for linear shrinkage and bulk density analyses, followed by the flexural strength (breaking each one at half) and, lastly, the compressive strength using the six halves. The fourth prismatic specimen was sawn into 3 cubes measuring 4 cm × 4 cm × 4 cm and used for the immersion test. The prismatic specimens were molded and maintained in the laboratory environment at 63 ± 5% relative humidity and 26 ± 3 °C. DIN 18947 [47] states that specimens should be tested after reaching a constant mass. For a fair comparison, all specimens were tested at the age of 30 days.

2.5. Mortar Test Methods

In the present study, the European standards defined in DIN 18947 [47] were used for testing. Starting with non-destructive tests, three prismatic specimens were used for a linear drying shrinkage evaluation and to determine the bulk density of the dry mortars.

The shrinkage occurring during the drying process was assessed as the percentage difference between the specimen and the mold dimensions. The shrinkage index was calculated as the mean between the ratio of the dimensional variation on three sides of the specimen (width, height, and length) and the size of each respective side of the mold.

Based on EN 1015-10 [50], the dry bulk density was measured by dividing the specimen's mass by its volume, which was assessed using a digital balance with 0.01 g precision and a digital caliper with 0.1 mm precision.

Finally, after the non-destructive tests, the three prismatic specimens were used for flexural and compressive tests, based on the EN 1015-11 methods [51]. First, the flexural strength was determined by rupturing three specimens per mortar formulated. A 2 kN load cell and a constant speed of 0.2 mm/min for vertical load application were used. Next, using the six specimens' halves, the compression strength was determined using the same 2 kN load cell but with a speed of 0.7 mm/min.

For the adhesive shear strength, the methodology suggested by Hamard et al. [49] was followed. Three specimens of each mortar applied on adobe and ceramic brick masonry walls were tested. The test was carried out using handmade equipment (Figure 5d), which included a tray to impose weight. The equipment was positioned on the upper surface of the plaster/render specimen. Weights of 250 g were sequentially added to the tray, creating an increasing vertical force parallel to the wall surface. The adhesive shear strength (in N/mm^2) was calculated as the highest weight (in g) supported by the specimen before shear, multiplied by the gravitational acceleration (g = 9.81 m/s^2) and divided by the adhesive area (in mm^2).

For the water immersion test, a 250 mL glass beaker filled with 150 mL of water was used to immerse the 4 cm × 4 cm × 4 cm cubes for each evaluated mortar. The test was carried out under laboratory conditions: 63 ± 5% relative humidity and 26 ± 3 °C. To observe, analyze, and compare the mortars' behavior, photographs were taken after 1, 2, 5, 10, 15, and 30 min of immersion. In order to achieve a more complete and longer evaluation, visual observations were also performed after 7 and 14 days of immersion in a large tray filled with water.

3. Results and Discussion

3.1. Linear Drying Shrinkage

Figure 6 presents the average linear drying shrinkage of the mortars. As demonstrated before by Pachamama et al. [5], the proportion of 20% of CD reduced the shrinkage, so this behavior was already expected. All of the evaluated CD additions reduced the linear shrinkage and all mortars presented a shrinkage index below 2%, which is the required limit specified in DIN 18947 [47].

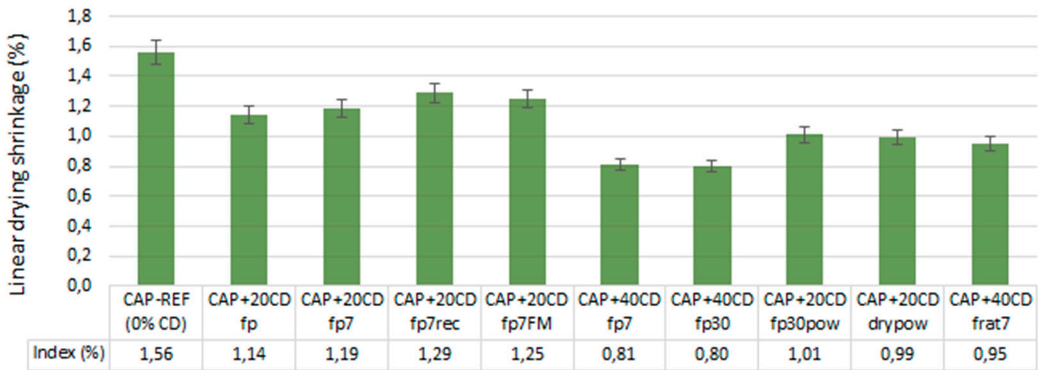


Figure 6. Linear drying shrinkage of earthen mortars with cow dung (CD) addition and reference mortar: average and standard deviation.

The 20% of CDfp addition reduced shrinkage by slightly more than 20% compared to CDfp7. Recycling and fermenting CD seems to be less efficient in reducing mortars' shrinkage. The larger proportion (40%) of CD addition greatly reduced the shrinkage. Both CD types in powder form were less able to limit shrinkage. The powder CD additions had shorter biofibers as a common aspect. These results indicate that the higher the integrity and availability of fibers, the greater the reduction in shrinkage.

According to Rao [32], over time, the bacteria available in CD decompose the fibers' structure, which reduces the effect of limiting shrinkage that could be offered by the fiber content. This effect can be observed in the following results. The addition of 20% CDfp (fresher) reduced shrinkage by more than 20% compared to CDfp7 (7 days older). Moreover, after the fermentation (humid curing) process of the mortar, CAP+20CDfp7FM offered a smaller reduction in shrinkage in comparison to CAP+20CDfp7 (the same mortar but no fermentation).

However, in addition to the contribution of fibers in limiting shrinkage, it was assumed that there was another reason for this finding, as even the CD powder additions also limited shrinkage in comparison to the reference mortar CAP-REF, albeit less so than the CD with whole fibers. Other research using dry CD powder also showed a reduction in shrinkage with CD addition. Bamogo et al. [8] added 0 to 6 wt.% of CD to earth plasters and Millogo et al. [29] added 0 to 3 wt.% of CD to adobe. Millogo et al. [29], Bamogo et al. [8], and Rao et al. [31] explained that, when using either silicate amines or EPS, loose earth particles were bonded together, and this rendered shrinkage difficult, optimizing even the ground fibers' contribution.

3.2. Apparent Dry Bulk Density

The bulk density does not indicate the mortar's quality or performance directly. However, for plastering mortars, lower-density mortars are easily applied and have benefits in terms of the action of gravity, thus also contributing to adhesion to the substrate.

The density of the mortars is shown in Figure 7. The differences between the mortars produced with different CD additions and proportions show that, in general, CD reduces the dry bulk density. Regarding the parameters established in DIN 18947 [47], the dry bulk densities of all mortars were classifiable. CAP-REF, CAP+20CDfp, CAP+20CDfp7, CAP+20CDfp7FM, and CAP+20CDfp7rec were of the 1.6 class; CAP+40CDfp7, CAP+40CDfp30, CAP+40CDfrat7, CAP+20CDfp30pow, and CAP+20CDdrypow were of the 1.4 class.

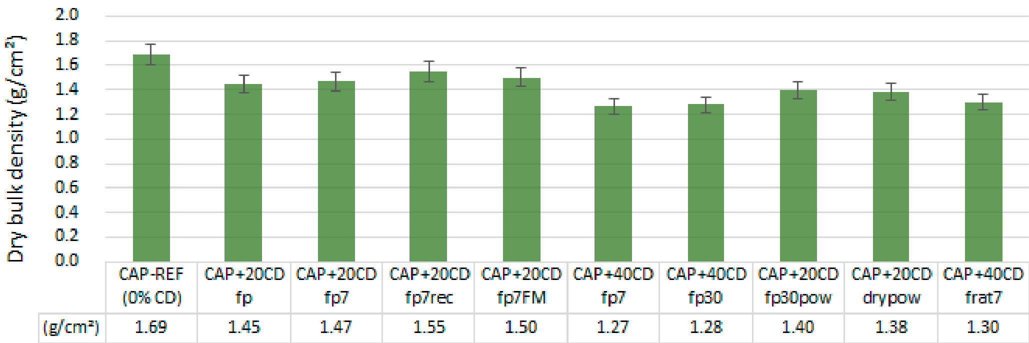


Figure 7. Dry bulk density of the earthen mortars with cow dung (CD) addition and the reference mortar: average and standard deviation.

3.3. Flexural and Compressive Strength

In the present research, the fresh CD (CDfp) addition offered the greatest contribution to limiting shrinkage (Figure 6). In the compressive and flexural strength test (Figure 8), the highest resistance was also offered by the fresh CD at the volumetric proportion of 20% (1.25 N/mm^2 and 0.60 N/mm^2, respectively). Moreover, the second-highest strength was obtained with the same CD after seven days of drying (CDfp7), in the same proportion of 20% (1.20 N/mm^2 and 0.57 N/mm^2, respectively). Both results reinforce the direct relation between the increase in mechanical resistance and the influence of freshly collected CD, the fiber content, and the bacterial activity.

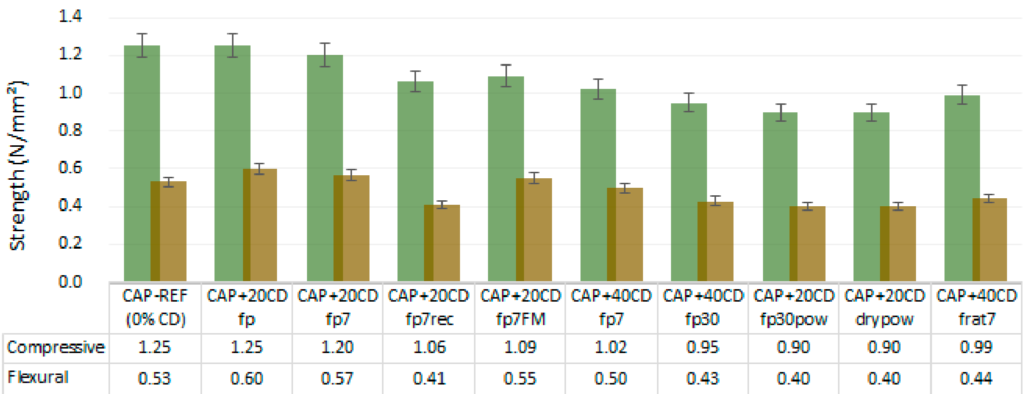


Figure 8. Compressive and flexural strength of earthen mortars with cow dung (CD) addition and reference mortar: average and standard deviation.

In comparison with the mortar (CAP+20CDfp7) molded immediately after mixing, the mortar subjected to 72 h of humid curing and fermentation with 20% of CDfp7 (CAP+20CDfp7FM) exhibited a reduction in compressive strength of 10% and in flexural strength of 4%. According to Rao et al. [31], this is justified by the action of the CD's bacteria, which decompose the fiber structure. On the other hand, the metabolic action of bacteria is desirable due to biocementation. For this reason, Rao et al. [31] recommend allowing the stabilized mortar's fermentation to increase the EPS production, while also adding ground hay fibers to increase the mechanical resistance and replace the CD fibers that will be damaged by the bacteria during the fermentation and drying process of the mortar.

The recycled mortar with CDfp7 addition (CAP+20CDfp7rec) presented lower resistance than the original CAP+20CDfp7. This can be explained using the same arguments as above. It is interesting that, even after being remixed with water and reused, the earth mortar with CD addition still exhibited sufficient resistance to be classified according to DIN 18947 [47]. This does not apply for earth mortars stabilized with air lime and cement, which cannot be reused as they are transformed into artificial stones.

Increasing the proportion of CDfp7 addition from 20% to 40% caused a 15% decrease in compressive strength, from 1.20 N/mm^2 (CAP+20CDfp7) to 1.02 N/mm^2 (CAP+40CDfp7), and a 12% decrease in flexural strength, from 0.57 N/mm^2 to 0.50 N/mm^2. The mortar with the same proportion of 40%, but with cereal-fed CD addition (CAP+40CDfrat7), exhibited slightly lower compressive strength, at 0.99 N/mm^2, and flexural strength, at 0.44 N/mm^2. The slight decrease in resistance is not a problem, although both strength measurements are below the DIN 18947 requirement [47]: the compressive and flexural strength must be greater than 1 N/mm^2 and 0.3 N/mm^2, respectively. Regardless, the results significantly exceed the minimal limit of 0.4 N/mm^2 for compressive strength specified in the standard EN 998-1 [9] for general-purpose mortars.

Comparing CAP+40CDfp30 with CAP+40CDfp7, the addition of the dryer CD (CDfp30) reduced the compressive strength by 7% and the flexural strength by 14%, which is not a problem. The likely cause of this occurrence is that, in CDfp30, the bacteria had already significantly damaged the fiber structure after 30 days of drying, which led to less food for bacterial development and EPS production when it was added to produce the earth mortar.

CAP+40CPfp30 exhibited compressive and flexural strength of 0.95 N/mm^2 and 0.43 N/mm^2, while CAP+40CDfp30pow exhibited values of 0.90 N/mm^2 and 0.40 N/mm^2 (the same results obtained when adding ground CD collected dry in the pasture). Thus, it was also verified that, compared to CDfp30, the use of CD in powder form does not cause a significant difference in relation to the mechanical resistance. However, the use of fresher CD is much more efficient than the use of dried CD.

For coating mortars, the compressive strength is commonly evaluated [9], although the flexural strength has an important contribution considering that it is the property that helps the coating to retain its shape and limits shrinkage and cracking during the drying process.

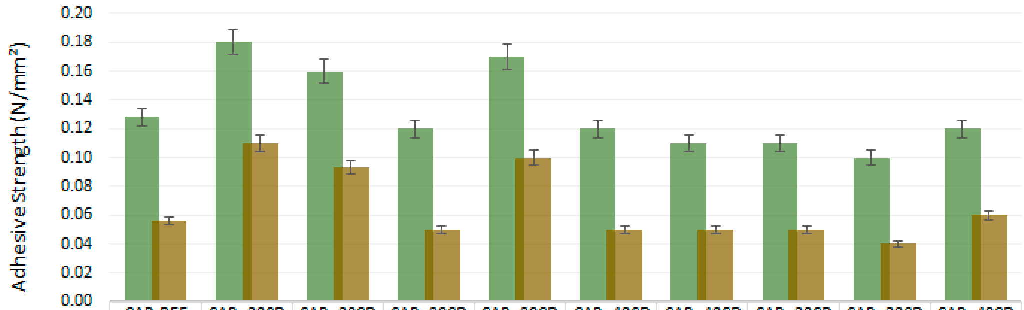
The fibers' contribution in increasing the mechanical resistance becomes evident when comparing CAP+20CDfp7 with the similar fermented mortar CAP+20CDfp7FM; CAP+40CDfp30 with the similar mortar with powder, CD CAP+40CDfp30pow; and CAP+40CDfp30 with the fresh CD, CAP+40CDfp7. However, the increase in the fiber content provided by the higher addition of 40% of CDfp7 slightly reduces the mechanical resistance in comparison to 20% of CDfp7 addition, regarding both the compressive and flexural strength.

Finally, CDfrat (fresh—fed with cereals) presents intermediary resistance: it is lower than that of CDfp (fresh—pasture-fed) and higher than that of CDdrypow (dry—pasture-fed). CDfrat7 had shorter fibers than CDfp7, but, since it was collected fresh, it still had a large number of bacteria from the cow's digestive system. Thus, the lower resistance offered by CDfrat7 is possibly related to the lower fiber presence in comparison to CDfp7, which was processed under the same conditions for seven days of drying/composting. Furthermore, there are some differences in the type and quantity of bacteria in the cow's digestive system, related to the diet consumed on the pasture (grazing) and in the feedlot [52], which can interfere with the effect of the CD on earth mortar stabilization. Despite this, and considering the average deviation, even the ration-fed CD offers classifiable values in terms of DIN 18947 [47] and EN 998-1 [9].

Millogo et al. [29] investigated CD powder addition in adobe, from 0 to 3% wt. The mechanical strength of the adobe increased as the amount of CD added increased. Bamogo et al. [8] investigated a similar range of addition, from 0 to 6% wt. of CD powder, but in earth plasters. The highest resistance was obtained with 6% wt. of CD addition. In a previous study, Pachamama et al. [26] observed that 10% of CD addition increased the flexural and compressive strength by 50% and 20% CD addition decreased both properties by 10%. These results indicate that there is an optimal proportion of CD addition to increase the mechanical resistance of earthen mortars, and it seems to be approximately 10%.

3.4. Adhesive Shear Strength

Figure 9 shows that the addition of CD increased the adhesive shear in comparison to the earth mortar with no CD addition. Moreover, the results obtained on the adobe masonry were always higher than those obtained on ceramic brick masonry. This can be explained by the high chemical compatibility between the earthen-plastering mortars and adobe. Ceramic bricks pass through a firing process under high temperatures, which transforms the clayish material into a ceramic, changing the behavior of the clayish material and reducing the compatibility between the earthen mortar and the ceramic bricks.



	CAP-REF (0% CD)	CAP+20CD fp	CAP+20CD fp7	CAP+20CD fp7rec	CAP+20CD fp7FM	CAP+40CD fp7	CAP+40CD fp30	CAP+20CD fp30pow	CAP+20CD drypow	CAP+40CD frat7
Adobe	0.13	0.18	0.16	0.12	0.17	0.12	0.11	0.11	0.10	0.12
Ceramic brick	0.06	0.11	0.09	0.05	0.10	0.05	0.05	0.05	0.04	0.06

Figure 9. Adhesive shear strength of earthen mortars with cow dung (CD) addition and reference mortars on adobe and ceramic brick masonry: average and standard deviation.

As for the compression and flexural resistance, the fresh CD exhibited higher adhesive shear resistance. In comparison to the reference mortar, 20% CDfp addition increased it by 38%.

In this study, 20% of CDfp7 addition increased the adhesion by 23% and the fermentation process of the same mortar (CAP+20CDfp7FM) provided a greater increase of 31%. According to Rao et al. [31], the fermentation process increases the bacterial activity, the metabolic production of EPS, and, consequently, the biocementation. Thus, the results achieved indicate that the fermentation of the mortar and the EPS content are also related to the adhesive properties.

When increasing the proportion from 20% to 40% of CDfp7, the adhesive strength was reduced from 0.16 N/mm^2 (CAP+20CDfp7) to 0.12 N/mm^2 (CAP+40CDfp7), similar to the reference mortar with no CD addition (CAP-REF).

Comparing CAP+40CDfp30 with CAP+40CDfp7, the addition of the dryer CD (CDfp30) reduced the adhesive strength by 8%. CAP+40CDfrat7 (cereal-fed CD) presented the same behavior as CAP+40CDfp7 (pasture diet).

The mortars with lower adhesive strength contained the driest CD (CDfp30 and CDdrypow) additions. The grinding of CD (CDfp30pow) did not change the behavior of CDfp30 in the adhesive test. Despite this, all mortars, except for the CD collected dry on the pasture (CDdrypow), exhibited results in accordance with the DIN standard [47] (adhesive strength must be greater than 0.05 N/mm^2). For this test, the referred standard indicates that the EN 1015-12 method [53] should be followed. However, because this method usually damages the specimens when applied on earthen and lime mortars, the test was performed using a different method, the adhesive shear strength test described by Hammard et al. [49], which reduces the rate of failure during the adhesion evaluation of earth mortar specimens.

Pachamama et al. [5,26] also registered an increase in the adhesive strength with CD addition (of 10% more than with 20% volumetric proportions) in all earth mortars produced with the same three different earth types.

3.5. Immersion in Water

This test carries greater demands than the typical requirements for earthen plasters and even for earthen renders that are applied indoors or outdoors, respectively, because, even considering the effect of rain run-off, the conditions are less aggressive than those in the immersion process.

Figure 10 exhibits the results for the CAP-REF mortar with no CD addition and the biostabilized mortars with volumetric proportions of 20% of CD addition. As mentioned before, the mortar specimens were immersed in water and images were taken after 1, 2, 5, 10, 15, and 30 min.

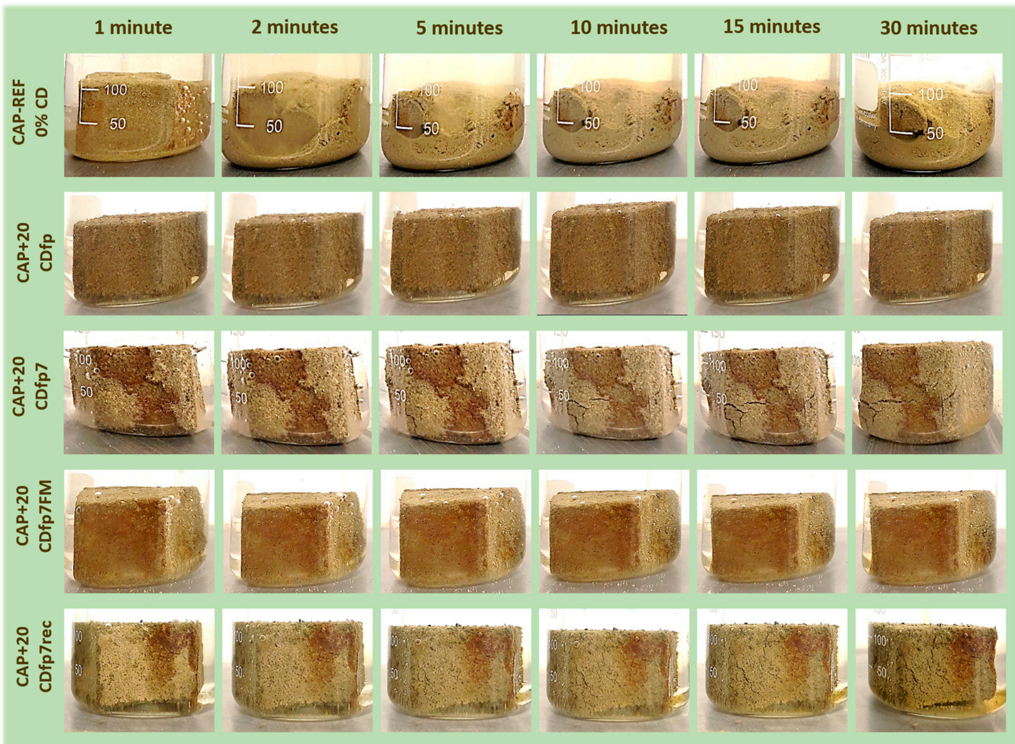


Figure 10. Immersion in water for up to 30 min, from top to bottom, for CAP-REF mortar (no CD addition) and mortars with 20% of fresh pasture-fed cow dung addition (CDfp), 20% of CDfp after seven days of drying (CDfp7), recycled CAP+20CDfp7, and CAP+20CDfpFM (fermented via 72 h hydrated curing).

When comparing the biostabilized mortars to the reference mortar (0% CD), the contribution of CD addition is clearly visible in terms of the increasing resistance to water. The CAP-REF mortar began to disaggregate after 1 min; after 5 min, it was almost completely transformed into grains. In contrast, all mortars with CD addition exhibited much greater durability.

CDfp addition led to higher durability in the test, probably because the CD was added to the mortar while it was still reasonably fresh. In this CD sample, there was the greater availability of fibers that had been minimally attacked by bacteria (after leaving the animal's body) [31], and there was a large presence of bacteria and smaller aggregates formed [30].

It is possible that, in this balanced composition, a layer of resistant fibers was formed, being gradually consumed by the bacteria and aggregated by the EPS produced, forming a resistant structure in the mortar.

CAP+20CDfp7 increased the durability of the specimen in relation to CAP-REF, but cracks began to appear after 10 min of immersion. In comparison to adding 20CDfp, the addition of 20CDfp7 led to lower durability. The lower structural integrity of the fibers, caused by the action of bacteria during the seven days of composting (drying) for CDfp7, may have contributed to reducing the strength of the structural network formed by the fibers compared to 20% of CDfp addition.

In the 72 h humid curing fermentation process of CAP+20CDfp7FM, the fibers were affected by bacterial activity, which degraded the cellulose and ribose sugars and proteins [31], reducing the mechanical resistance (Figure 8). However, due to the higher production of EPS by bacteria, the adhesive strength increased (Figure 9), and this considerably increased the durability of the specimens in the water immersion test (Figure 10).

The recycled mortar, CAP+20CDfp7rec, presented essentially the same behavior as CAP+20CDfp7. This shows that the addition of CD does not harm an important property of earth mortars: reusability. Even after the CAP+20CDfp7 specimens were dried for 28 days and were broken and mixed again with water to produce the CAP+20CDfp7rec mortar specimens, their water-repellent properties were not impaired, and they still exhibited higher durability to water immersion compared to CAP-REF (0% CD addition).

Figure 11 exhibits the results for the biostabilized earth mortars with a gradual increase in the proportion of CD addition, with volumetric proportions of 40% of CD addition (CDfp7, CDfp30, and CDfrat7) and 20% of powder CD addition (CDfp30pow and CDdrypow), equivalent to 40% of whole CD.

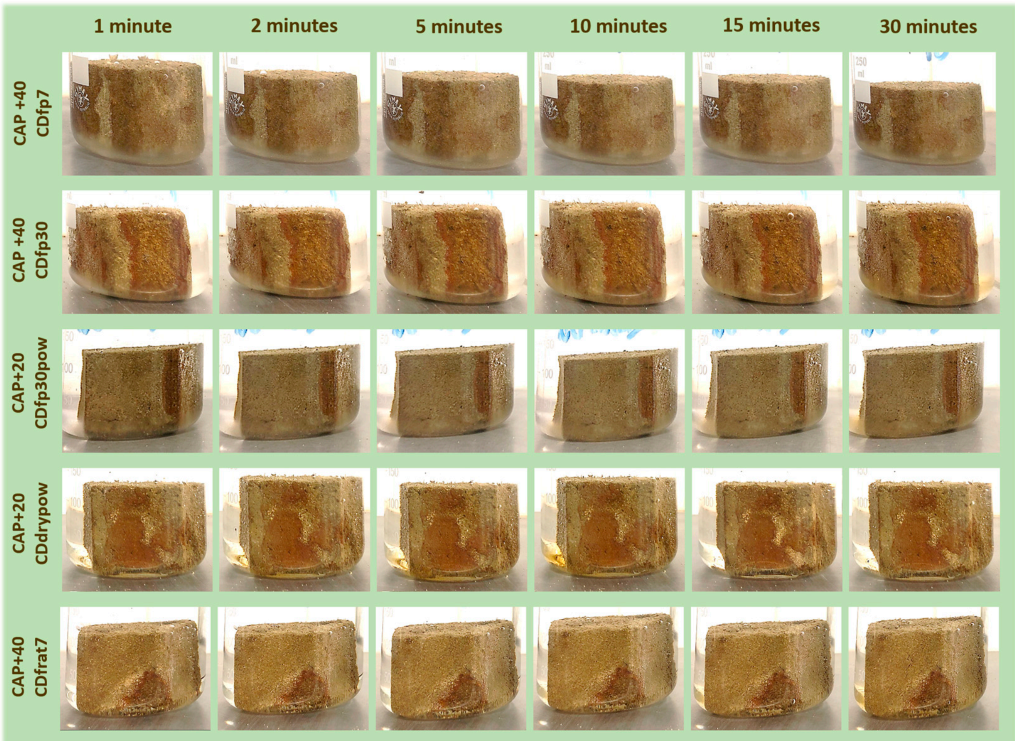


Figure 11. Immersion in water for up to 30 min for the earthen mortars with 40% of cow dung addition (CDfp7, CDfp30, and CDfrat7) and the equivalent (dry solid mass content) proportional addition of 20% CD powder (CDfp30pow and CDdrypow).

The photographs in Figure 11 show that the large amount of fiber content with 40% whole CDfp7 and CDfp30 addition contributed to maintaining the cubic form of the specimens after 30 min of immersion in water. Unexpectedly, the addition of CDfp30 powder and CDdrypow, at a volumetric proportion of 20% (equivalent to the same solid dry content), also maintained the cubic form of the specimens. The great durability in the immersion water test also evidenced the bacterial activity, even for the pasture-dried CD.

At the same 40% proportion of addition, CDfrat7 and CDfp7 exhibited very similar behavior. The animal's diet did not cause a significant difference in the hydrophobic properties during CD addition.

It is important to note that, after the test, the specimens were placed in another tray covered with 8 cm of water to observe the behavior of the biostabilized mortars for another 14 days. After an additional seven days of water immersion in the tray, CAP+40CDfrat7, CAP+40CDfp30, CAP+20CDfp30pow, and CAP+20CDdrypow showed deep cracks, but still maintained their cubic shapes without collapsing. After a total of 14 days, CAP+20CDfp, CAP+40CDfp7, and CAP+20CDfp7FM showed considerable cracks, but still maintained their cubic shapes.

Millogo et al. [29] and Bamogo et al. [8] attributed the CD's effects to the new compound formed: insoluble amine silicate. Rao et al. [31] attributed them to EPS cementation, which fills pores and reduces water absorption.

Kulshreshtha et al. [30] also investigated the hydrophobic effect caused by CD addition, but on 4 cm × 4 cm × 4 cm compacted earthen blocks with 2% wt. of CD addition. These researchers conducted the same water immersion test as in the present study, but only used one sample and a small proportion of CD addition, and they did not evaluate variations in the CD treatment conditions. From the photographs presented, it is also possible to verify the beneficial contribution of CD addition in increasing the duration and resistance of the immersed specimens in contact with water. To explain this effect, some specific characterization tests on the fresh CD were carried out, and the results showed that there were negatively charged clay-sized particles that were rich in fatty acids. One of the dominant fatty acids found, octadecanoic acid, has been used with silica nanoparticles to develop water-resistant hydrophobic coatings [54], which reinforces Kulshreshtha et al.'s [30] explanation. Therefore, the fatty acids present in the CD (and the EPS bacteria's products) also contributed to improving the water resistance of the mortars in the present study with 20% and particularly with 40% CD.

To increase the durability under water immersion for up to 24 h, Kulshreshta et al. [30] recommend removing the fibers before the addition of the CD for the production of compressed earth blocks. However, despite this, in the present study, for earth mortars for rendering and plastering, the largest proportion of fiber content with 40% of CDfp7 addition resulted in greater durability under water, rather than 20% addition (and 10% [26]). Even the 40% ground CD collected dry on the pasture (CDdrypow) and the whole CDfp30 presented long-term durability. Therefore, depending on the CD addition proportion and application, removing the fibers seems unnecessary for mortars.

3.6. Complementary Discussion

Earth mortars with cow dung addition have a pleasant and mild odor. When these biostabilized mortars are applied in buildings with common working site ventilation, a characteristic bovine leather odor appears for a maximum of three days. After this period, there is no trace of odor. In highly ventilated working sites, the mild odor disappears faster. Therefore, neither benefits nor drawbacks related to odor or toxicity exist. Furthermore, after the drying of the coating, a clay-based or lime-based paint finishing can be applied, which eliminates the possibility of direct contact with the mortar.

Comparing the results obtained in the present study and in the previous one [5] for earth mortars produced with the same CAP earth and earth–sand ratio (1:1.5), an interesting analysis can be performed regarding the effects of CDfp7 addition.

In comparison to CAP-REF, which exhibited compressive and flexural resistance of 1.25 and 0.53 N/mm^2, respectively, the 10% proportion increased these values to 1.44 N/mm^2 and 0.71 N/mm^2. The 20% proportion reduced them to 1.20 and 0.57 N/mm^2 and the 40% proportion of CDfp7 addition decreased them to 1.02 N/mm^2 and 0.50 N/mm^2, which are still classifiable values according to DIN 18947 [47]. In relation to the adhesion to the adobe and ceramic brick masonry walls, the proportion of 10% CDfp7 addition increased this property by more than 20%, while the 40% proportion decreased it. This means that the mechanical strength and adhesive property increased as the amount of CD addition decreased, ranging from 40% to 10%. On the other hand, the proportion of 40% offered more durability in the water immersion test than the proportion of 20%, as well as significantly greater durability than 10%.

Moreover, the 72 h humid curing fermentation process with 20% addition (CAP+20CDfp7FM) increased the durability in the immersion water test, as with the 40% CDfp7 addition, but achieved higher compressive and flexural strength (1.09 and 0.55 N/mm^2, respectively) in comparison to the non-fermented proportion of 40%.

Therefore, to obtain a balanced effect (mechanical strength, adhesion, and water resistance) on CAP earth mortars, the proportion of 20% CDfp7 addition with the fermentation process is an effective strategy.

Furthermore, it is shown that cow dung is indeed an effective traditional solution to increase the resistance of earth mortars when in contact with water. This has an impact on their durability but also expands the possible applications of this type of coating mortar. In addition, this study emphasizes the possibility of using eco-efficient waste instead of binders obtained by firing, such as at around 900 °C for air lime, which is particularly important for communities that lack financial resources.

4. Conclusions

The objective of this research was to evaluate the influence that the preparation of cow dung may have on the biostabilization of earthen coating mortars, including the conditions of cow dung collection (fresh or dry), whether it is in contact with the soil or not, the drying conditions (composting), grinding, the moisture content and density when used, the unit of measurement (weight or volume), and the proportion. This research also aimed, by comparing data from the literature with those from practical applications, to understand the function of the fiber content in the natural composition of cow dung and the influence of a 72 h period of humid curing fermentation. Furthermore, the influence of the animal's diet on the cow dung's effects on the earth mortar was analyzed, as well as the reusability of mortars biostabilized with cow dung addition.

Despite the difficulties in its collection, transport, and storage, using fresh cow dung provides a larger increase in the mechanical performance, adhesion, and durability when water contact occurs. However, using dry cow dung after it has been composted for 30 days (CDfp30) is not a problem, as it still shows satisfactory behavior in all tests. Furthermore, the fermentation process of the biostabilized mortar with CDfp30 addition provides an alternative to compensate for its lack of freshness (CDfp).

Collecting fresh cow dung and allowing it to dry (composting) in an impermeable plastic container before usage offers better effects on the CAP earth mortar than the use of cow dung that is already dry in the pasture, after air–sun drying in contact with the soil.

Despite the minor reduction in compression and flexion strength, the 72 h humid curing fermentation of CAP+20CDfp7FM increased the adhesive strength and durability when in contact with water, possibly by increasing the production of exopolysaccharides (EPS) and biocementation. In future studies, the effects of cow dung addition with extra fibers (also in situ and using the same CAP earth) should be evaluated to verify whether this can compensate for the loss of mechanical resistance that occurs with fermentation.

The cow's diet appears to result in no difference in relation to the effects caused on earth mortars. Despite the greater availability of carbohydrates offered by diet of cereals, which (theoretically) could enhance the production of EPS by bacteria, the lower presence of long fibers rich in cellulose, hemicellulose, and lignin (which is obtained with a pasture diet) may have constrained the mechanical resistance recorded for the addition of cereal-fed cow dung. Furthermore, CAP+40CDfrat7 presented excellent durability in the immersion test after 30 min and also after seven days.

The fibers appear to be directly related to reduced shrinkage and increasing mechanical resistance. Moreover, it seems that there is an optimal point between the presence of fibers and microbial activity, because, with 10% (as seen in a previous study) and 20% (present study) of CDfp7 addition, the mortars could not withstand 20 min of immersion. However, with 40% of CDfp7 addition (present study), the durability in water was high. Usually, the fibers enable water to enter via capillarity. Despite this, in this case, where the fibers were added together with bacteria (natural cow dung composition), microfibers can play a favorable role in creating a structural network biocemented by EPS produced by microbial action, which maintains the shape of the dry mortar under water immersion.

The addition of 40% of ground cow dung collected dry in the pasture allowed us to maintain the cubic shape of the specimens, indicating that the bacterial biocementation activity was retained after the drying of the cow dung.

Finally, the addition of cow dung proves to be an advantageous biostabilization method as it allows the mortar's reuse by simply remixing it with water. The dry mortar with the addition of 20% of CDfp7 was remolded and showed results that were superior to those of the reference mortar without further addition and similar (although inferior) to the same mortar without being recycled, i.e., CAP+20CDfp7.

Considering the results of the present research, and reinforced by the literature and traditional practices, cow dung addition provides earth mortars with important benefits, such as increased mechanical resistance, increased adhesion to the substrate (at least for adobe and ceramic brick masonry), reduced shrinkage, and increased durability when in contact with water. Furthermore, no negative issues related to odor or toxicity arise. These aspects make this material a powerful eco-friendly bioaddition for earthen mortars. Apart from being used for plastering mortars, these cow dung mortars may also be useful for other applications, such as adobe production, adobe bedding mortars, and repointing or cob production. The findings regarding the effects of cow dung processing are also important to support builders who already use cow dung addition for earth building and those who intend to use it or conduct research on it. Furthermore, the reusability of cow dung earth mortars positions this material as an important tool for the development of bioproducts and for sustainable building practices.

Lastly, the positive effects and ecological advantages of its use are undeniable. Therefore, studies should seek to further understand and optimize the effects of cow dung addition, the bacteria's EPS production, and the biocementation activity on the performance of earth mortars, namely to assess the effect on their water retention properties and the behaviors of these mortars when applied under different environmental conditions and when a finishing paint (clay-based, lime-based) is applied. An environmental assessment of cow dung earth mortars is also important, including the impact of local cow dung collection.

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