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Performance of composite soil reinforced with barley straw

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Abstract

The shortage of low cost and affordable housing in Algeria has led to many investigations into local low cost construction materials. Earth construction is widespread in desert and rural areas but suffers from shrinkage cracking, low strength and lack of durability. The use of natural and vegetable fibres could improve its performance. This paper reports on an experimental study to investigate a composite soil reinforced with chopped barley straw, using four different soils. The effect of fibre length and fibre fraction on shrinkage, compressive strength, flexural strength and shear strength was investigated. Preliminary tests to enhance durability by using different waterproof renders are also briefly reported.

Keywords: Straw; Low-cost construction; Earth blocks; Reinforcement; Shrinkage; Compressive strength; Flexural strength; Shear strength; Fibre length; Durability

1. Introduction

The shortage of housing units in Algeria is estimated to be more than two millions units. About 120 thousand extra units are needed each year for new families and efforts are being made to investigate methods of building affordable housing using local construction materials. Sand dune, gypsum, lime and adobe blocks have been widely investigated [1–4]. Moreover, a growing interest has been focussed on stabilising earth construction, as it is widely used in desert and rural areas because of its abundance and cheap labour. However, although a lot of ancient constructions and recent prototypes have been built, they tend to have a short lifetime span as earth construction suffers usually from lack of strength and shrinkage cracking due to the drying process and lack of resistance to water. To overcome this problem, two ways have been explored. The first is achieved by means of stabilisation of the earth either by using chemical binders such as cement and lime or by means of mechanical compaction while the second consists of adding natural fibres to the earth. Natural fibres have been used for a long time in many developing countries in cement composites and earth blocks because of their availability and low cost [5–7]. Barley straw is widely cultivated and harvested once or twice annually in almost all rural areas in Algeria and could be used in producing composite soil blocks with better characteristics, but no published data is available on its performance as reinforcement to soil or earth blocks. This paper reports on an experimental investigation into the physical and mechanical performance of a composite soil reinforced with chopped barely straw. The main objective of the work is to analyse the characteristics of four different soils available in the south Algerian desert region of Laghouat and to investigate the possibility of enhancing soil properties by reinforcement with chopped barley straw at different levels and different fibre lengths.

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2. Testing procedure

2.1. Materials and preparation

Four different local soils were tested and used in the experimental investigation. Physical properties and chemical composition of these soils are given in Tables 1 and 2. Apart from soil A, all three other soils (B, C and D), have a particle-size distribution within the maximum limits specified for compressed earth blocks. Soil A is a clayey silty soil, whereas soil B is a clay sandy soil and soils C and D are silty sands. The physical characteristics of the straw fibres are summarised in Table 3. It can be clearly seen that the water absorption of the straw is very high. This could lead to some durability problems and to lack of bond of the fibres to the soil. Material preparation and mixing was carried out manually in the laboratory. The mixing water was added to get a normal consistency and low total shrinkage and hence was fixed at a water/soil ratio of 28% for soil A, 19% for soil B and C and 25% for soil D. The water content was found to increase with the increase of fines (clay and silt) content. Fibres were obtained from local fields, cut to the required length, soaked in water for 24 h before being added randomly but in a homogeneous way to the humid soil and mixed until getting a complete homogeneous composite. However, for the flexural tests, long fibres were added and oriented in the direction of the applied stresses. Specimens were cured in the uncontrolled laboratory environment at 30–35 °C and about 65% RH.

Table 1
Physical properties of the soils used

Characteristics	Type of soil			
	A	B	C	D
Specific gravity	2.7	2.68	2.72	2.67
Liquid limit (%)	56.76	32.72	31.63	39.67
Plastic limit (%)	23.43	14.94	17.82	21.85
Plasticity index (%)	33.00	18.00	14.00	18.00
Activity coefficient	0.92	0.61	0.66	0.66
Clay (%)	40	28	21	26
Silt (%)	45	29	39	42
Fine sand (%)	8	23	5	4
Coarse sand (%)	7	20	35	27

Table 2
Chemical composition of the soils used

Soil	Content (%)					
	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	LOI
A	17.34	36.30	11.15	4.37	3.67	18.76
B	9.76	61.92	7.96	4.48	4.68	11.54
C	8.95	41.8	11.85	4.48	6.39	17.41
D	0.00	64.20	14.82	7.26	4.1	5.06

Table 3
Characteristics of the straw fibres used

Diameter (mm)	Length (mm)	Water absorption (%)	Specific density	Specific weight (kN/m^3)
1–4	10–500	500–600	2.05	12

2.2. Testing methods

Specimens used for the shrinkage and compressive strength tests were 220 mm × 107 mm × 60 mm whereas 60 mm × 60 mm × 36 mm specimens were used for shear tests and 70 mm × 70 mm × 280 mm prismatic specimens for the flexural tests. The compressive strength was obtained using a testing machine at a rate of 7 mm/min. The shear tests were carried out using a Casagrande apparatus at either a normal stress of 1, 2 or 3 bars and a shear velocity of 2 mm/min. The effect of fibre/soil ratio was analysed by increasing it from 0% to 3.5%. The effect of fibre length was investigated using the following ranges; 10–20 mm, 20–40 mm and a range of 40–60 mm. The development of the compressive strength and shrinkage with drying age was also investigated. The results reported in this paper are the average of four samples for compressive and flexural strengths, eight samples for shrinkage and three samples for shear and durability tests. The bulk density of all specimens varied between 1100 and 1300 kg/m^3 and their average moisture content at time of testing varied between 1.5% and 2.0%. All tests were made mainly according to the RILEM TC 153 guide and the local algerian CNERIB guide [8,9].

3. Results and discussion

3.1. Effect of fibre fraction on shrinkage

Linear and volumetric shrinkage were measured on the specimen and the effect of the drying time and level of reinforcement studied. As expected, shrinkage increases with time for all soils as drying increases but shrinkage decreases with the increase in reinforcement ratio and fibre length. Fig. 1 gives the variation of linear and volumetric shrinkage with various reinforcement levels. Shrinkage was higher for soils with higher levels of clay. Shrinkage stabilises at earlier ages with higher straw level showing that drying is quicker as straw accelerates the evaporation by the air channels it forms. The addition of straw reduces the shrinkage as the fibres tend to oppose the deformation. The positive effect of straws seems to be more pronounced with silty sand soils (C and D) than with clayey soils (A and B). The effect of increasing the length of the fibres up to 60 mm is shown in Fig. 2. A slight decrease of shrinkage is observed with the increase of fibre length at all levels of reinforcement. This could be attributed to the sufficient length of the straws for the bond stresses at the interface straw–soil

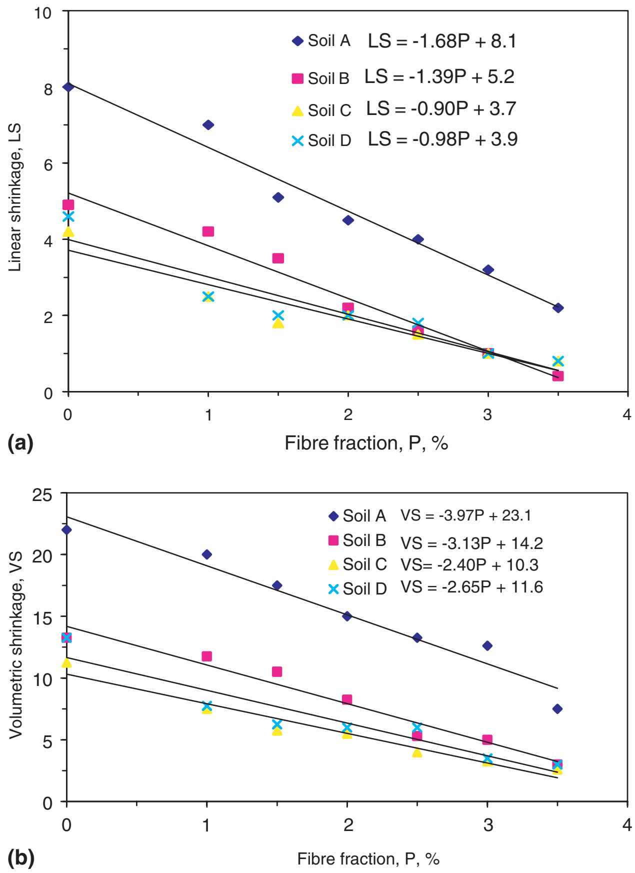

Fig. 1. Linear and volumetric shrinkage variation with fibre fraction.

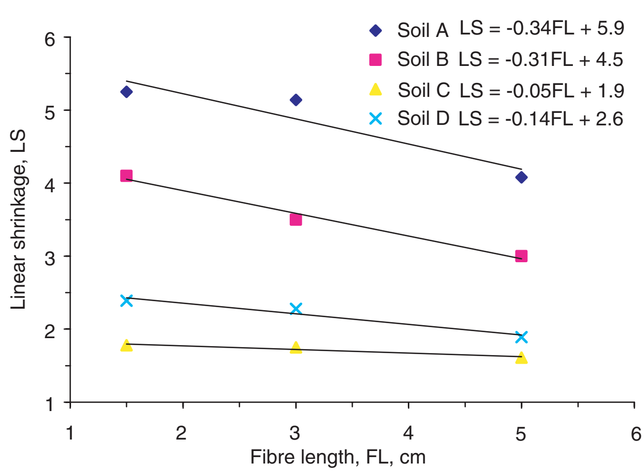

Fig. 2. Effect of fibre length on shrinkage with fibre fraction.

to develop and hence to oppose to the deformation and to soil contraction.

3.2. Effect of fibre length and fibre fraction on compressive strength

Fig. 3 summarises the compressive strength tests results at 28 days for various fibre/soil mass ratios and a fibre length of 20–40 mm. It can be clearly seen that

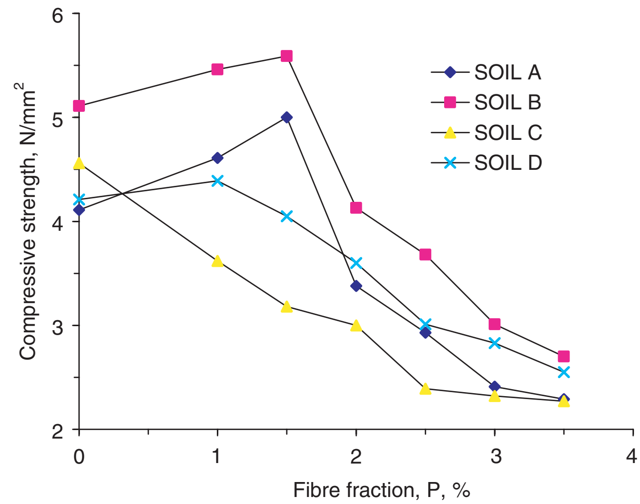

Fig. 3. Compressive strength variation with fibre fraction.

the increase of the reinforcement level up to about 1.5% enhances the compressive strength by 10–20% depending on the type of the soil used but further increase seems to reduce the compressive strength. The reduction in compressive strength at 3.5% reinforcement was about 45%. However, the obtained compressive strength of the composite soils with 3.5% reinforcement remains higher than the minimum of 20 bars found in the literature [10] for the adobe construction. The effectiveness of the reinforcement was more pronounced with clayey soils (soil A) as compared to the other sandy soils. The failure of specimens without reinforcement was sudden and in a brittle way with only one large crack. However, the failure of specimens with straw reinforcement was more ductile and with higher number of cracks.

The effect of increasing fibre length on the compressive strength was negligible but it seems to increase the capability of the blocks to deform at the failure stage. A limited study was conducted to investigate the effect of specimen size on the compressive strength by using smaller specimen having half the original width and hence a higher slenderness. As expected, the compressive strength decreased by about 35% for all types of soils.

3.3. Flexural strength

Four point flexural strength tests at a deflection rate of 5 mm/min were made using longer fibres (100–200 mm) and 70 mm × 70 mm × 280 mm specimens and a reinforcement ratio of 0%, 1.5%, 2.5% and 3.5%. Failure of plain specimens was sudden with only one crack at the middle and a complete separation of the specimens into two halves whereas the failure of the reinforced specimens was with multiple finer cracks and higher deflection. Fig. 4 shows the increase in flexural strength for all the soils used.

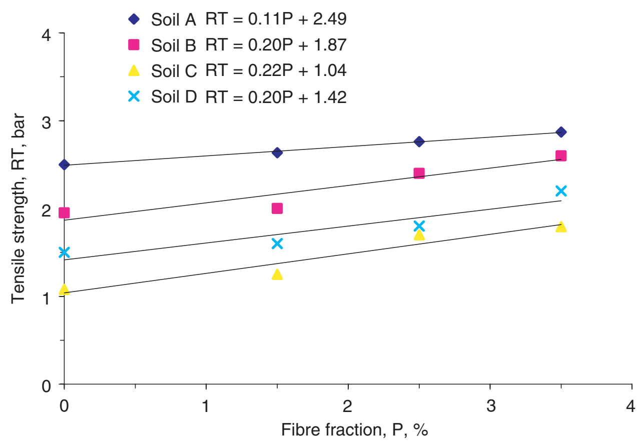

Fig. 4. Flexural strength variation with fibre fraction.

3.4. Shear strength

Tests were done using a Casagrande box at a normal stress of either 1, 2 or 3 bars and a shear speed of 2 mm/min on 60 mm × 60 mm × 36 mm specimen with reinforcement ratio of 0%, 1.5% and 3.5% at the age of 28 days. The shear force was measured and the shear stress computed. Table 4 summarises the deformation and shear stresses for the different soils used.

3.5. Durability

In order to enhance the durability of the composite and in particular its resistance to water penetration and water absorption, four different water repellent

Table 4
Shear stress and maximum deformation for different soils under shear tests

Soil	Fibre (%)	*N* = 1 bar		*N* = 2 bars		*N* = 3 bars	
		Deformation (mm)	*T* (bars)	Deformation (mm)	*T* (bars)	Deformation (mm)	*T* (bars)
A	0	4.14	9.67	4.80	10.81	4.14	10.86
	1.5	2.94	5.70	3.60	6.93	6.96	9.28
	3.5	4.98	5.63	5.34	8.26	5.34	8.72
B	0	4.98	6.28	4.14	9.89	5.16	12.55
	1.5	4.80	5.97	3.60	7.51	2.94	8.30
	3.5	4.80	5.48	4.14	6.19	5.16	7.51
C	0	2.94	3.23	5.78	5.51	4.14	6.21
	1.5	4.14	3.76	5.16	4.94	6.54	6.28
	3.5	5.34	3.65	6.00	5.04	5.16	6.24
D	0	2.76	4.54	2.94	5.94	2.94	7.40
	1.5	3.78	4.43	4.80	6.44	5.34	7.25
	3.5	4.80	4.42	5.16	5.79	5.34	6.76

Table 5
Summary of the durability tests results

Type of coating	Soil	Average water absorption (%)	Main visual observations
Lime render	A	–	Debonding of the coating
	B	9.2	Surface erosion and cracking of the specimens
	C	8.5	Same as soil B
	D	9.6	Same as soil B
Lime–cement render	A	4.2	No visible distress signs
	B	3.9	No visible distress signs
	C	3.7	No visible distress signs
	D	4.1	No visible distress signs
Soil render	A	11.6	Systematic cracking
	B	10.3	No visible distress signs
	C	9.4	No visible distress signs
	D	10.5	No visible distress signs
Cement render with polymers	A	3.9	No visible distress signs
	B	3.8	No visible distress signs
	C	3.7	No visible distress signs
	D	3.6	No visible distress signs

coatings were tested: lime render; lime–cement render; soil render with either cement or lime as a binder and a cement render with polymers. Details of the mixes used are given elsewhere [11]. The treatment with render was applied on the surface in three different layers. Specimens were subjected to "water showers" for two hours from a distance of 0.18 m at a water pressure of about 1 bar. Water absorption of the specimens was measured at the end of the test and the effect on the surface noted. The results of the tests which are summarised in Table 5 showed that cement render with polymers was the most durable as they seem to lead to the lowest water absorption with no noted surface erosion. Lime–cement renders performed better than lime renders and soil renders.

4. Conclusion

Four different local soils were tested and used to manufacture soil specimens with straw reinforcement at different reinforcement/soil ratios and fibres lengths. The results of the tests proved the positive effects of adding straw in decreasing shrinkage, reducing the curing time and enhancing compressive strength if an optimal reinforcement ratio is used. Flexural and shear strengths were also increased and a more ductile failure was obtained with the reinforced specimen. The best water repellent treatment seems to be that using a cement render with polymer addition. Further studies are necessary to elucidate the fracture mechanism, the effect of prior treatment of the fibres and the durability of the composite at long term and under more severe conditions.

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