Original Article

The influence of natural reinforcement fibers on erosion properties of earth plaster materials for straw bale buildings

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ABSTRACT In this article, a systematic experimental study into the erosion resistance of earth plasters is presented. The erosion rate, the time elapse till erosion failure and the amount of water leading to erosion failure are considered. Four recipes with different compositions of cohesive soil and sand combined with three different natural fibers are investigated. The natural fibers used in the tests are wheat straw, barley straw and wood shavings. Both the soil composition and the fiber content are varied in the tests. The fiber content and the fiber type are found to have remarkable effect on the erosion resistance of the plasters.

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INTRODUCTION

Natural earth plasters are experiencing a renaissance in sustainable building. Earth plasters may serve many functions in straw bale walls system, such as protecting the underlying surface, enhancing or preventing the migration of vapor or liquid moisture, mitigating the migration of air currents and carrying structural loads. An important issue for the durability of earth plasters is the stability against erosion. The main cause of erosion is the impact of rain drops driven by strong wind. Frequently, the erosion by heavy rain fall is aggravated by the fact that rain drops hit the wall surface at an acute angle. Experience shows that heavy rain, even for a short time, may cause more damage than prolonged light rain. Therefore, some knowledge of the local weather conditions and analysis of meteorological data can provide useful information on the erosion risk for choosing appropriate plaster materials and application methods. The local traditional

buildings and practices often provide useful information, as their evolution has been largely influenced by the local climate (Balak, 2005).

Some previous investigations show that earth plaster with high straw content performs much better than earth plaster without straw both in terms of the duration of erosion failure and the amount of dripped water. This is mainly because the straw cushions the impact of water drops and prevents earth plaster from the formation of large erosion channels. The interwoven straw network also holds the block together even when the block is saturated (Lerner and Donahue, 2003). In general, erosion rarely poses any structural problems, because earth walls are normally very massive compared with masonry walls. Erosion is more a problem of aesthetics, and a similarity can be drawn between acceptable levels of erosion and acceptable classes of surface finish in concrete work (Heathcote and Moor, 2002).

On the other hand, faced with the worldwide shortage of forest resources, industry is showing increased interest in the production of particleboard from agricultural residues (Sampathrajan *et al*, 1992). Wheat straw contains a large amount of fiber with the potential to replace wood for particleboard fabrication. Particleboard with a density range from 0.59 to 0.8 g/cm³ is designated as medium-density particleboard (ASTM D1554-86, 1995). It has broad applications for both structural and non-structural uses.

In addition, barley straw is a significant raw material used in cellulose production as an energy resource and for use in agriculture as ruminant feed. Barley straw is also used as a biodegradable substance for sorption in oil spill clean-up (Joergensen *et al*, 1997; Wollenberg *et al*, 1998; Witka-Jezewska *et al*, 1999) and for the inhibition of algae and cyanobacteria growth in aquatic reservoirs (Welch *et al*, 1990; Pillinger *et al*, 1994; Witka-Jezewska and Hupka, 2000).

Experimental studies on erosion of earth plasters are rare in the literature. Walker (2004) described methods used for strength and erosion resistance testing of earth blocks without fiber. Minke (2006) reported some erosion tests on plasters that are mixtures of clay and sand. Bui *et al* (2009) investigated the durability of different types of stabilised and unstabilised rammed earth walls without fiber. The result shows that the mean erosion depth of the studied walls is approximately 2 mm (0.5 per cent wall thickness) for stabilised earth wall and approximately 6.4 mm (1.6 per cent wall thickness) for unstabilised earth wall. Moreover, the angle of impact turns out to be an important factor affecting erosion (Moshchanskii and Orbelin, 1968; Ogunye and Boussabaine, 2006). According to Ogunye and Boussabaine (2002), Lima *et al* (2004) and Ogunye and Boussabaine (2002), the erosive environment plays a decisive role in determining the final chemical composition of the coating.

In this article, the erosion resistance of earth plasters reinforced with natural fibers is investigated systematically through laboratory experiments. Earth plasters of different compositions of cohesive soil and sand are considered. The earth plasters are reinforced with different natural fibers such as wheat straw, barley straw and wood shavings. Different fiber contents are used in the experiments.

MATERIALS AND TESTING METHODS

Materials tested

Three different materials are used: cohesive soil, sand and reinforcement fibers. The composition of the cohesive soil texture is as follows: 31 per cent clay (< 2 µm), 22 per cent silt (20–63 µm) and 47 per cent sand (63–2000 µm). Three different fiber types, barley straw, wheat straw and wood shavings, are used. The wheat and barley

straw was harvested in 2008 and wood shavings were used for animals as litter material. The length of straw is approximately 5 cm, whereas the length of wood shavings is approximately 2 cm.

Sample preparation

At first, the oversized gravels and organic matter (grass root) were removed from the natural cohesive soil. The soil was then oven dried at a temperature of 105°C to obtain a constant mass. After the drying process, the hard soil lumps were broken with a hammer. The natural fibers were also oven dried at 105°C to obtain a constant mass.

Different recipes of earth plasters with different compositions of cohesive soil, sand and fiber were used for testing. The dosage of different materials was controlled by volume with given density. This was done by compressing the materials in a mold. The densities of wheat straw, barley straw and wood shavings are 103.6 kg/m³, 106.9 kg/m³ and 111.4 kg/m³, respectively. The densities of soil and sand are 1666.8 kg/m³ and 1974.4 kg/m³, respectively. The amount of soil and the fiber of a given recipe were placed in a container and mixed without water by hand until the different materials are homogeneously distributed. Afterwards, 2 litre water was sprayed over the materials and the materials were mixed by hand for approximately 15 min until a homogenous mixture was obtained. The soil–fiber mixture was left for approximately 30 min and then manually mixed for approximately 15 min. Earth plaster of four different recipes combined with three different natural fibers used in the erosion tests are given in Table 1. The compositions of the materials in Table 1 are given in volume percentage with the average material densities mentioned above.

The soil–fiber mixture was poured into a steel mold placed on a wood board. The square steel mold has a side length of 30 cm and a depth of 5 cm (see Figure 1). The surface was leveled and compressed with a loading plate under a force of approximately 50 kg, which simulates the plaster operation on site. Afterwards, the steel mold was lifted leaving an earth plaster sample on the wood board. The samples were allowed to dry slowly to avoid any cracks. This was done in a climate chamber under a temperature of 30°C and humidity of 40 per cent for 60 days. After this process, the samples were further dried in an oven under the temperature of 105°C to obtain a constant mass, which was controlled by weighing the samples every 24 hours. Thirty block samples of different plaster materials were used for erosion test.

Erosion testing procedure

A simple testing device was set up in laboratory to simulate the erosion process by rain drops (Figure 2). Water drops dripped out of a nozzle at a constant rate of approximately 65 cm³/min. The nozzle was placed approximately 1.35 m above the block of earth plaster, and was connected with a water tank. The plaster block was positioned above a container, so that the water dripped through the plaster block could be collected.

Table 1: Four earth plasters with three natural fibers

Treatment	Wood shavings			Wheat straw			Barley straw		
	Soil (%)	Sand (%)	Reinforcement fibers (%)	Soil (%)	Sand (%)	Reinforcement fibers (%)	Soil (%)	Sand (%)	Reinforcement fibers (%)
A	25	0	75	25	0	75	25	0	75
B	25	25	50	25	25	50	25	25	50
C	25	50	25	25	50	25	25	50	25

Figure 1: Steel mold for sample preparation.

Figure 2: Testing setup.

In order to simulate the angle of impact of rain drops, the block was placed at an angle of approximately 30° from the horizontal with the help of a steel frame (Figure 3). At regular intervals, the depth of the eroded indentation in the block was measured with a digital scale. At the beginning of the test, readings were taken every 5 min. After 1 hour, the reading period was increased to 30 min. An erosion test was terminated when the block collapsed or disintegrated. At the end of the test, the amount of dripped water in the container was weighed. One earth plaster with one fiber type was tested on three samples to obtain a mean value.

RESULTS AND DISCUSSION

Plastering reinforced with wheat straw fibers

Measurements of moisture content and dry density

The average of moisture content of plaster reinforced with wheat straw fibers was 2.78, 1.3 and 0.61 per cent for reinforcement fibers percentages 75, 50 and 25 per cent,

Figure 3: Plaster block positioned at an angle from the horizontal.

Figure 4: Erosion rate of plaster reinforced with wheat straw fiber.

respectively. These measurements were made after the samples were left in the climate chamber for 60 days. On the other hand, the average of dry densities of plaster reinforced with wheat straw fibers were 1123.89, 1416.31 and 1699.55 kg/m³ for reinforcement fibers percentages 75, 50 and 25 per cent, respectively. The results revealed that the moisture content increases with the wheat straw content. As may be expected, the dry density decreases with increasing fiber content.

Erosion rate

The erosion rate of plaster material reinforced with wheat straw fibers is shown in Figure 4. This also shows that the erosion rate decreases with time. The average of erosion rates are 0.11, 0.67, 0.75 and 12 cm/hr for reinforcement fibers percentages 75, 50, 25 and 0 per cent, respectively.

The results indicated that an increase of fiber content from 0 per cent (pure earth plaster) to 75 per cent gives rise to a decrease in erosion rate from 12 cm/hr to 0.11 cm/hr. The following observation can be made from the results shown in Figure 4. In the initial

Figure 5: Water amount at collapse for plaster reinforced with wheat straw.

Figure 6: Time elapse at collapse for plaster reinforced with wheat straw.

stage of test the erosion rate is very high. Subsequently, the erosion rate shows strong reduction with time until collapse. This phenomenon is ascribed to the fact that the fiber content near the sample surface is lower than in the interior of the sample, and the fibers are more resistant to erosion than soil. After the soil at the surface is eroded, the higher fiber content in the interior of the sample gives rise to substantially lower erosion rate.

Figure 5 shows the average amount of water needed to cause erosion failure. This water amount is 32.13, 17.01, 15.12 and 1.58 litre for the fiber contents 75, 50, 25 and 0 per cent, respectively. This means that an increase of fiber content from 0 (pure earth plaster) to 75 per cent led to an enormous improvement of the erosion resistance by approximately 20 times (Figure 5).

Figure 6 shows the relationship between reinforcement content and the time elapse at erosion failure. It can be seen that the time at erosion collapse increases strongly with fiber content. The collapse time is 8:30, 4:30, 4:00 and 0:25 (hr:min) for the fiber content of 75, 50, 25 and 0 per cent, respectively.

The erosion curves for plaster reinforced with barley straw and wood shavings fibers show similar trend, but differ in values. Therefore, these results are not shown here but will be summarized later.

Pure earth plaster without reinforcement fiber

The average density of plaster without reinforcement fibers was 1804 kg/m³, while the moisture content for the same plaster was 1.11 per cent. The average erosion rate was

approximately 12 cm/hr. The collapse time was approximately 0:25 (hr:min). It is clear that earth plaster without fiber reinforcement is prone to erosion. The plaster blocks collapsed in less than half an hour.

Comparison between different plaster materials

Sample density

The average of dry densities of plaster with 75 per cent fiber content were 1123.9, 1100 and 1273 kg/m³ for plaster reinforced with wheat, barley and wood shavings, respectively. For plasters with 50 per cent fiber content, the average of dry densities were 1416.3, 1402 and 1397.5 kg/m³ for plaster reinforced with wheat, barley and wood shavings fiber, respectively. For plasters with 25 per cent fiber content, the average of dry densities were 1699.6, 1617.7 and 1605.1 kg/m³ for plaster reinforced with wheat, barley and wood shavings fibers, respectively. On the other hand, the average density of plaster without reinforcement fibers was 1804 kg/m³. The results indicate that the plaster density decreases with increasing fiber content. Note further that the dry density of plaster reinforced with wood shavings is slightly higher than those with wheat and barley straw. This may be due to the fact that the shavings are finer than wheat or barley straw fibers.

Moisture content

The average moisture content of plaster with 75 per cent fiber contents are 2.78, 2.68, and 1.11 per cent for plaster reinforced with wheat, barley and wood shavings, respectively. For plasters with 50 per cent fiber content, the average moisture contents are 1.3, 1.04 and 0.87 per cent for plaster reinforced with wheat, barley and wood shavings fibers, respectively. For plasters with 25 per cent fiber content, the average moisture contents are 0.61, 0.8 and 0.51 per cent for plaster reinforced with wheat, barley and wood shavings, respectively. On the other hand, the average moisture content of plaster without fiber is approximately 1.11 per cent. The results confirm that the moisture content increases with increasing fiber content. We believe that the fibers absorb more water than soil. The moisture content for plaster reinforced with wheat and barley straw fiber are slightly higher than plaster reinforced with wood shavings.

Erosion rate

Figure 7 summarizes the erosion rates of plaster materials with different fibers. For plasters with 75 per cent fiber content, the erosion rates are 0.11, 0.10, 0.34 and 12 cm/hr for plasters with wheat straw, barley straw, wood shavings and pure earth plaster without

Figure 7: Erosion rate of plasters with different fibers.

fibers, respectively. For plasters with 50 per cent fiber content, the erosion rates are 0.67, 0.47, 0.75 and 12 cm/hr for plaster with wheat straw, barley straw, wood shavings and pure earth plaster, respectively. For plasters with 25 per cent fiber content, the erosion rates are 0.75, 0.53, 1.73 and 12 cm/hr of plaster reinforced with wheat straw, barley straw, wood shavings and without fibers, respectively.

It can be seen that the erosion rate decreases with increasing fiber content. Moreover, the lowest erosion rate was observed in plaster reinforced with barley straw fibers, while plaster reinforced with wood shavings fibers showed the highest erosion rate. Furthermore, the erosion rate in pure earth plaster was found to be higher than plasters with fiber reinforcement.

Water amount at erosion failure

Water quantities at erosion failure for plasters with 75 per cent fiber content are 32.13, 34.02, 17.01 and 1.58 litre for plaster reinforced with wheat straw, barley straw, wood shavings and without fiber, respectively. For plasters with 50 per cent fiber content the water quantities are 17.01, 20.79, 11.34 and 1.58 litre for wheat straw, barley straw, wood shavings and sand plaster, respectively. For plasters with 25 per cent fiber content the water quantities are 15.12, 17.01, 5.67 and 1.58 litre for plaster reinforced with wheat straw, barley straw, wood shavings and without fibers, respectively. These experimental findings are given in Figure 8.

The results confirmed that plaster reinforced with barley straw shows higher erosion resistance than plaster reinforced with wheat and wood shavings fibers. As may be expected, pure earth plaster shows the lowest water quantity at failure.

Figure 8: Water quantities at erosion failure for different plasters.

Figure 9: Period of time for different treatments and materials.

Figure 9 shows time elapse at erosion failure for plasters reinforced with different fibers. For plasters with 75 per cent fiber content, the time of collapse is 8:30, 9:00, 4:30 and 0:25 (hr:min) for plaster reinforced with wheat straw, barley straw, wood shavings and pure earth plaster without fibers, respectively. For plasters with 50 per cent fiber content, the time elapse is 4:30, 5:00, 3:00 and 0.25 (hr:min) for plaster reinforced with wheat straw, barley straw, wood shavings and pure earth without fibers plaster, respectively. For plasters with 25 per cent fiber content, the time elapse is 4:00, 4:30, 1:30 and 0:25 (hr:min) for plaster reinforced with wheat straw, barley straw, wood shavings and without fibers, respectively.

Figures 10–13 show the eroded plaster blocks with different fibers. As can be seen from Figures 10 and 11, the straw fibers reduce the erosion action by distributing water drops uniformly to avoid the formation of concentrate erosion spots. Figure 12 shows clearly that plaster reinforced with wood shavings is more prone to erosion than plasters

Figure 10: Eroded block with wheat straw.

Figure 11: Eroded block with barley straw.

Figure 12: Eroded block with wood shavings.

Figure 13: Eroded block with pure earth.

reinforced with wheat and barley straw. A concentrated erosion spot can be clearly observed in the plaster without any fiber (Figure 13).

The results showed that plasters reinforced with barley and wheat straw are better than those reinforced with wood shavings fibers. The reason for these results is the advantages of straw particleboard, such as rigidity and strength (Parker, 1997). Moreover, the length of straw particles is longer than wood shavings. These straw particles become nets inside the plaster and interact with different plaster materials. On the other hand, the plasters reinforced with barley straw fibers are better than those reinforced with wheat straw fibers. The reason behind these phenomena relates back to the fact that wheat straw has more lignocelluloses than barley straw (Bourquin and Fahey, 1994). Therefore, barley straw is more elastic than wheat straw fibers. In addition, the width of barley straw stems is more than that of wheat straw, so the plaster reinforced with barley straw fibers is more resistant to erosion than plaster reinforced with wheat straw fibers.

Table 2: The constants of erosion rate equation for different plaster materials

Plaster materials	Clay percentages (%)	Fibers percentages (%)	Sand percentages (%)	Constants		R^2
				a	b	
Wheat straw fibers	25	75	0	0.0544	-0.7310	96.44
	25	50	25	0.2319	-0.6800	99.26
	25	25	50	0.2821	-0.6570	99.81
Barley straw fibers	25	75	0	0.0553	-0.6690	99.61
	25	50	25	0.1809	-0.6960	99.52
	25	25	50	0.2148	-0.6330	96.91
Wood shavings fibers	25	75	0	0.1356	-0.6030	96.93
	25	50	25	0.1800	-0.7160	99.61
	25	25	50	0.1636	-0.8080	99.24
Without fibers	25	0	75	2.1042	-0.4370	97.73

Multiple regression analysis

A regression analysis was performed for the experimental results on plasters reinforced with wheat straw, barley straw, wood shavings and plaster without fiber as a function of the time elapse till erosion failure. The optimum equation for the erosion rate is found to be a power function of the following form:

$$Y = a \cdot X^b$$

where, Y is the erosion rate (cm/min), X is the time at failure (min). The two material parameters a and b are determined through the regression analysis and their values are given in Table 2.

CONCLUSION AND RECOMMENDATIONS

A systematic experimental investigation into the erosion of earth plasters is presented. Some emphasis is given to the effect of the fiber reinforcement on the erosion resistance. The erosion rate, the time elapse of erosion and the amount of water leading to erosion failure were investigated in laboratory. Four plaster recipes combined with three natural fibers were considered.

The erosion resistance of earth plasters depends on fiber content, soil composition (cohesive soil, sand) and fiber type. The fiber content has by far the largest influence on the erosion resistance of plaster. Moreover, the plaster reinforced with barley straw fiber showed the lowest erosion rate, while the highest erosion rate was observed in plaster reinforced with wood shavings fiber. On the other hand, the erosion rate of pure earth plaster without reinforcement fiber is much higher than fiber-reinforced plasters. Increasing the fiber content from 0 (pure earth plaster) to 75 per cent reduces the erosion rate by 93 per cent.

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