Original Article

Absorption and desorption behavior of some clay–sandy plasters reinforced with natural fibers used for straw bale buildings

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ABSTRACT **This work aimed to study the absorption and desorption behavior of some clay–sandy plasters reinforced with natural fibers that could be used for straw bale buildings. The plaster materials consisted of soil, sand and chopped straw. Straw is used as a reinforcement fiber for plaster. Three types of fibers were used, namely wheat straw, barley straw and sawdust. The desorption behavior of plaster materials was tested at different temperatures of 30°C, 50°C and 70°C. The results showed that the plaster reinforced with fibers dried slower compared to those that have no fibers. On the other hand, faster drying led to cracks in the plaster, which is not desirable in building surface coating. The moisture absorption rate increased with increasing fibers content and decreased with increased sand content. Moreover, the highest value for the moisture absorption rate was obtained for the plaster reinforced with sawdust, whereas the lowest value of moisture absorption rate was obtained for the plaster without reinforcement fibers.**
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Keywords: earth plaster; natural reinforcement fibers; absorption; desorption

INTRODUCTION

The use of natural earth plasters is experiencing a renaissance in sustainable building practice. Earth plasters may serve multiple purposes, for example, protection of the underlying surface, enhancing or preventing the migration of moisture and carrying structural load. An important issue for the performance of earth plasters is their shrinkage behavior. The excessive formation of drying cracks has a negative impact on the durability of earth plasters.

Ashour and Wu (forthcoming) studied the shrinkage behavior of earth plasters reinforced with different natural fibers under different curing conditions. The specimens of plaster material were dried under a constant temperature of 30°C, 50°C and 70°C, respectively. It was established that shrinkage crack formation decreases with increasing fiber content and increases with increasing soil content. In general, it was also found that lower curing temperature and higher fiber content are to be preferred to improve the performance of earth plasters.

Furthermore, the reinforcement of mineral binders (cement, concrete or plaster) has been a matter of major concern for several decades. Since then, efforts have been made to replace the usual mineral reinforcing agents (glass or asbestos fibers) by organic agents such as sisal, Kraft pulp or cellulose fibers (Coutts, 1983; Coutts *et al*, 1994). Maddison *et al* (2009) measured the amount of moisture absorption and desorption in clay–sand plaster mixed with 'fiber-wool' from Typha spadixes and chips of Typha and Phragmites. Common cattail (Typha latifolia) and common reed (Phragmites australis) are the most common plants in constructed and semi-natural wetlands for wastewater recipe. They are highly valued in ecologically oriented construction. The cattail and reed for the experiment were harvested in a wastewater recipe subsurface flow semi-natural wetland and in two free water surface constructed wetlands that showed reliable aboveground phytomass production over a 5-year period (for Typha, 0.37–1.76 kg DWm^{-2} in autumn and 0.33–1.38 kg DWm^{-2}, and for Phragmites, 0.61–1.32 and 0.61–1.02 kg DWm^{-2}, respectively). The quantity of moisture absorption and desorption was measured in a climatic chamber where the humidity of ambient air was suddenly raised from 50 to 80 per cent (absorption) and reduced from 80 to 50 per cent (desorption). Over 12 hours, all of the samples released the same amount of water as they absorbed. The clay–sand plaster samples absorbed slower than they desorbed, whereas the gypsum wallboard required significantly more time for desorption. Added phytomass gave positive effects by reducing the weight of the clay–sand plaster, thus accelerating and increasing moisture absorption.

On the other hand, drying temperatures for gypsum were between 35°C and 50°C. The results showed that gypsum samples after drying over 80°C always exhibited two peaks, but separation of these peaks was complicated (Wirsching 1984). CDI and CRATerre-EAG (1995) mentioned that requirements set the material water absorption (WA) in the 10–20 per cent range. The gathered data show that all the processed compressed earth block were in the 10–20 per cent WA range. All the fully and partially stabilized materials therefore met the minimum requirements for their use in house construction with respect to this parameter.

Hewlett (1998) reported that the overall absorptivity of aggregates either depends on a consistent degree of particle porosity or represents an average value for a mixture of variously high and low absorption materials. The higher WA of the coarse aggregate resulted from the higher absorption rate of cement mortar attached to the aggregate particles (Hansen, 1986; Lamond *et al*, 2002). Kornarzyñski *et al* (2002) and Tam *et al* (2008) measured WA using real-time assessment of WA. The results of the experiment showed that the water absorption rate (WAR) was high in the first 5 hours. This produces up to 80 per cent of the total WA.

To understand the relevance of the plasters in hot and humid conditions, the main aim of this work is to study the absorption and desorption behavior of some clay–sandy plasters reinforced with natural fibers that are used for straw bale buildings.

MATERIALS AND METHODS

Thirty six types of plaster recipes were prepared from different percentages of clay and sand soils, mixed with different types of fibers, namely barley straw, wheat straw and sawdust, as shown in Table 1.

The samples were pressed by hands. The sample dimensions were 5 cm long, 5 cm wide and 5 cm high, as shown in Figure 1.

The materials were put in the drying oven at three temperatures of 30°C, 50°C and 70°C; low relative humidity ranged from 2 to 5 per cent. The samples were weighed, each for 24 hours till the constant weight. Moisture content (MC) for the materials was measured according to ASHRAE (1997) using the following equation:

$$\mathrm{MC}(\%) = \frac{(W_m - W_d)}{W_d} \times 100 \quad (1)$$

where, MC, is the moisture content (%, *db*), W_m is the moist weight (kg), and W_d, is the dry weight (kg).

Amount of WA

The samples were put in the drying oven to constant weight and then weighed to calculate dry weight (W_d). The samples were submerged in water for 10 min according to Medjo

Table 1: Mixing percentages for experimental recipes

Earth plaster recipes	*Wood shavings*			*Barley 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
D	25	75	0	25	75	0	25	75	0

Figure 1: Samples prepared for drying test and water absorption.

Eko *et al* (2006) and then taken out and weighed (W_m). The amount of WA was calculated using the following equation:

$$\text{The amount of water absorption} = W_m - W_d \tag{2}$$

Water absorption rate

WAR was calculated as follows:

$$\text{WAR}\,(\%) = \frac{(W_w - W_d)}{W_d} \times 100 \tag{3}$$

where W_d is dry weight and W_w is the wet weight after submersion.

RESULTS AND DISCUSSION

Desorption behavior

Plaster material reinforced with barley straw fibers

Figures 2(a)–(c) show the MC of plasters reinforced with barley straw fibers at different temperatures with time. Figures 2(a)–(c) show MC at drying temperatures of 30°C, 50°C and 70°C.

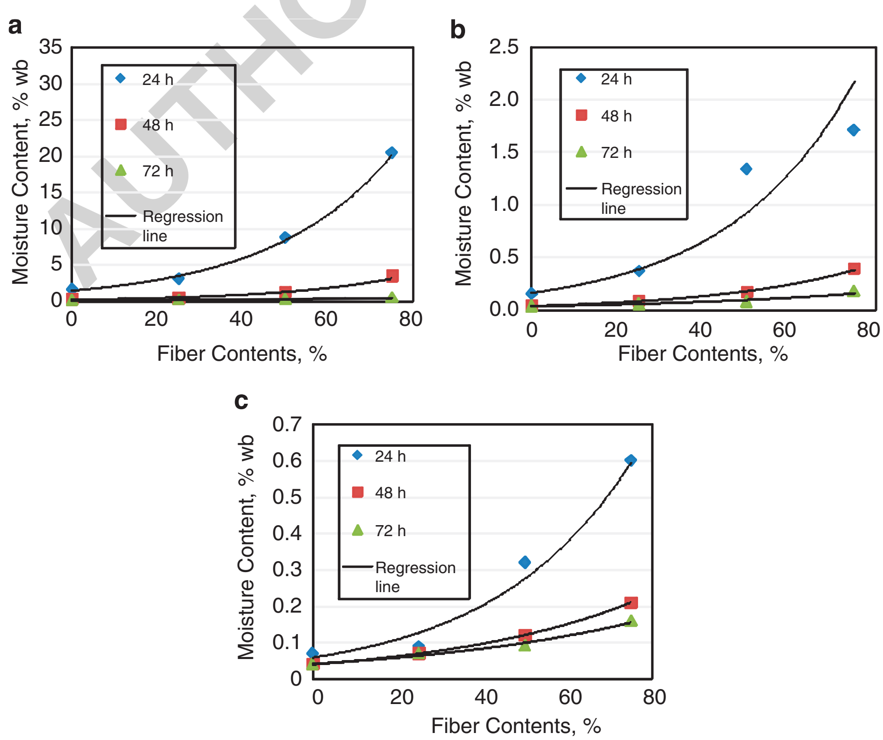

Figure 2: Moisture content of clay plasters reinforced with different percentages of barley straw fibers: (**a**) 30°C, (**b**) 50°C, (**c**) 70°C.

Table 2: Moisture content for plasters reinforced by barley straw fibers under different drying temperature

Drying time (hour)	*Moisture content (%)*								
	A			*B*			*C*		
	30°C	*50°C*	*70°C*	*30°C*	*50°C*	*70°C*	*30°C*	*50°C*	*70°C*
0	70.23	72.04	72.40	34.52	32.70	34.21	20.00	21.02	21.50
24	20.40	7.14	0.60	8.71	1.34	0.32	3.05	0.37	0.09
48	3.45	0.39	0.21	1.25	0.17	0.12	0.40	0.09	0.07
72	0.51	0.18	0.16	0.26	0.06	0.09	0.14	0.08	0.07
96	0.10	0.09	0.08	0.04	0.04	0.03	0.04	0.03	0.07
120	0.08	0.09	0.08	0.03	0.03	0.03	—	—	—

For recipe A: At the beginning, the MCs of recipe A were 70.2, 72 and 72.4 per cent at 30°C, 50°C and 70°C drying temperatures, respectively. After 24 hours, the MC decreased dramatically to 20.4, 7.1 and 0.6 per cent at the same pervious temperatures, respectively. Meanwhile, MC after 48 hours decreased to 3.5, 0.4 and 0.2 per cent for the same pervious order of temperatures. On the other hand, MCs after 72 hours were 0.5, 0.2 and 0.2 per cent at the same conditions.

The results revealed that the MC of the plaster material reinforced by barley straw fiber decreased slowly at the lower temperature (30°C), whereas it declined sharply at a temperature of 70°C, for the plasters that have lower contents of fibers (recipes B and C) that caused cracks for the plaster, which is not desirable in the building coating.

For recipe B: The initial MCs of recipe B were 34.5, 32.7 and 34.2 per cent, which were dried at 30°C, 50°C, 70°C, respectively. After 24 hours, the MCs were decreased to 8.7, 1.3 and 0.3 per cent at temperatures of 30°C, 50°C and 70°C, respectively. The MC at 48 hours decreased to 1.3, 0.2 and 1 per cent for the same conditions. On the other hand, MC at 72 hours was less than 1 per cent for all thermal conditions, as shown in Table 2.

The results revealed that the plaster material reinforced by barley straw fiber dried slowly at temperature of 30°C, whereas it was faster at 50°C and 70°C, with slight differences.

For recipe C: These types of plasters with initial MC of 20, 21 and 21.5 per cent were dried at 30°C, 50°C and 70°C, respectively. After 24 hours, the MC decreased to 3.1, 0.4 and 0.1 per cent for the temperatures of 30°C, 50°C and 70°C, respectively. The water content at 48 hours was less than 1 per cent for all thermal conditions, as shown in Table 2.

The results indicate that at 30°C, about 70 per cent of the initial MC of recipe A, 90 and 99 per cent of the MC of the same recipe at 50°C and 70°C were lost after 24 hours. Recipe B lost 74, 95 and 99 per cent of the initial MC after 24 hours at 30°C, 50°C and 70°C, respectively. Recipe C lost 85, 98 and 99 per cent of the initial MC after 24 hours at the same conditions, respectively. At higher temperatures, cracks were seen on the plaster surface; these cracks increased with decreasing the plaster fiber contents.

Plaster material reinforced by wheat straw fibers

Figures 3(a)–(c) show the MC of plasters reinforced with wheat straw fibers at different temperatures over time. Figures 3(a)–(c) show MC at drying temperatures of 30°C, 50°C and 70 °C.

For recipe A: The initial MCs of recipe A were 71.7, 72.5 and 7.4 per cent for thermal conditions of 30°C, 50°C and 70°C, respectively. At 24 hours, the MC decreased to 28.8, 0.8

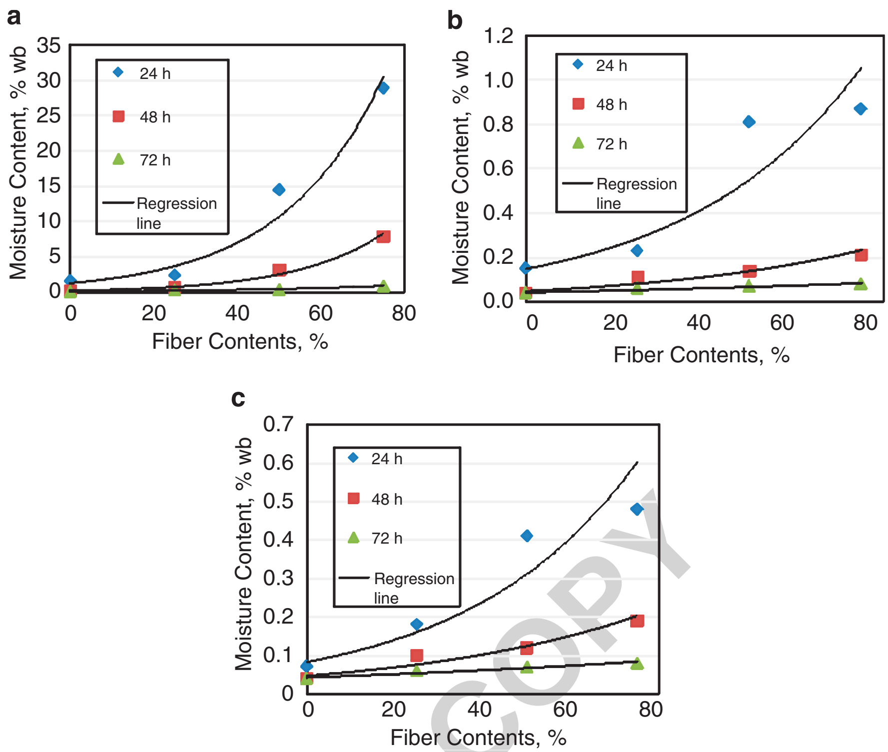

Figure 3: Moisture content of clay plasters reinforced with different percentages of wheat straw fibers: (**a**) 30°C, (**b**) 50°C, (**c**) 70°C.

and 0.5 per cent at the temperatures of 30°C, 50°C and 70°C, respectively. The MC at 48 hours decreased to 7.8, 0.2 and 0.2 per cent for the temperatures. On the other hand, MCs at 72 hours were 0.9, 0.1 and 0.03 per cent under the same conditions.

The results indicated that at 30°C, about 60 per cent of the initial MC of recipe A, and 99 per cent of the MC of the same recipe at 50°C and 70°C were lost after 24 hours. Recipe B lost 63, 97 and 99 per cent of the initial MC after 24 hours at 30°C, 50°C and 70°C, respectively. Recipe C lost 89, 98 and 99 per cent of the initial MC after 24 hours at the same conditions, respectively.

For recipe B: The MCs of recipe B were 39.2, 38.1 and 38.4 per cent and dried at 30°C, 50°C and 70°C, respectively. At 24 hours, the MC decreased to 14.4, 0.8 and 0.4 per cent for the temperatures of 30°C, 50°C and 70°C, respectively. The MC at 48 hours decreased to 3.1, 0.1 and 0.1 per cent for the temperatures of 30°C, 50°C and 70°C, respectively. On the other hand, MC at 72 hours was less than 1 per cent for all thermal conditions.

Table 3 illustrated the MC of plaster reinforced with wheat straw fibers The results revealed that the MC of the plaster material reinforced by wheat straw fiber decreased slowly at a temperature of 30°C. It seems also that there was no big difference between MC obtained at thermal conditions of 50°C and 70°C.

For recipe C: First, the MC of recipe C ranged from 19.8 to 20.3 per cent. At 24 hours, it decreased to 2.4, 0.2 and 0.2 per cent for the temperatures of 30°C, 50°C and 70°C, respectively. The MCs at 48 hours were less than 1 per cent for all drying temperatures.

Generally, at 30°C about 60 per cent of the initial MC of recipe A, and 99 per cent of the MC of the same recipe at 50°C and 70°C were lost after 24 hours. Recipe B lost 63,

Table 3: Moisture content under different drying temperature for plasters reinforced by wheat straw fibers

Drying time (hour)	*Moisture content (%)*								
	A			*B*			*C*		
	30°C	*50°C*	*70°C*	*30°C*	*50°C*	*70°C*	*30°C*	*50°C*	*70°C*
0	71.71	72.45	72.43	39.24	38.10	38.40	19.78	19.32	20.30
24	28.80	0.78	0.48	14.41	0.81	0.41	2.38	0.23	0.18
48	7.82	0.21	0.19	3.10	0.14	0.12	0.61	0.11	0.10
72	0.92	0.06	0.03	0.42	0.07	0.07	0.34	0.07	0.06
96	0.06	0.04	0.03	0.08	0.07	0.07	0.04	0.03	0.03

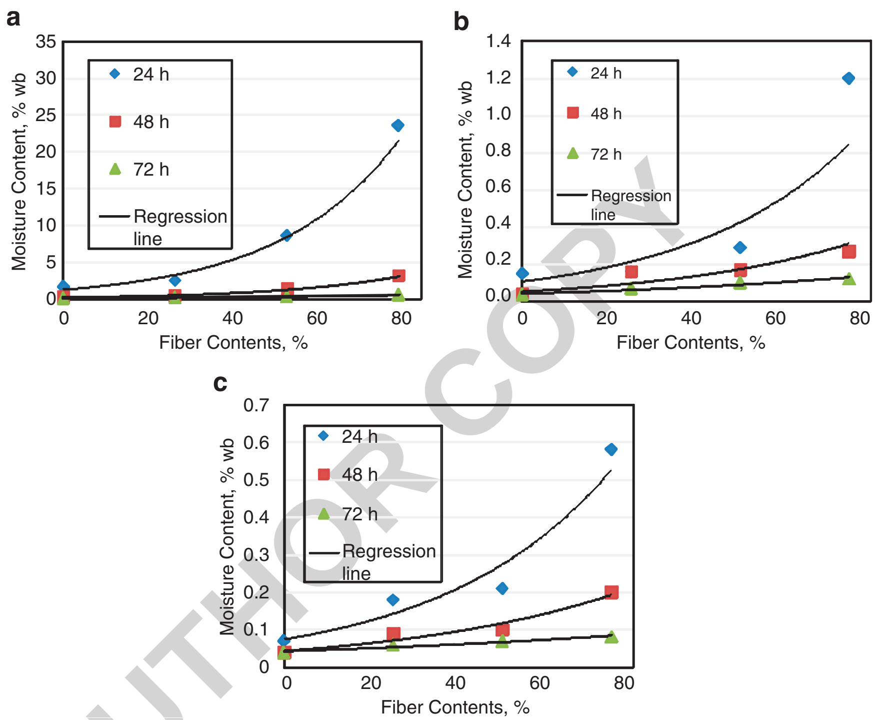

Figure 4: Moisture content of clay plasters reinforced with different percentages of sawdust fibers: (**a**) 30°C, (**b**) 50°C, (**c**) 70°C.

97 and 99 per cent of the initial MC after 24 hours at 30°C, 50°C and 70°C, respectively. Recipe C lost 89, 98 and 99 per cent of the initial MC after 24 hours at the same conditions, respectively. At higher temperatures, cracks were seen on the plaster surface; these cracks decreased with decreasing the plaster fiber contents.

Plaster material reinforced by sawdust fibers

Figures 4(a)–(c) show the MC of plasters reinforced with sawdust fibers at different temperatures with time. Figures 4(a)–(c) show MC at drying temperatures of 30°C, 50°C and 70 °C.

For recipe A: The initial MCs were 75.9, 73.5 and 74.6. At 24 hours, the MC decreased to 23.5, 1.2 and 0.6 per cent at 30°C, 50°C and 70°C, respectively. The MC at 48 hours decreased to 3.2, 0.1 and 0.2 per cent for the temperatures of 30°C, 50°C and 70°C. On the other hand, MCs at 72 hours were 0.6, 0.1 and 0.1 per cent of thermal conditions 30°C, 50°C and 70°C, respectively.

Table 4: Moisture content under different drying temperature for plaster reinforced by sawdust fibers

Drying time (hour)	*Moisture content (%)*								
	A			*B*			*C*		
	30°C	*50°C*	*70°C*	*30°C*	*50°C*	*70°C*	*30°C*	*50°C*	*70°C*
0	75.85	73.50	74.60	36.94	37.49	37.70	19.74	20.10	21.10
24	23.53	1.20	0.58	8.53	0.29	0.21	2.42	0.28	0.18
48	3.22	0.07	0.20	1.34	0.17	0.10	0.40	0.16	0.09
72	0.57	0.02	0.07	0.29	0.10	0.07	0.17	0.11	0.07
96	0.18	0.05	0.05	0.06	0.06	0.06	0.10	0.07	0.07

The results revealed that the MC of the plaster material reinforced by sawdust fiber inclined slowly at temperature of 30°C, while it decreased quickly at temperature of 70°C. It seems that the drying period at 70°C was very short, which caused more cracks on the surface of the plaster.

For recipe B: The MCs were 36.9, 37.5 and 37.7 per cent, after 24 hours, the MC decreased to 8.5, 0.3 and 0.2 per cent for the temperatures of 30°C, 50°C and 70°C respectively. The MCs at 48 hours were 1.3, 02 and 0.1 per cent for the temperatures of 30°C, 50°C and 70°C. On the other hand, MC at 72 hours was less than 1 per cent at different drying temperatures.

For recipe C: The initial MCs of recipe C were 19.7, 20.1 and 21.1 per cent. At 24 hours, the MC decreased to 2.4, 0.3 and 0.2 per cent for the temperatures of 30°C, 50°C and 70°C, respectively. The water content at 48 hours was less than 1 per cent for all thermal conditions.

The results revealed that the MC of the plaster material reinforced by sawdust fiber decreased slowly at temperature of 30°C. It seems that there was a small difference between the moisture lost at both 50°C and 70°C as presented in Table 4.

It is worthy to mention that at 30°C about 69 per cent of the initial MC of recipe A, 98 and 99 per cent of the MC of the same recipe at 50°C and 70°C were lost after 24 hours. Recipe B lost 77, 99 and 99 per cent of the initial MC after 24 hours at 30°C, 50°C and 70°C, respectively. Recipe C lost 88, 99 and 99 per cent of the initial MC after 24 hours at the same conditions, respectively. At higher temperatures, cracks were seen on the plaster surface; these cracks increased with decreasing the plaster fiber contents.

Regression analysis showed that the best relationship between the plaster desorption (D) and fiber contents (F_c) was described exponentially as follows:

$$\mathrm{D} = a(F_C)^b \tag{4}$$

The equation constants (a and b) at different drying temperatures for the different plasters under study are listed in Table 5.

Plasters without fibers

The average of plaster densities for plaster without reinforcement fibers was 1629 kg/mł for recipes A, B and C. The initial MC of recipe C was 15.5, 15.3 and 15.6 per cent for thermal condition of 30°C, 50°C and 70°C, respectively. At 24 hours, the MC was decreased to 1.6, 0.2 and 0.1 per cent for the temperatures of 30°C, 50°C and 70°C, respectively. The MC at 48 hours were less than 1 per cent for all thermal conditions as showed in Table 6.

The results revealed that the MC of the plaster material without reinforcement fiber (sand plaster) decreased slowly at a temperature of 30°C.

Table 5: Equation constants and coefficient of determination of the relationship between desorption and plaster fiber content of at different temperatures

Time (hour)	*Constants*								
	At 30°C			*At 50°C*			*At 70°C*		
	a	*b*	R^2	*a*	*b*	R^2	*a*	*b*	R^2
				Wheat straw fibers					
24	1.287	0.042	0.94	0.148	0.026	0.90	0.082	0.026	0.93
48	0.237	0.047	0.95	0.048	0.020	0.91	0.047	0.019	0.92
72	0.137	0.025	0.98	0.043	0.008	0.92	0.043	0.008	0.92
				Barley straw fibers					
24	1.448	0.035	0.97	0.164	0.034	0.95	0.058	0.030	0.95
48	0.215	0.035	0.96	0.040	0.029	0.99	0.040	0.022	0.99
72	0.103	0.019	0.94	0.037	0.019	0.95	0.041	0.017	0.98
				Sawdust					
24	1.28	0.037	0.97	0.108	0.027	0.83	0.074	0.026	0.94
48	0.22	0.035	0.97	0.054	0.023	0.82	0.043	0.019	0.93
72	0.11	0.020	0.98	0.044	0.014	0.95	0.043	0.008	0.92

Table 6: Moisture content under different drying temperature for plaster without reinforcement fibers

Drying time (hour)	*Moisture content (%)*		
	30°C	*50°C*	*70°C*
0	15.49	15.30	15.60
24	1.56	0.15	0.13
48	0.26	0.10	0.07
72	0.12	0.04	0.04
96	0.08	0.04	0.04

Generally, at 30°C, about 88 per cent of the initial MC of this recipe and 99 per cent of its moisture at 50°C and 70°C were lost after 24 hours. More cracks were observed on the surface of this type of plaster compared to the other plasters reinforced with fibers.

Amount of WA

The average amounts of WA for recipe A were 73.4, 76.1, 83.9 and 38.2 g for plaster reinforced with barley, wheat, sawdust and without reinforcement fibers, respectively. For recipe B, the amounts of WA were 61.7, 59.5, 60.4 and 38.2 g for plaster reinforced with barley, wheat, sawdust and without reinforcement fibers, respectively. On the other hand, the amounts of WA for recipe C were 40.1, 50.1, 46.1 g for plaster reinforced with barley, wheat, sawdust and without reinforcement fibers, respectively (Figure 5).

The results show that the amount of WA increased with increasing fiber content and decreased with increasing sand content. Moreover, the highest value for the amount of WA was obtained for the plaster reinforced with sawdust, whereas the lowest amount of WA was obtained for the plaster without reinforcement fibers.

Regression analysis was carried out to determine the relationship between fiber content and WA for the plasters under study, the best form of the relationship was as follows:

$$\mathrm{WA} = a(F_C)^b \qquad (5)$$

where, F_c is the fiber content (%), a and b are constants.

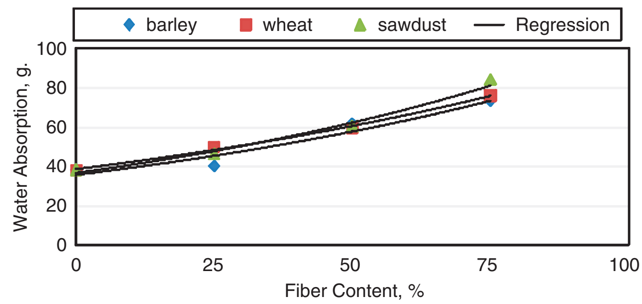

Figure 5: The water absorption as influenced by fiber content of different types of plasters reinforced with different fibers.

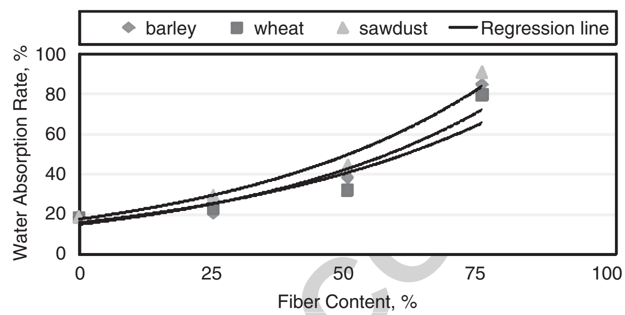

Figure 6: The water absorption rate as influenced by fiber content of different types of plasters reinforced with different fibers.

Table 7: Constants and coefficient of determination of the relationship between water absorption and fiber content of clay plaster reinforced with natural fibers

Recipes	*Constants*		
	a	*b*	R^2
Plaster with barley fibers	35.85	0.009	0.92
Plaster with wheat fibers	38.77	0.009	0.99
Plaster with sawdust fibers	36.83	0.010	0.99

Table 7 shows the lists of constants of the relationship between WA and fiber content of clay plaster reinforced with natural fibers.

Water absorption rate

The average WARs for recipe A were 85.4, 79.7, 90.7 and 18.3 per cent for plaster reinforced with barley, wheat, sawdust and without reinforcement fibers, respectively. For recipe B, WAR were 37.9, 32, 44.3 and 18.4 per cent for plaster reinforced with barley, wheat, sawdust and without reinforcement fibers, respectively. On the other hand, the WAR for recipe C were 19.9, 22.9, 29.3 and 18.4 per cent for plaster reinforced with barley, wheat, sawdust and without reinforcement fibers, respectively (Figure 6).

The results indicate that WAR increased with increasing fiber content and decreased with increased sand content. Moreover, the highest value for the WAR was obtained for the plaster reinforced with sawdust, and the lowest value of WAR was obtained for the plaster without reinforcement fibers.

CONCLUSIONS

The results indicate that for plaster reinforced by wheat straw fibers, recipe A lost 70, 99 and 99 per cent of the initial MC after 24 hours at 30°C, 50°C and 70°C, respectively. Recipe B lost 74, 95 and 99 per cent of the initial MC after 24 hours at 30°C, 50°C and 70°C, respectively. Furthermore, recipe C lost 85, 98 and 99 per cent of the initial MC after 24 hours at the same conditions, respectively. For plaster reinforced with barley straw fibers, recipe A lost 60, 95 and 99 per cent of the initial MC, while 63, 97 and 99 per cent for recipe B and 74, 89, 98 and 99 per cent for recipe C after 24 hours at 30°C, 50°C and 70°C, respectively.

Furthermore, plaster reinforced with sawdust fibers, recipe A, moisture lost 69, 98 and 99 per cent, while 77, 99 and 99 per cent for recipe B and 88, 99, 99 and 99 per cent for recipe C after 24 hours at 30°C, 50°C and 70°C, respectively. Investigation revealed that cracks were seen on the plaster surface at higher temperatures, and that these cracks increased with decreasing plaster fiber contents. In addition, moisture lost for plasters without reinforcement fibers were 88, 98 and 99 per cent at temperatures of 30°C, 50°C and 70°C after 24 hours. More cracks were observed on the surface of this type of plaster compared to the other plasters reinforced with fibers.

The results showed that WAR increased with increasing fiber content and decreased with increased sand content. Moreover, the highest value for the WAR was obtained for the plaster reinforced with sawdust, while, the lowest value of WAR was obtained for the plaster without reinforcement fibers.

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