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Engineering properties of earth mortar produced with cow dung ash and *Cissus populnea* powder

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Abstract

Cement mortar is a widely used construction material due to its excellent strength, fire resistance, and durability properties. However, the environmental concerns associated with cement production have necessitated the development of eco-friendly building materials such as earth mortar. This study explores the potential of using cow dung ash (CDA) and *Cissus populnea* powder (CPP) as sustainable binders in earth mortar. Earth mortar was prepared using laterite, 2.5–10% by weight of CDA and CPP added at 2.5% intervals, and water. Sixty cubic (100 × 100 × 100 mm) and 30 cylindrical (100 × 200 mm) specimens were prepared, cured for 28 days, and tested for erosion, compressive strength, split tensile strength, and water absorption. The inclusion of CPP and CDA in earth mortar significantly improved the compressive strength of the mortar by 46.5–81.5%, while the tensile strength was improved by 94.7–126%. The 7.5% CPP specimen recorded the lowest water absorption of 1.204%, as compared to the control of 3.440%, representing a 186% improvement in water absorption resistance of the specimen. The control specimen exhibited erosion depths of 4–5 mm, while all the CPP and CDA specimens recorded zero erosion. The study concludes that mortar produced with CDA and CPP significantly enhances the mechanical, physical, and durability properties of the earth mortar. It is recommended that stakeholders use 7.5% CPP and 2.5% CDA for lightweight structural applications. Further studies are recommended to investigate the thermal properties and cost benefits of using CPP and CDA in sustainable earth mortar production.

Keywords: Compressive strength; *Cissus populnea* powder; Cow dung ash; Earth mortar; Engineering properties; Erosion; Tensile strength

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1. Introduction

Mortar is widely utilized in construction due to its numerous attributes, encompassing outstanding compressive strength, resistance to fire, and the capacity to be shaped and sized as desired.[1] Mortar is primarily composed of cement, coarse aggregates, fine aggregates, water, and sometimes, additives or admixtures, which are proportioned to enhance specific properties.[1,2] Cement is the primary binder for making earth mortar used in building infrastructure.[3] However, several binders have been utilized to stabilize the earth during construction to enhance its waterproofing and wear-resistant properties.[4]

These binders, consist of cement, lime, tars, bitumen, sodium silicate, casein, oils and fats, molasses, and specific plant-based materials like gum arabic, resins, and tree sap.[4,5] Since the local building sector is constantly expanding, there is a strong demand for cement as the main binder in earth-mortar production, which has led to substantial production and importation of cement.[6] The global production of cement increased from 1.39 billion tons in 1995–4.4 billion tons in 2021 and is projected to reach 5.5 billion tons by 2050.[7]

It is generally acknowledged that cement plays an important role in the development of contemporary infrastructure and industrialization.[8] However, there are concerns with the use of cement as a binder for earth mortar; first, the cement production process necessitates a large amount of thermal energy and is said to account for 5–6% of global carbon dioxide (CO_2) emissions.[9] It is important to note that the construction industry is identified by scientists as one of the major sectors that contribute to global warming due to high levels of CO_2 emission into the atmosphere during cement manufacturing.[10] According to the International Energy Agency,[11] the construction sector contributes approximately 39% of the annual global CO_2. Due to the high emission of CO_2 from cement manufacturing, researchers and governments are encouraging the use of more sustainable and environmentally friendly construction materials.[12] Futhermoe, the Ghana national housing policy has emphasized using locally sourced resources for building while supporting environmentally friendly manufacturing practices.[13] The second concern is the outrageous cost of cement, especially in developing countries. As indicated by Ige and Danso,[14] earth mortar has traditionally been improved by the addition of organic materials such as cow dung, ashes, and many more from agro-processing waste. Cement is a widely utilized binder for earth mortar as a result of its excellent engineering, including compressive strength, workability, and fire resistance. However, its production poses significant environmental problems, such as high energy consumption, resource depletion, and CO_2 emissions, prompting a shift toward sustainable alternatives.

Studies revealed that instead of using conventional materials such as cement as binders, many different traditional, environmentally friendly, and low-cost materials can be used as binders, including cow dung ash (CDA), clay, and many more.[1,4,6,15,16] According to Alelegn *et al.*,[17] gypsum, lime, and CDA were the materials used in the past to construct buildings and forts due to their strength and reduction of heat conduction, and due their waterproof properties. Cow dung is a type of waste material that is produced by cows and is the undigested remains of the food consumed by the animals.[18] Potassium, magnesium, and phosphorus, which are abundant in cow dung, serve as effective binders. A substantial amount of fibers in cow dung acts as a shield in plaster mortar against fracturing.[18,19]

Organic materials like cow dung, the waste in agricultural produce, and natural fibers have shown the potencies as eco-friendly and cost-effective binders, providing improvement in the physical, mechanical, and thermal properties of construction materials. *Cissus populnea* has been investigated as a potential binder for earth mortar in several studies. A study by Ismail and Aboshio[20] used extracts from *C. populnea* plants as an admixture in mud-based mortar for rendering. Adebowale *et al.*[21] found that up to 20% of *C. populnea* gum could be used without adverse effects on the basic properties of the composites. The study further indicates that *C. populnea* has the potential to be used as a binder in earth mortar, but further research is needed to fully understand its effects on the properties of earth mortar production. However, research utilizing CDA and *C. populnea* powder (CPP) as binders in earth mortar remain limited. There is less focus on the physical, mechanical, and durability properties of earth mortar produced with CDA and CPP. This study addresses this gap by investigating the engineering properties of earth mortar produced with CDA and CPP. Specifically, the properties such as compressive and tensile strengths, water absorption, density, and erosion resistance of earth mortar produced with CDA and CPP as sustainable binders are investigated in this study.

This study on the engineering properties of earth mortar with CDA and CPP is both timely and crucial due to growing concerns about the environmental impact of cement and its health implications. With the rising costs of cement and other building materials, there is a need to explore less expensive and more environmentally friendly substitutes. This research aligns with UN Sustainable Development Goal (SDG) 11, which aims to "build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation by 2030." The construction industry, a major contributor to the global environmental crisis, must adopt innovative building practices that minimize adverse environmental impacts. In addition, the study supports SDG 11, which focuses on making cities and human settlements inclusive, safe, resilient, and sustainable by 2030.

The findings of this study will attain valuable insights into the erosion, compressive strength, split tensile strength, and water absorption properties of earth mortar made with CDA and CPP. These results will not only contribute to the existing body of knowledge on sustainable construction materials but also offer practical solutions for the building industry. The study's objectives include determining the mechanical properties (compressive and tensile strength), assessing the durability in terms of erosion resistance, and analyzing the physical properties (water absorption and density) of earth mortar using CDA and CPP as alternative binders.

2. Literature review

2.1. CDA

Cow dung is the undigested residue of botanical material that has traversed the digestive system of the cow.[22] It consists of organic materials comprising fibrous substance that passes through the digestive system of the cow. The rumen of these animals is home to symbiotic bacteria that mostly break down leftover herbivorous material. On a global scale, an estimated 1.3 billion metric tons of cow dung is generated annually.[23] Even though cow dung is utilized in numerous domains, such as organic fertilizer in agriculture, biogas for electricity production, and thermal energy generation, Moses *et al.*[9] indicated that certain quantities are left as refuse in the grazing field and cattle shed and occasionally carried away through drainage pipes in slaughterhouses. Cow dung is abundant in minerals such as potassium, magnesium, sodium, and manganese, making it a good binder when mixed with other materials such as sand and water.[24] The chemical composition of cow dung is as follows: carbon, nitrogen, hydrogen, oxygen, phosphorus, salt, urea, mucus, as well as cellulose, lignin, and hemicellulose.[9] Lime, which makes up 0.36%, is the main chemical component in cow dung that has cementitious properties. This enhances the compressive strength by reducing the quantity and size of pores in construction materials.[25]

A recent study has explored CDA as a partial replacement for ordinary Portland cement in mortar and found that the pozzolanic activity due to high silica content (SiO_2) enhances compressive strength and durability, and obtained an optimal replacement levels range from 10% to 20%, which improved the strength without compromising workability. It also found that the microstructural benefits include increased formation of calcium silicate hydrate (C–S–H) gels, improved bonding, and reduced porosity.[26] Another study on durability and strength properties of CDA-modified mortars showed improved resistance to chemical attack (e.g., HCl, NaCl, H_2SO_4), and a decrease of water absorption and sorptivity with higher CDA content, indicating better long-term durability. It was also found that the thermal stability remains unaffected up to 600°C for mixes with 10–30% CDA.[27] A study on the sustainability and cost efficiency of CDA in mortar found that CDA is abundantly available and low-cost, making it ideal for sustainable construction.[28] The use of agricultural waste like cow dung and *C. populnea* aligns with circular economy principles and reduces carbon footprint.

2.2. Earth mortar

Earth has been used across the globe as a building material for thousands of years. In addition to being affordable and available, earth construction provides a low-energy substitute for traditional building materials, aspects that are especially crucial given the growing global awareness of the need to minimize energy use.[29] The grains that make up the earth are categorized based on their sizes.[30] Sunusi *et al.*[25] indicated that earth could be used as a ready-made building material with minimal processing needed. When combined with water, clay, a component of the earth, becomes pliable, plastic, or liquid, enabling it to be molded, which functions as cement.[29]

Earth mortars are created by mixing earth materials such as clay, silt, sand, and gravel with water.[31] Additional elements such as binders, aggregates, and pellets can be added to improve the quality of the mortar for construction applications. Earth mortars stabilized with natural binders, such as cement, hydrated lime, fly ash, and metakaolinite, offer technological, economic, and environmental advantages compared to conventional mortars.[31] These mortars have been found to have good workability and mechanical properties. The partial replacement of cement with fly ash has been shown to increase workability and decrease the environmental impacts of earth-based mortars.[32] According to Gomes *et al.*,[31] earth mortars are composed of commercially available soil, primarily clay, alongside supplementary components such as sand, hydrated air-lime powder, natural hydraulic lime, Portland cement, and natural fibers.

2.3. *C. populnea* in mortar

C. populnea is mostly found in the forest areas of Ghana and other African countries, Asia, and Australia. It is a dicotyledonous shrub that climbs to a height of three meters or more, depending on how old it is and how tall the tree providing support is.[33] In the Northern part of Ghana, the *C. populnea* plant is used as a traditional building material. The local people cut the plant into pieces and put it in water to obtain the slime. The slime water is mixed with fresh cow dung and used for plastering their local houses. This practice is widely adopted in rural areas, where availability of cement is restricted due to limited accessibility and high cost. The *C. populnea* plant has been investigated for its many characteristics and possible uses.[32] It has been found to contain sugars and extractives, which may impair cement bond formation; therefore, pre-treatment measures like soaking in water or the application of chemical additives like calcium chloride have been found to reduce these components, thus enhancing strong crystalline bond formation.[34] *C. populnea* has been investigated as a potential binder for earth mortar in previous studies.[34,35] Amoo *et al.*[34] used *C. populnea* in composite materials as reinforcement for tile production. A study by Olorunnisola *et al.*[35] used *C. populnea* gum and rubber latex as partial replacement of Portland cement in a composite material and found that up to 20% of gum and up to 2.5% of rubber latex in a rattan-cement composite influence the basic properties of the composite materials. Extract from *C. populnea* plants has been used in the rendering of mud-based structures as admixtures,[35] indicating that *C. populnea* powder has the potential to be used as a binder in earth mortar, but further research is needed to fully understand its effects on the properties of earth mortar.

3. Materials and methods

3.1. Materials

The materials used for the experimental work are laterite, CDA, CPP, and water. Laterite soil was also obtained from a site near the construction technology laboratory of the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED), in Kumasi. It had a density of 1528 kg/m^3 and a specific gravity of 2.62. The laterite, which was free from harmful substances, was dried and sieved through a 5.0 mm BS sieve (Figure 1A). The CDA was prepared from cow dung obtained from naturally fed cows in Wa, Upper West Region of Ghana. The cow dung was dried in the sun (Figure 1B), pulverized, and calcined (Figure 1C) at 500°C, a temperature identified as optimal for producing high-quality CDA.[36,37] After cooling, the ash was sieved using a 0.6 mm BS sieve (Figure 1D). Table 1 presents the chemical composition of CDA as studied by Szymajda *et al.*[38] The CPP was prepared from the stem of the *C. populnea* plant obtained in Wa, Upper West region of Ghana. The harvested parts of the *C. populnea* plant were cleaned to remove any dirt or contaminants, were then dried (Figure 1E) thoroughly to remove moisture, and then ground into a fine powder using a grinding mill. The powdered *C. populnea* was sieved using a 0.6 mm BS sieve to obtain the CPP (Figure 1F). The water used for manufacturing the earth mortar consisted of clean potable water, which was sourced from the construction technology laboratory of AAMUSTED.

3.2. Preparation of specimen

The study used 0%, 2.5%, 5%, 7.5%, and 10% of each CDA and CPP by weight of laterite for preparing mortar for the specimens. CDA and CPP were also combined at 50% each to prepare combined mortar specimens. The quantities of materials used are shown in Table 2, and the quantities of the materials were mechanically batched. An electric pan mixer was used for mixing the mortar, and before mixing, the pan was thoroughly cleaned to remove debris. The laterite, DCA, and CPP were added sequentially in their corresponding weight proportions while the mixer was rotating, and the water was gradually added until a uniform and plastic mix was achieved. The mortar was molded into 100 × 100 × 100 mm cubes and 100 × 200 mm cylinders (Figure 2A). Overall, 90 specimens were molded, consisting of 60 cubes (Figure 2B) and 30 cylinders. The molded specimens were then cured by water sprinkling for up to 28 days adhering to BS 7542:1992 standard.[39]

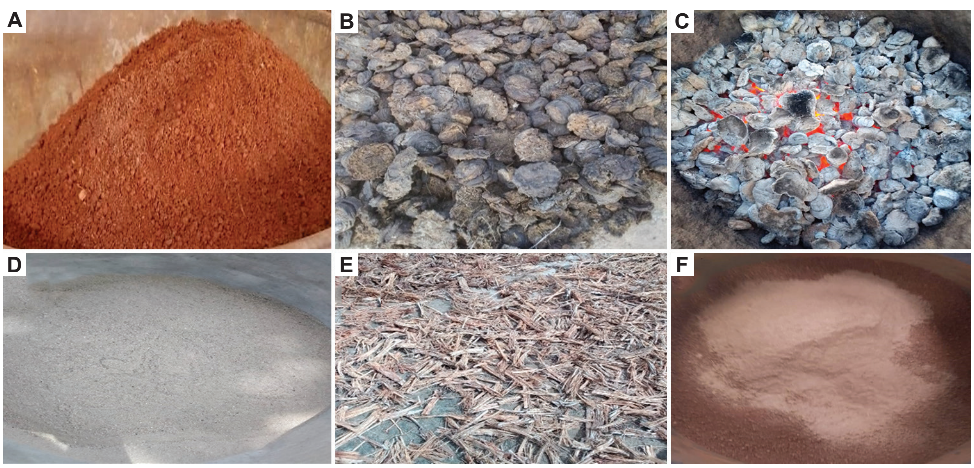

Figure 1. Materials used in this study: (A) laterite sample, (B) cow dung, (C) burning of cow dung, (D) cow dung powder, (E) drying of chopped *C. populnea* stem, (F) sieving of *C. populnea* into powder

Table 1. Chemical composition of cow dung ash[38]

Chemical composition of ash	Own research January	Own research February	Own research MARCH	Own research April	Own research May	Own research June
Ashes (%)	12.49	8.90	9.25	10.53	8.75	13.90
Na (%)	5.27	3.05	1.02	0.96	3.10	1.50
Mg (%)	7.12	9.48	7.25	6.23	7.88	5.79
AI (%)	1.28	1.10	1.40	0.98	1.16	1.13
Si (%)	15.80	11.94	14.24	11.55	15.57	10.77
F (%)	16.92	19.20	18.82	19.04	16.43	17.74
S (%)	3.46	3.83	3.11	3.00	3.75	3.22
K (%)	7.47	7.99	9.22	6.30	6.37	3.99
CI (%)	2.08	2.76	2.10	1.81	1.32	0.08
Ca (%)	41.01	32.62	28.69	32.88	29.06	39.33
Fe (%)	0.96	0.98	1.12	0.80	0.57	0.60
Rb (%)	0.04	0.06	0.00	0.04	0.04	0.04
Cu (%)	0.16	0.12	0.16	0.008	0.16	0.10
Zn (%)	0.53	0.48	0.52	0.34	0.53	0.24
Sr (%)	0.06	0.05	0.07	0.04	0.06	0.05
Mn (%)	0.57	0.72	0.72	0.55	0.57	0.37

Table 2. Quantity of materials

Materials	CDA/CPP				
	0%	2.5%	5%	7.5%	10%
Laterite (kg)	26.84	26.17	25.5	24.83	24.16
CDA/CPP (kg)	0.00	0.67	1.34	2.01	2.68
Water (kg)	13.42	13.42	13.42	13.42	13.42

Abbreviations: CDA: Cow dung ash; CPP: *Cissus populnea* powder.

3.3. Testing of specimens

3.3.1. Compressive strength

The test procedure adhered to ASTM C109/C109M-20 standard.[40] To carry out the compressive strength test, three cubic specimens were selected from each mix design for testing. ELE 2000KN compressive testing machine was used for the test. Each specimen was weighed, and the weight was recorded. It was then placed in the test machine, and the load was exerted on the specimen until it failed (Figure 2C), and then the compressive strength was determined.

3.3.2. Tensile strength

The test procedure adhered to ASTM C496/C496M-11 standard.[41] The tensile strength test was carried out on cylindrical specimens. Three specimens were selected from each mix design for testing. ELE 2000KN compressive testing machine was used for the test. Each specimen was weighed, and the weight was recorded. It was then placed in the test machine horizontally, and the load was exerted on the specimen until it failed (Figure 2D), and then the tensile strength was determined.

Figure 2. Preparation and testing of specimens: (A) molding of specimens, (B) cube specimens, (C) compressive strength test setup, and (D) tensile strength test setup

3.3.3. Erosion test

The test procedure conformed to New Zealand Standard NZS 4298:1998.[42] Three cubic specimens were selected from each mix design for testing. The specimens were placed in the erosion test setup, with water supplied from a beaker positioned above the specimen and allowed to drip continuously through a Wettex sponge onto the surface. This was done for 60 min, and subsequently, the diameter and the depth of erosions on the cubic specimens created by the dropping water were measured.

3.3.4. Water absorption

The test procedure was conducted in adherence to the ASTM C642-21 standard.[43] Three cubic specimens were selected from each mix design for testing. The specimens were dried in an electronic oven for 24 h at a temperature of 105°C and were allowed to cool in the open air and the weight of each specimen was measured with an electronic balance, and their weights were recorded. The bottom part of the specimens was then immersed in water for 10 min. The specimens were weighed again to obtain their wet weight so as to determine the water absorption percentage.

3.3.5. Density determination

The test procedure conformed to the ASTM C138/C138M-23 standard.[44] Three cubic specimens were selected from each mix design for testing. The specimens were dried in an electronic oven for 24 h at a temperature of 105°C and were allowed to cool in the open air and the weight of each specimen was measured with an electronic balance, and their weights were recorded. The specimen dimensions were measured, and their volumes were computed. The densities of the specimens were then determined.

3.4. Statistical analysis

The data obtained from the experimental work were analyzed using descriptive analysis in percentages and average values in the form of tables and figures. The data were analyzed using Microsoft Excel software, version 2021 (Microsoft Corporation, Washington, United States). Analysis of variance (ANOVA) was used to assess the significant differences between the test results. To determine the existence of any significant differences between test groups, Sigma Plot software (Jandel Corporation, United States) was used.

4. Results and discussion

4.1. Mechanical properties of earth mortar produced with CDA and CPP

Mechanical properties are critical determinants of earth mortar's structural performance. Compressive strength measures the ability of the mortar to resist compressive loads, while tensile strength evaluates the mortar's resistance to splitting force. These properties are essential for ensuring the structural integrity of buildings and other structures that will be constructed with the earth mortar. Details of the mechanical strength data obtained from the experimental work are provided in Table 3.

The data provide valuable insights into how different binders alone and combined mixtures affected the compressive and tensile strengths of earth mortar across various binder concentrations. For the compressive strength result as shown in Figure 3, the control (0%) obtained an average value of 0.990 N/mm^2, serving as a reference point for comparison. The CPP binder displayed significant improvements, with compressive strength increasing steadily and peaking at 7.5% concentration with a strength of 1.797 N/mm^2, which represents an 81.5% increase over the control. Beyond this optimal level, the strength slightly declined to 1.660 N/mm^2 at 10%, indicating diminishing returns at higher concentrations of the CPP. Studies have reported that excessive binder concentrations can lead to reduced compressive strength due to increased porosity and decreased past-aggregate bonding.[45,46] Conversely, the CDA binder was most effective at 2.5% concentration, achieving a peak strength of 1.437 N/mm^2, representing a 45.2% improvement over the control. However, its strength gradually decreased at higher concentrations, though it still outperformed the baseline, even at its lowest value of 1.133 N/mm^2 at 10%. Research has shown that optimal binder concentrations can vary depending on the type of binder and specific application.[47,48] The improved strength can be linked to the pozzolanic activity of CDA due to high silica content (SiO_2) and increased formation of calcium

Table 3. Results of mechanical properties

Binder	Compressive strength (N/mm^2)					Tensile strength (N/mm^2)				
	0%	2.5%	5%	7.5%	10%	0%	2.5%	5%	7.5%	10%
CPP	0.990	1.073	1.317	1.797	1.660	0.19	0.24	0.30	0.37	0.33
CDA	0.990	1.437	1.400	1.340	1.133	0.19	0.43	0.41	0.38	0.25
CPP/CDA	0.990	1.140	1.410	1.450	1.357	0.19	0.26	0.31	0.37	0.31

Abbreviations: CDA: Cow dung ash; CPP: *Cissus populnea* powder.

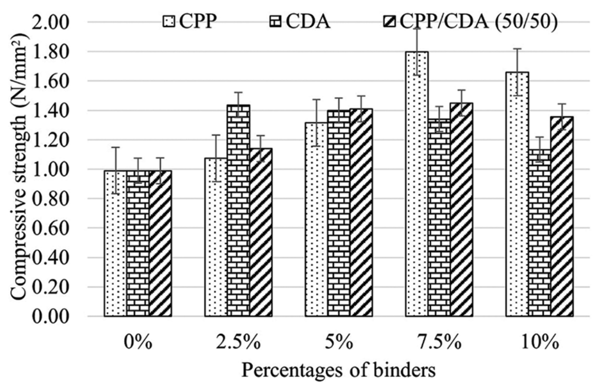

Figure 3. Compressive strength of earth mortar produced with CPP and CDA
Abbreviations: CDA: Cow dung ash; CPP: *Cissus populnea* powder.

silicate hydrate (C–S–H) gels, which improve bonding and reduced porosity.[26] The improved strength can also be associated with the bond mechanism of the materials in the blocks; thus, the friction generated between the fiber and the soil matrix.[49]

The combined CPP and CDA specimens provided a balanced performance, showing consistent strength improvements up to 7.5% concentration, where it peaked at 1.450 N/mm^2. At 10%, the strength slightly dropped to 1.357 N/mm^2. While the combined specimens did not match the peak strength of CPP alone, the specimen offered steady enhancements across the range of concentrations. These findings suggest that the effectiveness of binders depends on both their type and concentration. CPP proved to be the most effective for compressive strength, especially at higher concentrations, while CDA showed promise at lower concentrations. The combined offered moderate yet consistent improvements, making it a practical choice for applications requiring balanced performance. Notably, the results emphasize that increasing binder concentrations does not always lead to higher strength, as all binders experienced slight declines at the highest concentrations tested. Similarly, a study by Jannat *et al.*[50] concluded that as the percentage of waste binders increases, the matrix becomes more porous and makes it permeable to moisture. Corinaldesi *et al.*[51] also added that, when producing mortar with by-products as a stabilizer, it may be necessary to lower replacement rates, as higher percentages may result in deterioration or declining returns, necessitating extensive mechanical testing and optimization in consideration of multiple factors.

The ANOVA test results shown in Table 4 indicate that there was a significant difference in compressive strength among the different mortar mixes (F = 18.105; $p<0.001$). This means that at least one of the mortar mixes had a significantly different compressive strength than the others. To determine which specific mixes were significantly different, pairwise comparisons were conducted. The results of these comparisons revealed that the mortar with 7.5% CP had significantly ($p<0.001$) higher compressive strength than all other mixes. This suggests that adding 7.5% CP to the mortar significantly improves its compressive strength. This confirms that the addition of different percentages of CDA and CPP to earth mortar has a significant impact on compressive strength. The mortar with 7.5% CP was found to have the highest compressive strength among all the tested mixes. However, while 7.5% CP is the overall best performer, there are also significant differences between other mixes. For example, both 2.5% CD and 5% CD significantly ($p<0.001$) outperform the control mortar (0% binder), indicating that even lower percentages of these binders can improve compressive strength.

Table 4. One-way repeated measures ANOVA results of compressive strength at 28 days of curing

Source of variation	DF	SS	MS	F	*p*-value
Between subjects	2	0.0026	0.0013		
Between treatments	12	1.842	0.1540	18.105	<0.001
Residual	24	0.204	0.0085		
Total	38	2.048	0.0539		

Abbreviations: DF: Degrees of freedom; MS: Mean square; SS: Sum of squares; ANOVA: Analysis of variance.

For the tensile strength result as shown in Figure 4, it was observed that the control specimens of the earth mortar attained a strength of 0.19 N/mm^2, against which the improvements from various binder concentration specimens are measured. The CPP showed a steady increase in tensile strength, peaking at 0.37 N/mm^2 at 7.5% concentration, representing a 94.7% improvement. However, at 10% concentration, a slight decline was observed. The CDA exhibited a dramatic increase at low concentrations, reaching its peak of 0.43 N/mm^2 at just 2.5%, representing a 126% enhancement in tensile strength. Beyond this point, the strength gradually decreases, but even at its lowest value (0.25 N/mm^2 at 10%), it remains superior to the control. The combined mix of CPP and CDA provided a balanced strength improvement, peaking at 7.5% concentration with 0.37 N/mm^2 strength and maintaining higher-than-individual-binder values at 10% concentration. According to Ansah,[52] on the 28th day of curing, the tensile strength of the mortar increases as the percentage of cow dung and palm fiber in the earth brick earth mortar mix increases.

The findings highlight the potential of these natural materials in sustainable construction, as they offer substantial improvements in strength while being locally available and environmentally friendly. Studies have shown

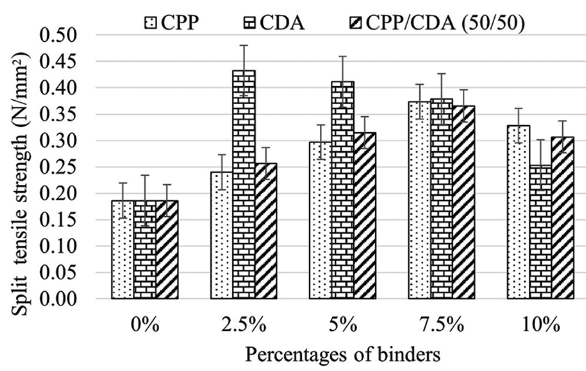

Figure 4. Tensile strength of earth mortar produced with CPP and CDA
Abbreviations: CDA: Cow dung ash; CPP: *Cissus populnea* powder.

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that these materials can provide significant improvements in mechanical properties while reducing environmental impact.[45,46] CDA is particularly effective at low concentrations, making it a viable option where minimal material use is preferred. CDA has been reported to exhibit high reactivity and binding properties due to its fine particle sizes and high surface area.[21] This is consistent with the study's findings, where CDA showed a dramatic increase in strength at lower concentrations. CPP, in contrast, provides a more consistent strength increase across a wider range of concentrations, offering flexibility in application. CPP has been found to contain organic compounds with natural adhesive properties, which can enhance its binding performance.[35,36] This is in line with this study's results, where CPP provided a consistent strength increase across a wider range of concentrations. The combined mixture balances the benefits of both binders, ensuring stable improvements even at higher concentrations. These variations in performance suggest that binder selection should be tailored based on construction needs, whether prioritizing high early strength with CDA or consistent performance with CPP.

The ANOVA test results (Table 5) indicate that there was a significant difference in split tensile strength among the different mortar mixes ($F = 61.25$; $p<0.001$). This means that at least one of the mortar mixes had a significantly different split tensile strength than the others. To determine which specific mixes were significantly different, pairwise comparisons were conducted. The results of these comparisons revealed that the mortar with 2.5% CDA had significantly higher split tensile strength than all other mixes. This suggests that adding 2.5% CDA to the mortar is the most effective way to improve its split tensile strength. The addition of different percentages of CDA and CPP to earth mortar has a significant impact on split tensile strength. The mortar with 2.5% CDA was found to have the highest split tensile strength among all the tested mixes.

Table 5. One-way repeated measures ANOVA results of split tensile strength at 28 days of curing

Source of variation	DF	SS	MS	F	*p*-value
Between subjects	2	0.000107	5.33E-05		
Between treatments	12	0.189	0.0158	61.25	<0.001
Residual	24	0.00619	0.000258		
Total	38	0.196	0.00515		

Abbreviations: DF: Degrees of freedom; MS: Mean square; SS: Sum of squares; ANOVA: Analysis of variance.

Table 6. Results of durability properties

Binder (%)	CDA		CPP		CDA/CPP	
	Depth (mm)	Width (mm)	Depth (mm)	Width (mm)	Depth (mm)	Width (mm)
0	5	4	5	4	5	4
2.5	0	0	0	0	0	0
5	0	0	0	0	0	0
7.5	0	0	0	0	0	0
10	0	0	0	0	0	0

Abbreviations: CDA: Cow dung ash; CPP: *Cissus populnea* powder.

4.2. Durability properties of earth mortar produced with CDA and CPP

Understanding the durability properties of earth mortar produced with CDA and CPP is essential for determining their suitability as binders for construction applications. These properties influence the long-term durability performance of earth mortar structures. Studies have shown that earth mortar is vulnerable to erosion, particularly in environments with high rainfall.[53,54] The durability results obtained from the erosion test of the earth mortar produced with CDA and CPP are shown in Table 6.

The erosion test results reveal a consistent pattern in the performance of earth mortar specimens treated with varying percentages of CDA, CPP, and a combined mixture of the two binders. It can be observed from Table 6 that the control specimens exhibited erosion average depth and width were 4 mm and 5 mm, respectively, highlighting the vulnerability of untreated earth mortar to erosion. In contrast, the specimens containing binders, regardless of the type or concentration (2.5%, 5%, 7.5%, or 10%), demonstrated a remarkable improvement, with erosion consistently recorded at 0 mm for depth and width. This outcome underscores the effectiveness of both CDA and CPP in significantly enhancing the erosion resistance of earth mortar, which is likely due to their binding properties.

Interestingly, there was no observable difference in erosion resistance between CDA, CPP, and their combined specimens across all concentrations. This suggests that while the binders are highly effective individually, combining them does not provide additional advantages in terms of erosion prevention. The uniform performance across all binder-treated specimens indicates that both CDA and CPP are equally capable of protecting earth mortar from erosion. Studies have found that the use of binders such as lime, cement, and ashes improves the durability properties of earth matrix.[55-57] According to Gallagher,[58] assessing the durability of earth mortar is vital to ensure it can withstand long-term exposure to adverse conditions while maintaining its integrity, making them a viable and eco-friendly alternative to traditional building materials.

Table 7. Results of physical properties

Binder	Water absorption (%)					Dry density (kg/m³)				
	0%	2.5%	5%	7.5%	10%	0%	2.5%	5%	7.5%	10%
CPP	3.440	2.018	1.864	1.204	2.974	1072.05	1053.85	979.49	946.92	872.05
CDA	3.440	1.870	2.063	2.535	2.773	1072.05	1118.21	1103.59	1089.74	1080.51
CPP/CDA	3.440	2.944	2.800	2.062	2.383	1072.05	1043.08	1047.69	1057.18	1024.87

Abbreviations: CDA: Cow dung ash; CPP: *Cissus populnea* powder.

4.3. Physical properties of earth mortar produced with CDA and CPP

Determination of the physical properties of earth mortar produced with CDA and CPP is a good measure for construction applications. The physical properties of the earth mortar were determined through water absorption and dry density tests. The average results obtained from these tests are shown in Table 7.

For the detailed water absorption result as presented in Figure 5, it was seen that the control specimens of the earth mortar exhibited a water absorption rate of 3.440%, serving as a baseline for comparison. The addition of CPP significantly reduced water absorption, with a sharp decline to 2.018% at 2.5% concentration, reaching a minimum of 1.204% at 7.5%, representing a 65% reduction in absorption rate as compared with the baseline. However, at 10% concentration, the absorption rate increased to 2.974%, indicating an optimal concentration at 7.5% for maximum reduction. CDA demonstrated a distinct pattern, with water absorption rate dropping to 1.870% at 2.5% concentration, a 45.6% reduction as compared with the baseline. Beyond this point, absorption gradually rose, peaking at 2.773% at 10%, though it remained below the baseline. The combined CPP/CDA specimens provided a balanced reduction, achieving the lowest absorption rate of 2.062% at 7.5% concentration while delivering consistent improvements across tested ranges. A study by Azeez and Okechukwu[59] on the effects of *C. populnea* extract on the water absorption of earth blocks concluded that *C. populnea* extract increases the resistance of water absorption in earth blocks. Previous studies by Turkson *et al.*[55] and Aidoo and Danso[57] with lime as a binder in earth mortar demonstrated similar results.

These findings underscore the potential of CPP and CDA as sustainable binders for improving the water resistance of earth mortars. CPP's dramatic reduction in water absorption, especially at 7.5%, makes it suitable for use in humid climates, while CDA's effectiveness at lower concentrations highlights its value as a cost-effective binder. The mixture offers flexibility and consistent performance, making it a viable option for diverse applications. By leveraging locally available and eco-friendly materials, this research contributes to the development of more durable, weather-resistant, and sustainable construction practices. It emphasizes the importance of precise material proportioning to achieve optimal performance and expands the potential for earth-based construction in regions with abundant natural and waste resources.

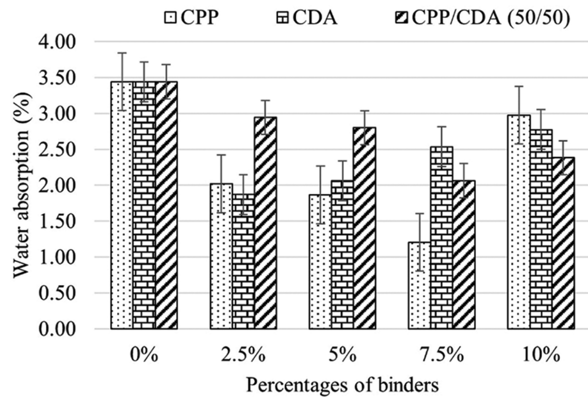

Figure 5. Water absorption of earth mortar produced with CPP and CDA Abbreviations: CDA: Cow dung ash; CPP: *Cissus populnea* powder.

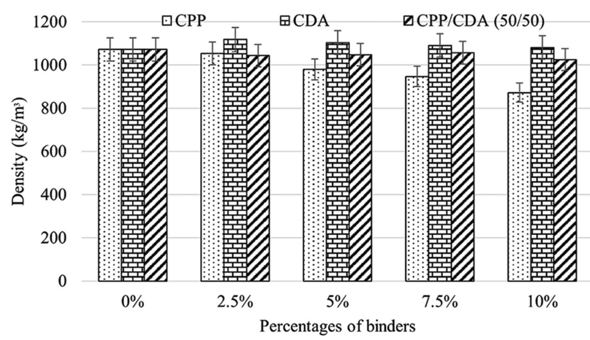

Figure 6. Dry density of earth mortar produced with CPP and CDA Abbreviations: CDA: Cow dung ash; CPP: *Cissus populnea* powder.

The average density results of the specimens of the earth mortar are shown in Figure 6. The earth mortar control specimens had a density of 1072.05 kg/m³, serving as a baseline. The introduction of CPP consistently reduced density, which dropped from 1053.85 kg/m³ at 2.5% concentration to a minimum of 872.05 kg/m³ at 10%, marking an 18.7% reduction in density as compared with the baseline. This suggests CPP's potential for applications requiring lightweight materials, such as those focused on thermal insulation or reduced structural load. Conversely, CDA initially increased the density, reaching 1118.21 kg/m^3 at 2.5% concentration, which represents a 4.3% rise from the baseline. Although the density gradually decreased with higher concentrations, it remained above the baseline level, at 1080.51 kg/m^3 with 10% CDA. This indicates CDA's suitability for applications demanding denser materials, potentially improving compactness and water resistance. The combined CPP and CDA present a balanced approach, maintaining a density close to the baseline with slight fluctuations between 1024.87 kg/m^3 and 1057.18 kg/m^3 across concentrations, making it adaptable for scenarios requiring both binding strength and moderate density.

The findings highlight the versatility of CPP and CDA in tailoring earth mortar density for specific construction needs. CPP's ability to create lighter mortar is advantageous for non-load-bearing applications, while CDA's capacity to enhance density can be beneficial for improved durability. The combination of both additives offers flexibility in adjusting material properties, aligning with sustainable construction goals. As the industry explores environmentally friendly solutions, this study underscores the potential of natural and waste-derived binders in producing customizable, eco-friendly building materials suited to various architectural and engineering demands. These findings of density are similar to a study conducted by Ismail and Aboshio[20] on the effect of wild-vine powder and *C. populnea* as admixture in compressed lateritic earth blocks, their findings concluded that the density of earth blocks and mortar can drastically reduce due to the presence of *C. populnea* and other alternative materials. According to Honda *et al.*,[60] there was a general reduction in the density, which became more significant at higher *C. populnea* contents. The mortar, however, had relatively lower (about 5–40%) dry density values for all the levels of replacement. Similarly, these findings were also observed by Azeez and Okechukwu.[59]

5. Limitations

The results of this study demonstrate the potential of CDA and CPP as promising binders for earth mortar. Further research and development are needed to fully explore their potential applications and optimize their performance as the current study only focused on some engineering properties. Additional research is necessary to fully understand the long-term durability of these mortars under different environmental conditions, which was not covered in this study. Abrasion and erosion tests, as well as long-term durability studies, would provide valuable insights into their suitability for various applications. In addition, investigating the effects of different environmental conditions on the durability of these mortars would be valuable. Furthermore, investigating the chemical composition of the CDA and mortar to identify the content of minerals such as potassium, magnesium, and phosphorus would be a valuable addition.

6. Conclusion and recommendations

This study explored the use of CDA and CPP as alternative and eco-friendly binders in earth mortar. The research aimed to assess the influence of these binders on the physical, durability, and mechanical properties of earth mortar. The findings of the study are summarized as follows:

- The peak compressive strengths of 1.797, 1.437, and 1.450 N/mm^2 were achieved by 7.5% CPP, 2.5% CDA, and 7.5% combined CPP/CDA binder inclusion in earth mortar, representing 81.5%, 45.2%, and 46.5% strength improvement, respectively, over the control of 0.990 N/mm^2. This implies that the inclusion of CPP and CDA in earth mortar significantly improved the compressive strength of the mortar by 46.5–81.5%.
- The peak tensile strengths of 0.37, 0.43, and 0.37 N/mm^2 at 7.5% were achieved by 7.5% CPP, 2.5% CDA, and 7.5% combined CPP/CDA binder inclusion in earth mortar, representing 94.7%, 126.0%, and 94.7% strength improvement, respectively, over the control of 0.190 N/mm^2. The findings suggest that the inclusion of CPP and CDA in earth mortar significantly improved the tensile strength of the mortar by 94.7–126%.
- The CPP and CDA inclusion in the earth mortar resulted in no erosion for all the binder concentrations, while the control specimens recorded erosion depth and width of 4 mm and 5 mm. This suggests improved durability properties of earth mortar with the addition of CPP and CDA.
- The addition of CPP, CDA, and combined CPP/CDA significantly reduced water absorption by 45–65% as compared with the control, indicating improved absorption properties of the earth mortar.
- The addition of CPP and CDA in earth mortar resulted in relatively low dry densities for all the concentration levels. The earth mortar observed a decrease in density with increasing concentrations of the binders. This provides a beneficial feature for lightweight structural application.

The study concludes that the use of CDA and CPP demonstrates considerable potential as sustainable and effective binders for earth mortar, offering significant improvements in mechanical, durability, and physical properties. The study recommends the use of 7.5% CPP and 2.5% CDA for earth mortar production, taking into account the soil characteristics and the binder properties reported in this study. In terms of practical application, the construction industry, including professionals and researchers, should support sustainable and cost-effective building practices by promoting the use of locally available CDA and CPP in earth mortar to reduce overreliance on traditional binders such as cement. In addition, future studies should explore the thermal properties of earth mortar prepared with CPP and CDA binders. By demonstrating the viability of these alternative binders, this study contributes to the advancement of eco-friendly and durable building materials, supporting sustainable construction practices in resource-limited regions. As agricultural by-products, the utilization of CDA and CPP promotes waste minimization by providing a valuable applicable for otherwise discarded materials, thereby advancing environmentally responsible building practices. These binders represent promising options for improving mortar performance while contributing to global sustainability initiatives in the construction industry.

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Conflict of interest

The authors declare that they have no competing interests.

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Conceptualization: Amatus Naapuo
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Investigation: All authors
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Writing–original draft: Amatus Naapuo
Writing–review & editing: Humphrey Danso

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Availability of data

Data are available from the corresponding author on reasonable request.

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