Compressive strength of fibre reinforced earth plasters for straw bale buildings

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Abstract

An experimental study into the compressive strength of fibre reinforced earth plasters is presented. The plaster material is composed of cohesive soil and sand. Three types of natural fibers are used as reinforcement, namely, wheat straw, barley straw and wood shavings. Ten different types of plasters with different compositions of earth materials and reinforcement are investigated. The fiber has positive effect on both the strength and ductility of plasters. While the fibre has remarkable effect on the strength and ductility of plasters, its effect on the elastic modulus of plasters is relatively small.

Key words: Compressive strength, failure strain, modulus of elasticity, earth plaster, straw bale buildings

Introduction

In recent years, the traditional practice of plastered straw bale structures has experienced a renaissance due to its economic and environmental benefits. Straw bale walls can be built either as non-load-bearing or load-bearing elements. Load-bearing straw bale walls typically consist of a sandwich panel of stacked straw bales with plaster skins of Portland cement, lime, gypsum, earth, or a combination of these binders. Earthen plasters incorporating chopped straw are commonly used in straw bale wall construction because the straw provides tensile strength and is readily available. The straw fibre in earth plaster has similar function as the fibre in fibre reinforced composites, which are widely used as modern material in various fields from civil engineering to aerospace engineering (Fu et al., 2006; Baklanova et al., 2006; Brownie et al., 1993; Thomason et al., 2000 and Shi et al., 2000). The straw fibre helps to increase the strength, to control shrinkage cracks and improve toughness (King et al., 2006). 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. Also barley straw is a significant raw material used in cellulose production as an energy resource (Johnson, 1973; Wollenberg et al., 1998; Witka-Jezewska et al., 1999; Joergensen et al., 1997; Welch et al., 1990 and Pillinger et al., 1994). Earthen plasters are typically mixed on-site and consist of local clay-rich soil, sand, water and chopped straw. They have been successfully used for centuries but are still viewed with some skepticism by building officials.

This is due, in part, to the lack of published research pertaining to the parameters that affect the strength of earthen plasters (Witka-Jezewska et al., 2000 and Lerner et al., 2005). Some tests in the literature have provided promising strength values as high as 2.00 MPa (Ash et al., 2003). These strength values are close to some published values for Portland-cement plaster, ranging from 0.75 to 1.98 MPa (Lerner et al., 2005 and Bou-ali, 1993). However, some testing results are poorly documented (material preparation and testing conditions) and hardly reproducible. There are many issues to be investigated. A better understanding of how soil components and moisture content affect the strength of earthen plasters is essential to straw building practice and will allow for more widespread use of this environmentally friendly building material. The bearing capacity of straw bale walls has been investigated without considering the earth plasters (Watta et al., 1995). Our paper presents a systematic investigation into the compressive strength of fibre reinforced earth plasters.

Materials and methods

Materials Tested

Three different materials are used for earth plasters, i.e. cohesive soil, sand and reinforcement fibres. The composition of the cohesive soil texture is as follows: 31% clay (< 2 µm), 22% silt (20-63 µm) and 47% sand (63-2000 µm). Three different fibre types are used, i.e. barley straw, wheat straw and wood shavings. The wheat and barley straw was harvested in 2008 and wood shaving was used for animals as litter material. The length of straw is about 5 cm, while the length of wood shavings is about 2 cm.

Table 1. Mixing percentages for experimental treatments

Recipes	Wood Shavings			Wheat Straw			Barley Straw		
	Clay (%)	Sand (%)	Reinforcement fibres (%)	Rlay (%)	Sand (%)	Reinforcement fibres (%)	Clay (%)	Sand (%)	Reinforcement fibres (%)
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
D	25	75	0	25	75	0	25	75	0

Sample preparation

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

Different recipes of earth plasters with different compositions of cohesive soil, sand and fibre were used for testing. The dosing 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, 106.9 kg/m³ and 111.4 kg/m³ respectively. The densities of soil and sand are 1666.8 and 1974.4 kg/m³ respectively. The amount of soil and the fibre of a given recipe were placed in a container and mixed by hand without water until the different materials are homogeneously distributed. Afterwards, 2 Liter water was sprayed over the materials and the materials were mixed by hand for about 15 minutes until a homogenous mixture was obtained. The soil-fibre mixture was left to rest for about 30 minutes and then manually mixed for about 15 minutes. Earth plaster of four different recipes combined with three different natural fibres used in the compression test 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-fibre mixture was poured into a steel mold placed on a wood board. The steel mold has a side length of 5 cm, width of 5cm and a depth of 5 cm. The surface was leveled and compressed with a loading plate under a force of about 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 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.

Compression test procedure

Ten different types of plasters were investigated including three plasters with different soil compositions combined with three fibre types plus one clay-sandy plaster without fiber. The compression tests were carried out according to (ASTM C 109, 2007). The plaster sample was placed between the loading piston and the pedestal and loaded until failure (Fig. 2). The load and the displacement were measured during the tests. After each test, the sample was put in an oven and dried according to (DIN EN ISO 12570, 1996). The moisture content (MC) for the materials was determined according to (ASHRAE, 1997). The mechanical properties were calculated according to (Kozachenko et al., 1988).

Fig 1. Plaster materials preparation

Fig 2. Compression test instrument

Results and discussion

Bulk density, cross-sectional of area and strength

Plasters reinforced with wood shavings fiber:

The bulk density and cross-sectional of area of the plasters reinforced with wood shaving are shown in Table 2. The bulk density decreases with the fiber content. The dry density of plaster ranged from 669 to 731 kg/m³ with an average of 700±24.4 kg/m³ for recipe A with 75% fiber content. While for recipe B (50% fibers), dry density ramged from 941.9-1084 kg/m³ with an average of 1026±56.29 kg/m³. It ranged from 1372.6-1433.6 kg/m³ with an average of 1398.4±24.69 kg/m³ for recipe C (25%
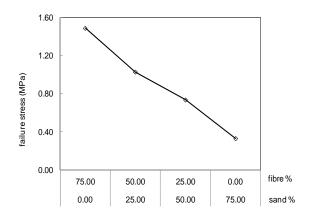
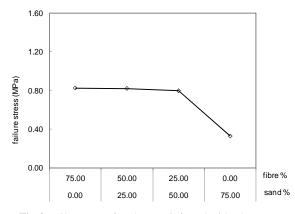**Fig 3.** Failure stress for plaster reinforced with wood shavings fibers

Fig 4. Failure stress for plaster reinforced with wheat straw fibers

Fig 5. Failure stress for plaster reinforced by barley straw fibers

Fig 6. Failure strain for plaster reinforced with wood shavings fibers

fibers). The average cross-sectional areas was 24.9±0.3 cm^2 for recipe A, while for recipe B it was 24.9±0.1 cm^2. The average cross-sectional area was 25.4±0.2 cm^2 for recipe C. Fig. 3 shows the relationship between plaster fiber contents and the compressive strength for plaster reinforced with wood shavings fibres. It can be seen that the plaster strength increases with fiber content. The maximum strength of about (1.486 ± 0.111 MPa) was recorded for plaster A with the maximum fiber content of about 75%. The minimum strength of about 0.329 ± 0.09 MPa was obtained for the plaster without fiber. Similar trend was reported in (Lerner et al. 2003). Since both the fibre content and the sand content were changed simultaneously, it is difficult to separate the influence of each of them.

Plasters reinforced with wheat straw fibers:

The plaster density ranged from 588-693 kg/m³ with an average of 638±44.8 kg/m³ for recipe A, 1007.9-1227 kg/m³ with an average of 1129±76.75 kg/m³ for recipe B and 1409.7-1515.3 kg/m³ with an average of 1457.8±47.38 kg/m³ for recipe C. The average cross-section area of the plasters were 27.5±0.6, 25.6±0.6 and 25.6±0.4 cm^2 for recipes A, B and C, respectively. The densities are given in Table 2. Fig. 4 shows the relationship between different recipes and the compressive strength of plaster reinforced
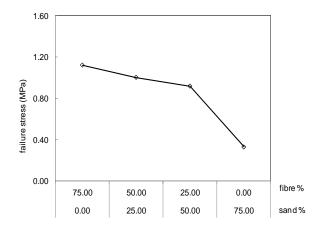
with wheat straw fibre. The average strength was about 0.824 ± 0.105, 0.819± 0.231, 0.795 ± 0.115 and 0.329 ± 0.09 MPa for recipes A, B, C and D, respectively. It is interesting to observe that there is only small change in strength for fibre content from 75% to 25%, which is followed by a strong reduction for pure earth plaster. It seems that even relatively low fibre content has remarkable effect on the strength. A further increase of the fibre content brings only marginal improvement in strength. This interesting behavior can be compared with plasters with wood shavings, where the compressive strength increases almost linearly with the fibre content. A further comparison between Fig. 3 and Fig. 4 shows that the plasters with wood shavings has higher strength than the plasters with wheat straw, which can be ascribed to the stronger fibres of wood shavings.

Plasters reinforced with barley straw fibers:

The plaster density ranged from 531-600 kg/m³ with the average of 574±28 kg/m³ for recipe A, while it was 1017-1080 kg/m³ with the average of 1051±27.7 kg/m³ for recipe B. The plaster density for recipe C was 1526.9-1559.9 kg/m³ with the average of 1511.6±33.39 kg/m³. The average cross-sectional areas was 26.5±0.6 cm^2 for recipe A, while it is 27.2±0.9 cm^2 for recipe B. The average cross-sectional areas was 25.1±0.3 cm^2 for recipe C. Fig. 5

shows the relationship between different recipes and the compressive strength of plaster reinforced by barley straw fiber. The results show that the strength increases with fibre content. The average strength of recipe A was 1.120 ± 0.112 MPa, 1.001 ± 0.304 MPa for recipe B and 0.917 ± 0.169 MPa for recipe C. As might be expected, the minimum strength of about 0.329 ± 0.09 MPa was obtained for plasters without any reinforcement. A comparison among Figs. 3, 4 and 5 shows that plasters with barley straw shows stronger dependence on fibre content than plasters with wheat straw but weaker dependence than plasters with wood shavings. The compressive strength for the same recipe and fibre content lies between those of plasters with wood shavings and wheat straw.

Failure strain

Failure strain for plasters reinforced with wood shavings:

The average strain at failure was 0.336 ± 0.014 for recipe A, 0.26 ± 0.012 for recipe B and 0.092 ± 0.011 for recipe C. For plasters without reinforcement the failure strain was 0.036 ± 0.005. It can be noticed that failure strain decreased gradually from recipe A to recipe D. It is clear that the failure strain increases with fiber content. The minimum failure strain was occurred for plaster without reinforcement. It seems that the reinforcement fiber has larger effect on the failure strain than soil composition (see Fig. 6). Our tests show that the reinforcement fibres have large effect on the ductility of plasters, which is of great importance for the building practice of straw bale building. In straw bale buildings, the plasters are usually used as cladding for the straw bale walls (both interior and exterior). The plasters and the straw bales can be regarded as a composite panel. Usually the stiffness of plasters is much larger than that of straw bales. The overall behaviour of the composite panel depends strongly on the performance of plaster. A too stiff plaster will give rise to spalling, which has in turn negative effect of the protection and bearing capacity of the load carrying straw bale wall.

Failure strain for plasters reinforced with wheat straw:

The average strain of recipe A was 0.260 ± 0.012, while it was 0.265 ± 0.073 for recipe B. The average strain of recipe C was 0.110 ± 0.012, while it was 0.036 ± 0.005 for recipe D as presented in (Fig. 7). It is observed that failure strain decreases from recipe A to recipe D. A comparison between Fig. 6 and 7 shows that the failure strain of plasters with wood shavings and wheat straw shows similar trend. The failure strain of plasters with wood shaving is slightly higher than those with wheat straw, although the wood shaving fibres are substantially shorter than the wheat straw fibres. we believe that the rough surface of wood shaving fibres is responsible for its higher ductility.

Failure strain for plasters reinforced with barley straw fibers

For recipe A, the average of failure strain was 0.347 ± 0.012, while it was 0.244 ± 0.076 for recipe B. Furthermore, for recipe C the average strain was 0.105 ± 0.021, while it was 0.036 ± 0.005 for recipe D (Fig. 8). The results revealed that strain at failure decreases gradually from recipe A to recipe D. A perusal of Fig. 8 shows that
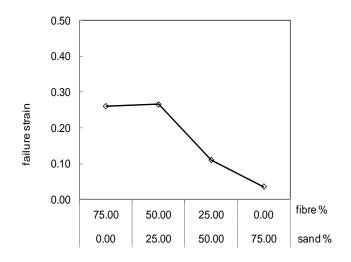

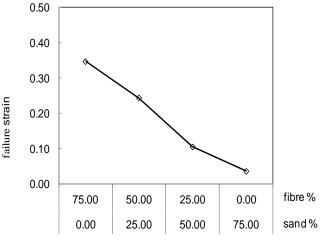**Fig 7.** Failure strain for plaster reinforced with wheat straw fibers

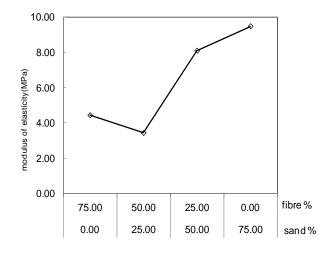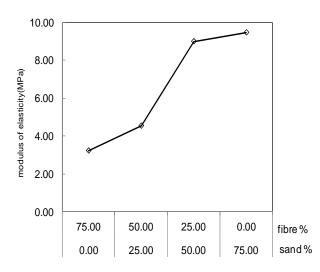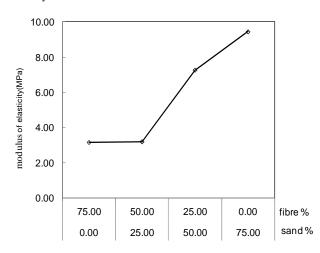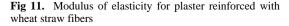**Fig 8.** Failure strain for plaster reinforced with barley straw fibers

Fig 9. Modulus of elasticity for plaster reinforced with wood shavings fibers

Fig 10. Modulus of elasticity for plaster reinforced with barley straw fibers
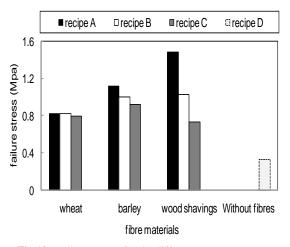

Fig 11. Modulus of elasticity for plaster reinforced with wheat straw fibers

Fig 12. Failur stresses for the different treatments

the failure strain increases almost linearly with fibre content. A comparison among Fig. 6, 7 and 8 shows that the failure strain remains fairly constant for plasters of the same recipe and with the same fibre content, irrespective of the fibre type.

Modulus of elasticity

Modulus of elasticity for plasters reinforced with wood shaving fibers:

The modulus of elasticity of recipe A was 4.43 ± 0.361 MPa, while it was 3.43 ± 0.1322 MPa for recipe B (Fig. 9). Moreover the average modulus of elasticity of recipe C was 8.07 ± 0.1583 MPa, while it was 9.45 ± 0.324 MPa for recipe D. It can be seen from Fig. 9 that the modulus of elasticity of the plaster material reinforced with wood shavings fiber increased with decreasing the fiber content.

Modulus of elasticity for plasters reinforced with wheat fibers:

For recipe A, the average modulus of elasticity was 3.15 ± 0.326 MPa, while it was 3.19 ± 0.448 MPa for recipe B (Fig. 10). On the other hand, modulus of elasticity of recipe C was 7.27 ± 0.1008 MPa, while it was 9.45 ± 0.324 MPa for recipe D. There is only small difference in the elastic modulus for recipe A and recipe B. The results showed also that the modulus of elasticity increased gradually from recipe B to recipe D.

Modulus of elasticity for plasters reinforced with barley fibers:

For the plaster reinforced with barley straw fibres, the average modulus of elasticity of recipe A was 3.23 ± 0.319 MPa, while it was 4.54 ± 0.227 MPa for recipe B. In addition, the modulus of elasticity of recipe C was 8.98 ± 0.1945 MPa, while it was 9.45 ± 0.324 MPa for recipe D (Fig. 11). Fig 11. shows that modulus of elasticity increased with decreasing of fibre content. This due to increase the compressive strength with increasing of fibre content. The minimum modulus of elasticity was observed for recipe. While the minimum modulus of elasticity was obtained for recipe D.

Comparison between the different plaster materials:

The compressive strength of plaster reinforced with wood shavings fiber was higher than the other materials for recipe A and B, while the compressive strength of plaster reinforced with wheat straw fiber was also recorded to be higher than the other materials for recipe C as shown in (Fig. 12). The results showed also that the minimum compressive strength was obtained for plaster without reinforced fiber (recipe D). For recipe A, the compressive strength was 1.406, 1.120, 0.824 and 0.329 MPa for plaster reinforced with wood shavings, barley, wheat and sand, respectively. While the values of compressive strength for recipe B were 1.026, 1.001, 0.819 and 0.329 for plaster reinforced with wood shavings, barley, wheat and sand, respectively. On the other hand, compressive strength values for recipe C were 0.734, 0.917, 0.795 and 0.329 MPa for plaster reinforced with wood shavings, barley, wheat and sand, respectively. Fig. 13 shows the failure strain for the treatments under study. For recipe A, the

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Table 2. Bulk density and cross-sectional of area of the plasters under study

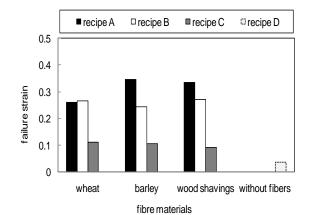| Reinforcement fibers plaster	Recipes	Bulk Density (kg/m^3)		Cross- sectional of area (cm^2)
		Range	Mean±SD	
Wheat plaster	A	588-693	638±44.8	27.5±0.6
	B	1007.9-1227	1129±76.8	25.6±0.6
	C	1409.7-1515.3	1457.8±47.4	25.6±0.4
Barley plaster	A	531-600	574±3	26.5±0.6
	B	1017-1080	1051±27.7	27.2±0.9
	C	1526.9-1559.9	1511.6±33.4	25.1±0.3
Wood shavings	A	669-731	700±24.4	24.9±0.3
	B	941.9-1084	1026±56.3	24.9±0.1
	C	1372.6-1433.6	1398.4±24.7	25.4±0.2
Clay-sandy	D	2066.7-2431.9	2215.8±151	29.3±1.4

Fig 13. Failure strain for the different treatments

Fig14. Modulus of elasticity for the different treatments at failure condition

failure strains were 0.336, 0.347, 0.260 and 0.036 for plaster reinforced with wood shavings, barley, wheat and sand, respectively. While failure strains of recipe B were 0.0.270, 0.244, 0.265 and 0.036 for plaster reinforced with wood shavings, barley, wheat and sand respectively. Furthermore, strains at failure for recipe C were 0.092, 0.105, 0.110 and 0.0.036 for plaster reinforced with wood shavings, barley, wheat and sand respectively. Our tests showed also that the failure strain of plaster reinforced with barley straw fiber was higher than those of the other materials for recipes A and C, while failure stresses of plaster reinforced with wood shavings fiber was also higher than those of the other materials for recipe B. The

results showed also, the minimum failure strain was recorded for plaster without reinforced fiber (recipe D). For recipe A, modulus of elasticity values were 4.43, 3.23, 3.15 and 9.45 MPa for plaster reinforced with wood shavings, barley, wheat and sand respectively. While the values of modulus of elasticity for recipe B were 3.43, 4.54, 3.19 and 9.45 MPa for plaster reinforced with wood shavings, barley, wheat and sand respectively. The modulus of elasticity values of recipe C were 8.07, 8.980, 7.27 and 9.450 MPa for plaster reinforced with wood shavings, barley, wheat and sand respectively.Fig. 14 showed the modulus of elasticity for the different treatments. The figure showed also, that the modulus of elasticity of plaster reinforced with barley straw fiber was higher than those of the other materials for recipes B and C, while the modulus of elasticity of plaster reinforced with shavings fiber was found to be higher than those of the other materials for recipe A. The results showed also, the maximum modulus of elasticity was recorded for recipe D.

Discussions

The results revealed that the compressive strength increases with fiber content for all samples. Similar trend was reported in Lerner et al. (2003) for other reinforcement fibres. This is due to the reinforcing effect and tensile strength of fibres (Parker, 1997). The fibres form irregular networks inside the plaster and reinforce the plaster material. The fibres improve also the ductility of plasters. The failure strain increases with increasing fibres content. The rough surface of wood shavings is responsible for the higher ductility. On the other hand the strength of plasters reinforced with barley straw fibres is higher than those reinforced by wheat straw fibres. The reason is that wheat straw contains more lignocelluloses than barley straw (Bourquim et al., 1994). As a consequence, barley straw fibres are more elastic than wheat straw fibres. Also the width of barley straw fibres is somewhat larger than wheat straw. So the plaster reinforced with barley straw fibres shows higher strength than plaster reinforced with wheat straw fibres.

Conclusions

For all tested plasters, the compressive strength increases with fiber content. The strength values depend on the specific recipes of the plasters. The compressive strength for recipe A is 1.406, 1.120, 0.824 and 0.329 MPa for plaster reinforced with wood shavings, barley and wheat, respectively. The strength for recipe B is 1.026, 1.001 and 0.819 for wood shavings, barley and wheat, respectively.

For recipe C , the following strength values are observed, i.e. 0.734, 0.917 and 0.795 MPa for wood shavings, barley and wheat straw fibers, respectively. The strain at failure is found to increase with fiber content as well. The failure strain of recipe A for barley plaster is higher than the other materials. The maximum failure strain of recipe B with shavings fiber is higher than the other materials. The maximum failure strain of recipe C is about 0.110 for plaster reinforced with wheat straw. The modulus of elasticity decreases with increasing the fiber content. The elastic modulus of plaster reinforced with barley straw fiber is higher than the other materials for recipes B (4.54 MPa) and C (8.98 MPa), while the elastic modulus of plaster with wood shavings is higher than the other materials for treatment A (4.43 MPa). The maximum modulus of elasticity is about 9.45 MPa for recipe D.

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