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Physical-Mechanical Experimental Tests on Adobe Bricks Reinforced With Hemp Fibres

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ABSTRACT

The man's evolution history is marked by technological advances, but shared by a constant search for a place to live, capable of providing shelter and protection. For thousands of years, man transformed environment by using natural products through techniques used in geographically unpopular areas or in quite different historical contexts. Combined with wood, raw earthwork has a millennial history as long as the evolution of man himself, but much longer than that of wood, which is subjected to natural degradation cycles. If land-based testimonies are present everywhere in the world, from the ziqqurat in Syria to the Mali mosques, from monuments in Nigeria to Yemen buildings, from homes in New Mexico to urban aggregates in Morocco, today it is necessary to resume and rediscover from the scientific point of view these techniques, so to understand materials and processing necessary to preserve and protect this immense historical and social heritage. Only through a modern experimentation, characterised by theoretical researches and tests, it is possible to define "engineering" criteria to be complemented with restoration techniques, which allow to intervene to protect these historic assets.

Keywords: *Natural fibres, adobe bricks, hemp, experimental tests, ductile behaviour.*

INTRODUCTION

The use of raw earth as building material has very ancient origins. Raw constructions were advantageous compared to masonry stone ones due to the greater material availability and execution speed. Traces of adobe technique (raw earth bricks) were found in Babylonian, Greek and Egyptian civilizations (Fig. 1), where the dough was based on mixtures of ground and straw. An interesting aspect of the various raw earth constructive techniques was their development in different ways, depending on the characteristics of the local material available, which characterised and modified the appearance of architectures of different cultures.

The Iranian citadel of Bam (Fig. 2), founded around 500 B.C. and inhabited until 1850, had an urban layout quite similar to the city of Chan Chan in Peru, capital of the Chimu Empire (Fig.3).

However, raw earth was used in recent times also in constructions erected in Italy until mid '900. If the lack of stones in the Po valley led to the construction of rural buildings made of raw earth bricks, other constructive exampleswere found in Piedmont where, despite the humid and rainy weather, rural buildings made of a mixed masonry were erected by using burnt and raw bricks. More important

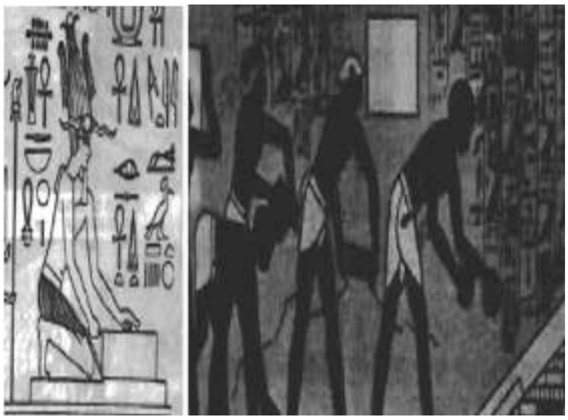

Figure1. *Hatchepsout queen (1490-1469 a.C.) with a formwork for adobe (left) and slave used for the construction of the Ammon temple of Tebe (right)*

examples of these constructions are found in Calabria and in Sardinia, where "court houses" used in the second post-war period for either reconstruction or recovery of small and medium-size agricultural centres were erected.

Figure2. *The city of Bam in Iran*

Figure3. *The city of Chan Chan in Perù*

The most diffused masonry type was that made of adobe bricks, made of a combination of earth, sand and straw, which were mixed according to percentages dictated by the experience of workers. Such mixtures were packaged by adding straw or hay, used either as bedding for animals or for filling bed mattresses, which representaagricultural production waste. The purpose was to both increase and reduce the mixture volume in order to obtain light and more easily transportable bricks. Another purpose was the greatest impact resistance compared to solutions made of clay and sand only. The gravel was often manually removed from the hand made mixture, because it tended to cut or skew during the manufacturing process. The amount of water employed derived from results of performed tests, by taking into account the origin place, the packaging period and the work experience of the manpower. With the straw, used under form of stems cut with shears and trimmers, highly inhomogeneous brickswere manufactured. In the framework of resuming this process in a more modern version, instead of straw, hemp production wastes under form of fibres were used in the experimental activity herein presented. Abandoned about 50 years ago because ofboth the cost no longer competitive with that of synthesis products and the emerging legal issues related to the percentages of THC enclosed into seeds, hemp came back in Europe in the early 1990s, thanks to some government incentives for the development of innovative technologies able to derive fibres from plants. In 2017the law regulating the hemp cultivation in Italy was modified. Such a law, if on one hand increases the police controls, on the other hand allows for a greater liberalization of the cultivation of certain seed species, such as those belonging to the Cannabis sativa family (Fig. 4).

The current growing interest towards vegetal fibres is linked, other than their physical and mechanical characteristics (Table 1), to their complete biodegradability, since living organisms recognise carbohydrate polymers (mainly hemicelluloses) in the cell wall and possess highly specific enzymatic systems capable of hydrolysing these polymers in digestible units.

Figure4. *View of the Cannabis sativa plantation before the flowering phase*

Table1. *Physical and mechanical properties of main vegetable fibres*

Type of fibre	Diameter (micron)	Relative density (g/cm^3)	Ultimate stress (MPa)	Elastic modulus (GPa)	Ultimate strain (%)
E-glass	<17	2.5-2.6	2000-3500	70-76	1,8-4,8
Abaca	-	1.5	400-980	6,2-20	1,0-10
Bamboo	25-40	0.6-1.1	140-800	11-32	2.5-3.7
Banana	12-30	1.35	500	12	1,5-9
Coir	10-460	1.15-1.46	95-300	2.8-6	15-51.4

Cotton	10-45	1,5-1,6	287-800	5,5-12,6	3-10
Linen	12-600	1.4-1.5	343-2000	27.6-103	1.2-3.3
Hemp	**25-600**	**1,4-1,5**	**270-400**	**23,5-90**	**1-3,5**
Isora	-	1.2-1.3	500-600	-	5-6
Juta	20-200	1.3-1.49	320-800	30	1-1.8
Nettle	-	-	650	38	1.7
Palm	-	1.4	134-143	1.07-4.59	7.8-21.9
Pilaf	20-80	0,8-1,6	180-1627	1,44-82,5	1,6-14,5
Sisal	8-200	1,33-1,5	363-700	9,0-38	2,0-7,0

Materials And Methods

The performed experimentation is based on the production of raw earth bricks, seasoned in a natural way and packed with water and hemp fibres already experimented in other researches [1, 2]. In the absence of code indications about these mixtures and considered the lack of data from similar experiments and/or technical information acquired by workers, preliminary tests and analyses have been executed in order to package homogeneous mixtures with semi-solid or plastic consistency, suitable for producing adobe bricks. The total water $\mathbf{A_{tot}}$ to be used in the mixture is basically linked to three factors:

- Absorption Water $\mathbf{W_{abs}}$, that is the water quantity that the fibres absorb in a first stage, due to their high hygroscopic behaviour, and that is gradually released during the seasoning phase;
- Mixture water $\mathbf{W_{mix}}$, defined as the water content that ensures the passage of the earth from dry behaviour to plastic one;
- Workability water $\mathbf{W_{wor}}$, namely the greater amount of water needed to ensure a proper workability of the mixture, ensuring homogeneous filling of formworks and, therefore, the formation of adobes with regular faces.

With reference to the value $\mathbf{W_{abs}}$, in the absence of provisions, tests based on the total immersion of fibres into drinking water, under standard environmental conditions, have been performed by measuring the weight variation with respect to the initial sample one. In this way it is possible to determine both the absorption modes and the time necessary to have water full hemp. After the set time has elapsed, the sample has been extracted from the immersion vessel, tamped with a cloth to eliminate the additional water and subsequently weighed, taking a step of about 10 minutes. The test has been carried out on two types of different fibres resulting from the combing stage of hemp: a first type under form of "flakes" (Fig. 5) with length L variable from 5 to 10mm (used for samples C.1 and C.2, as it will be illustrated later) and a second most coarse type (Fig.6), characterised by fibres with length L from 10 to 20mm.

Figure5. *Hemp short fibres (length L=5÷10mm) under form of "flakes"*

Figure6. *Hemp roughfibres (length L=10÷20mm)*

After the test (Fig. 7), it has been noticed that each gram of hemp fibre absorbs a water content about 1.5 times its weight. In particular, the completed absorption phase, providing the stabilization of the mixture, has been achieved with the saturation of fibres after about 30 minutes.

Since adobe bricks have been packed with predominantly clay soils, the W_{mix} quantity has been assumed equal to the value of the Atterberg Plasticity Limit W_{pl}, which represents the transition value from the semi-solid state to the plastic one.

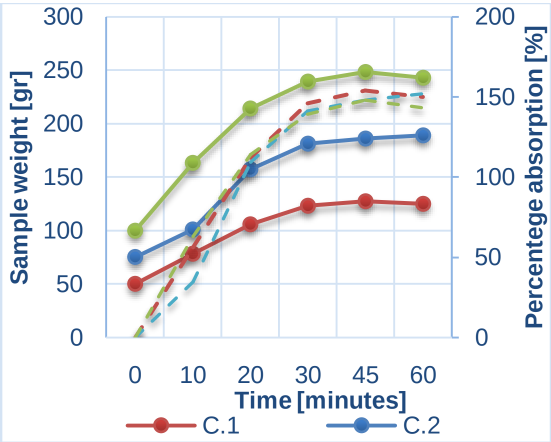

Figure7. *Absorption diagram of hemp fibres*

Following the tests carried out, W_{pl} = 0.22 is determined, it representing the weight percentage of water over the earth one. After further tests carried out for assessing the mixture workability, packaging tests, based on filling formworks with reinforced earth, have been performed. Taking into account such aspects, a total water value of W_{tot} = 0.25 has been employed. Ultimately, a number of mixtures have been made by adopting variable percentages of hemp fibres (%F) with a limit value equal to 2.0%, beyond which the mixture has assumed an insufficient workability for packaging(Table 2). In this table W/E represents the water/earth ratio, while SF and LF indicate short fibres and long ones, respectively.

Table2. *The adobe samples under investigation*

Acronym	Specimen	W/E [%]	Amount of hemp fibres [%]	Fibre type	Fibre weight [g]	Brick weight [kg]
P0_A22_C0.0	P0.1	22	-	-	-	2,184
	P0.2	22	-	-	-	2,198
	P0.3	22	-	-	-	2,121
P1_A25_C0.0	P1.1	25	-	-	-	2,251
	P1.2	25	-	-	-	2,280
	P1.3	25	-	-	-	2,215
P2_A25_C0.5_SF	P2.1	25	0,5	SF	11,2	2,302
	P2.2	25	0,5	SF	11,2	2,236
	P2.3	25	0,5	SF	11,2	2,246
P3_A25_C1.0_SF	P3.1	25	1,0	SF	22,5	2,236
	P3.2	25	1,0	SF	22,5	2,216
	P3.3	25	1,0	SF	22,5	2,170
P4_A25_C1.0_LF	P4.1	25	1,0	LF	22,5	2,208
	P4.2	25	1,0	LF	22,5	2,227
	P4.3	25	1,0	LF	22,5	2,203
P5_A25_C1.5_SF	P5.1	25	1,5	SF	34,0	2,283
	P5.2	25	1,5	SF	34,0	2,238
	P5.3	25	1,5	SF	34,0	2,322
P6_A25_C2.0_SF	P6.1	25	2,0	SF	45,0	2,342
	P6.2	25	2,0	SF	45,0	2,158
	P6.3	25	2,0	SF	45,0	2,276
P7_A25_C2.0_LF	P7.1	25	2,0	LF	45,0	2,230
	P7.2	25	2,0	LF	45,0	2,107
	P7.3	25	2,0	LF	45,0	2,187

Due to the availability of two different types of fibres, the first with a length range of 5-10mm and the second with a length range of 10-15mm, for some mixtures further specimens, having the same total water used, have been packaged to check the possible influence of the fibre length on both the physical characteristics and the mechanical behaviour of the composite material. The formworks used for packaging adobe bricks, according to the UNI code provisions, are composed of three compartments, each having the dimensions of 5.5x12x25 cm. They are made of timber chipboard panels, which are internally coated with melamine paper to avoid absorption of the mixing water. The specimens have been continuously monitored (approximately each two days) through subsequent weighing (Table 3),so as to verify the time needed for the complete drying of the manufactured adobe bricks. For each sample it has been also recorded the average daily temperature and relative environmental humidity. After about 7 days, the specimens have assumed a right consistency to be pulled out from the formworks, taking care to place them in a room protected by the weather and the sun, but with an adequate ventilation. After about 25 days,under an average temperature of 16.8 ° C and a relative humidity U = 63.2 %, the stabilization of the specimens weight due to their natural drying has been observed (Fig. 8).

Table3. *Monitoring of samples*

Curing days	Weight of samples [g]								Environmental conditions	
	P0_A22_C0.0	P1_A25_C0.0	P2_A25_C0.5_SF	P3_A25_C1.0_SF	P4_A25_C1.0_LF	P5_A25_C1.5_SF	P6_A25_C2.0_SF	P7_A25_C2.0_LF	Relative humidity [%]	Medium temperature [°C]
1	2783	3052	3072	3016	2988				68	12
3	2632	2881	2890	2854	2830	3022	3041	3081	81	14
5	2575	2838	2850	2819	2748	2967	2972	2864	77	15
7	2513	2790	2814	2695	2685	2809	2818	2703	48	19
9	2412	2666	2674	2592	2582	2668	2692	2573	50	19
11	2321	2562	2584	2517	2506	2572	2582	2457	61	18
13	2206	2335	2365	2309	2322	2358	2353	2256	52	20
16	2181	2303	2327	2265	2276	2327	2314	2225	75	13
17	2178	2296	2319	2256	2266	2319	2303	2216	54	15
20	2160	2277	2295	2231	2241	2298	2280	2194	74	19
22	2159	2272	2292	2229	2239	2296	2274	2190	74	16
24	2146	2259	2275	2213	2221	2279	2260	2177	45	20
26	2146	2258	2275	2211	2219	2277	2257	2174	62	18

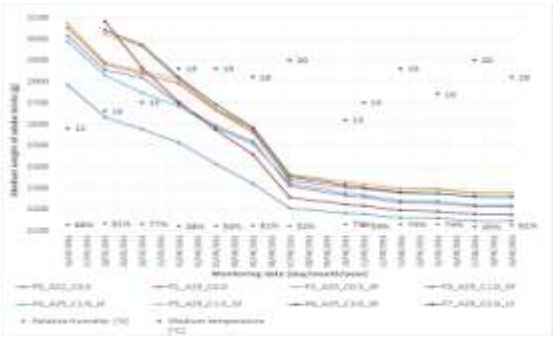

Figure8. *Monitoring of the weight of adobesduring curing time*

After aging (Fig. 9), an obvious shrinkage phenomenon of adobe bricks, resulting from water evaporation, has been observed (Table 4), it producing a significant reduction of their volume and weight. No abnormalities during the seasoning of specimens, except than small boundary effects of the raw earth brick edges adherent to the formworks, have been detected. From the data of the measurements made (Table 4), it has been observed that the presence of hemp fibres significantly influences the shrinkage phenomenon. In fact, with respect to the initial volume of the formwork (5.5x12x25 = 1650 cm^3), the unreinforced specimen P0_A22_C0.0 has a reduced volume of 26.2%, whereas the specimen P7_A25_C2.0_LF has a volume reduction of about 18.5% and a specific weight decrease of about 10.4%. Therefore, in general, the presence of hemp fibres allows to stabilise the specimens, limiting the rheological effects of the used clay.

Figure9. *Shrinkage effect of specimens in the timber formworks*

Table4. *Physical properties of adobe specimens*

Acronym	Specimen	Length [m]	Width [m]	Height [m]	Volume [cm]	Density [Kg/m^3]	Medium density [Kg/m^3]
P0_A22_C0.0	P0.1	0,235	0,109	0,048	1229,3	1776,7	1779,0
	P0.2	0,237	0,109	0,047	1214,2	1810,3	
	P0.3	0,236	0,107	0,048	1212,0	1750,0	
P1_A25_C0.0	P1.1	0,229	0,109	0,050	1248,1	1803,6	1804,9
	P1.2	0,231	0,109	0,050	1259,0	1811,0	
	P1.3	0,230	0,107	0,050	1230,5	1800,1	
P2_A25_C0.5_SF	P2.1	0,230	0,109	0,049	1228,4	1873,9	1840,8
	P2.2	0,230	0,109	0,049	1228,4	1820,2	
	P2.3	0,230	0,109	0,049	1228,4	1828,4	
P3_A25_C1.0_SF	P3.1	0,230	0,108	0,050	1242,0	1800,3	1780,1
	P3.2	0,230	0,108	0,051	1266,8	1749,2	
	P3.3	0,229	0,108	0,049	1211,9	1790,6	
P4_A25_C1.0_LF	P4.1	0,232	0,110	0,049	1250,5	1765,7	1713,3
	P4.2	0,232	0,110	0,051	1301,5	1711,1	
	P4.3	0,234	0,111	0,051	1324,7	1663,1	
P5_A25_C1.5_SF	P5.1	0,235	0,109	0,051	1306,4	1747,6	1768,8
	P5.2	0,233	0,109	0,049	1244,5	1798,4	
	P5.3	0,233	0,111	0,051	1319,0	1760,4	
P6_A25_C2.0_SF	P6.1	0,234	0,111	0,051	1324,7	1768,0	1720,2
	P6.2	0,235	0,108	0,051	1294,4	1667,2	
	P6.3	0,233	0,111	0,051	1319,0	1725,5	
P7_A25_C2.0_LF	P7.1	0,235	0,113	0,052	1380,9	1614,9	1616,7
	P7.2	0,236	0,109	0,051	1311,9	1606,0	
	P7.3	0,235	0,112	0,051	1342,3	1629,3	

RESULTS AND DISCUSSION

After the maturing process, all specimens have been subjected to flexural bending and compression tests by using the provisions of UNI-EN 772-1 [3] and UNI-EN 771-1 [4] codes for bricks. The mechanical tests have been carried out in the laboratory of the TecnolabS.r.l. Italian company by using the LOSENHAUSENWERK UPH10 testing machine with the LONOS TESTacquisition system (Fig. 10). The specimens P0_A22_C0.0have been used for the calibration of the test speeds, set equal to 0.02 N/mm^2/s for bending tests and 0.05 N/mm^2/s for compression tests.

Figure10. *The LOSENHAUSENWERK UPH10 testing machine used for experimental tests*

Three point bending tests have been carried out on adobe bricks simply supported at their ends and loaded in the middle (Fig. 11).

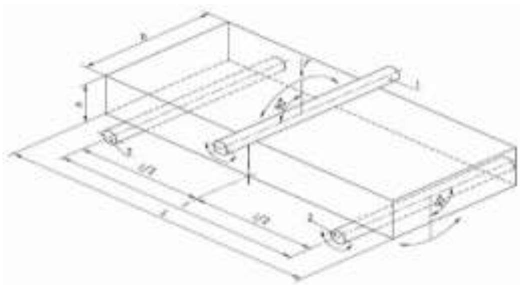

Figure11. *Loading scheme for bending tests*

The distance between supports (L) has been assumed as equal to 200 mm, taking care to centre the specimens inside the testing machine with respect to the supports (Fig.12).

Figure12. *Placement of the specimen into the testing machine*

The bending stresshas been found from the following equation:

$$F_{cf} = \frac{3FL}{2d_1 d_2^2} \qquad (1)$$

where:

F_{cf} = tensile failure stress due to bending;

F = maximum applied load;

L = distance between supports;

d_1 = specimen base;

d_2 = specimen height.

From the observation of mechanical tests, no abnormalities have been detected in terms of the rupture type of samples (Fig. 13), which has occurred because of the formation of a crack in their middle section.

Figure13. *Bending failure of a tested specimen*

In the experimental tests the unreinforced specimens have experienced a very brittle rupture, while the fibre-reinforced ones have shown a more ductile rupture thanks to fibres randomly dispersed in the clay matrix. Analysing the bending tests (Table 5) in terms of mechanical stress values of fibre-reinforced specimens, a minimum and maximum reduction of the tensile resistance of 15.1% and 32.0%, respectively, has been observed with respect to the strength of the unreinforced specimen P1_A25_C0.0.

Examining separately the data derived from tests carried out on specimens manufactured with short fibres (P2_A25_C0.5_SF, P3_A25_C1.0_SF, P5_A25_C1.5_SF and P6_A25_C2.0_SF) and long ones (P4_A25_C1.0_LF and P7_A25_C2.0_LF), it has been detected a greater decay of the bending flexural stress for the latter specimens (Fig. 14). In fact, stress reductions equal to 32.0% and 27.1% with respect to the unreinforced specimen stress have been detected for the specimens P7_A25_C2.0_LF and P6_A25_C2.0_SF, respectively.

Given the similar trend of the stress decrease for the two types of fibres, presumably such a resistance reduction derives from the greater porosity of these samples with respect to unreinforced ones. Therefore, the presence of fibres, as previously mentioned, involves a reduction of the material density, which decrease also the resistance of bricks.

By analysing the data in terms ofductility (Fig. 15), it appears that fibre-reinforced specimens have an increase of both the breaking displacement and the ultimate one with respect to those achieved with unreinforced specimens.

However, it is noticed that samples with short fibres have largely dispersed displacements with respect to those of mixtures having long fibres. This difference is essentially due to the different length of fibres, since the longer ones activate, after the opening of the first crack, a sewing mechanism of the crack itself, ensuring a more ductile behaviour with displacements greater than 100% of those recorded for unreinforced adobe bricks.

Table5. *Results of bending tests*

Specimen acronym	Amount of hemp fibres [%]	Fibres type	F [kN]	W_{ul} [mm]	$W_{ul,m}$ [mm]	f_{ctf} [MPa]	$f_{ctf,m}$ [MPa]	ΔW_{ul} [%]	Δf_{ctf} [%]
P0.1	-	-	1,954	(**)				-	-
P0.2	-	-	1,919	(**)	-		-	-	-
P0.3	-	-	2,006	(**)				-	-
P1.1	-	-	1,954	0,78 (*)		2,15			
P1.2	-	-	1,919	0,85 (*)	0,64	2,11	2,17	-	-
P1.3	-	-	2,006	0,29 (*)		2,25			
P2.1	0,5	SF	1,384	0,550		1,59			
P2.2	0,5	SF	1,196	1,090	1,13	1,37	1,59	76,0	-26,5
P2.3	0,5	SF	1,594	1,740		1,83			
P3.1	1,0	SF	1,875	1,000	1,17	2,08	1,84	82,8	-15,1

P3.2	1,0	SF	1,682	0,870		1,80			
P3.3	1,0	SF	1,424	1,640		1,65			
P4.1	1,0	LF	1,717	1,460		1,95			
P4.2	1,0	LF	1,818	0,640	1,22	1,91	1,80	91,1	-16,9
P4.3	1,0	LF	1,498	1,570		1,56			
P5.1	1,5	SF	1,406	0,430		1,49			
P5.2	1,5	SF	1,975	1,320	1,01	2,26	1,79	57,8	-17,6
P5.3	1,5	SF	1,555	1,280		1,62			
P6.1	2,0	SF	1,524	0,910		1,58			
P6.2	2,0	SF	1,507	0,860	0,89	1,61	1,58	38,5	-27,1
P6.3	2,0	SF	1,498	0,890		1,56			
P7.1	2,0	LF	1,581	0,790		1,55			
P7.2	2,0	LF	1,367	1,380	1,34	1,45	1,48	109,4	-32,0
P7.3	2,0	LF	1,389	1,850		1,43			
(*) elastic-brittle behaviour of the specimen									
(**) Invalid test - samples used for testing the press machine									

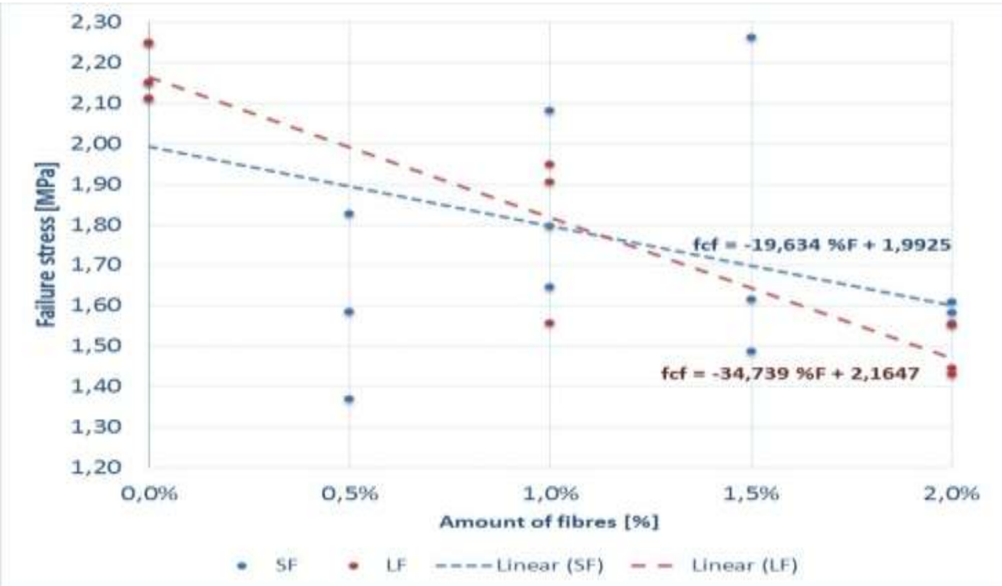

Figure14. *Results of bending tests: failure stress vs. percentage of fibres*

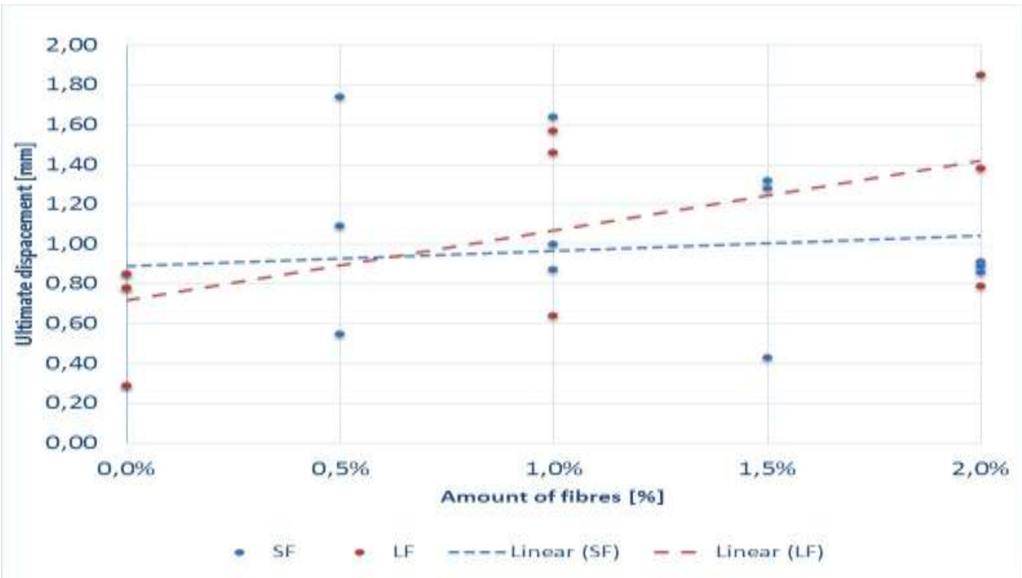

Figure15. *Results of bending tests: ultimate displacement vs. percentage of fibres*

After performing bending tests, half samples derived from breakage of original specimens have been reused for compression testing. The UNI standard stipulates that these parts must be joined each other with a concrete paste, manufactured by using a 32.5type cement mixed with water (ratio 1: 3) andhaving thickness of 1 cm, to form brick sandwiches. By adopting this manufacturing process, it has been observed an abnormal behaviour of samples, since the concrete layer has resulted much more resistant than raw earth under compression axial loads. In fact, samples have collapsed due to crushing of the raw earth half brick above or below the concrete layer. The collapse has been characterised by nearly vertical cracks and earth cleavage. As a consequence, as connecting layer among half samples, it has been used a mixtureweaker than that previously employed. This mixture has been made of cement with raw earth and clay residues in the ratio 1:1, which have been mixed with water in a ratio 1:6 in relation to cement. This has allowed for the involvementin the failure mechanism of the bonding layer between brick samples. The new samples obtained (Fig. 16) have been left to mature for one week under standard environmental conditions.

Figure16. *Adobe specimens for compression tests*

Compression tests have been carried out with the same testing machine previously used, taking care to grasp fully the sample with respect to the overlying loading plate(Fig.17).

Figure17. *Execution of the compression test and failure of the specimen*

In the experimental tests the failure type of specimens and the corresponding strength and stress values have been recorded. Unlike what happens with concrete specimens, which undergo a bipyramid type collapse, the adobe bricks have shown cracks orthogonal to their base surface, with typical crushing mechanisms. Moreover, it has been also noticed that, at the test end, the uplift of the load dimmer has produced the complete crumble of bricks, which have lost cohesion.Examining the values of the compression failure tests (Table 6), a gradual increase of the collapse stress, with a maximum value of + 38.3%, has been observed for fibre-reinforced specimens in comparison to that of the unreinforced specimen P1_A25_C0.0.

Analysing separately data from tests on short fibres (P2_A25_C0.5_SF, P3_A25_C1.0_SF, P5_A25_C1.5_SF and P6_A25_C2.0_SF) and long fibres (P4_A25_C1.0_LF and P7_A25_C2.0_LF), a gradual improvement of the compression strength for specimens with short fibres has been recorded (Fig. 18). Such a result can be explained from the microscopic point of view and it is linked to the crystalline structure of clays. In fact, the presence of hemp "flakes" probably interfere with the natural slip of clay layers, creating a kind of internal nailing that increases the mechanical strength. However, from performed tests, it is not clear whether fibres produce a confining effect analogous to that exerted by the most common synthetic fibres.About long fibres, it is noted that, unlike the behaviour of mixtures with short fibres, the increase of their percentage has provided a reduction of the mechanical resistances of bricks up to 9.9% for the specimen P7_A25_C2.0_LF.

Table6. *Results of compression tests*

Specimen acronym	Amount of hemp fibres [%]	Fibre type	F [kN]	W_{ul} [mm]	f_{cf} [MPa]	$f_{cf,m}$ [MPa]	Δf_{cf} [%]
P0.1	-	-	16,706	5,95	1,305	-	-
P0.2	-	-	21,385	7,56	1,656		-
P0.3	-	-	20,045	6,85	1,588		-
P1.1	-	-	16,706	5,95	1,339	1,56	-
P1.2	-	-	21,385	7,56	1,699		
P1.3	-	-	20,045	6,85	1,629		
P2.1	0,5	SF	18,002	6,39	1,436	1,37	-12,2
P2.2	0,5	SF	13,911	5,32	1,110		
P2.3	0,5	SF	19,426	5,72	1,550		
P3.1	1,0	SF	22,143	6,37	1,783	1,79	14,9
P3.2	1,0	SF	19,828	3,76	1,596		
P3.3	1,0	SF	24,539	6,87	1,984		
P4.1	1,0	LF	16,474	5,20	1,291	1,44	-7,4
P4.2	1,0	LF	19,755	4,93	1,548		
P4.3	1,0	LF	19,244	7,55	1,482		
P5.1	1,5	SF	27,838	3,25	2,174	2,23	43,1
P5.2	1,5	SF	24,870	8,00	1,958		
P5.3	1,5	SF	32,935	5,11	2,547		
P6.1	2,0	SF	35,120	4,51	2,704	2,15	38,3
P6.2	2,0	SF	24,010	6,74	1,892		
P6.3	2,0	SF	24,020	7,14	1,857		
P7.1	2,0	LF	19,120	5,24	1,440	1,40	-9,9
P7.2	2,0	LF	15,492	7,11	1,204		
P7.3	2,0	LF	20,538	5,83	1,561		

Analysing also the displacement data (Table 7) and determining the value of the secant elastic modulus at the maximum force value (Fig. 19),it has been observed that, with the use of long fibres, the elastic modulus practically does not change with respect to that of raw earth specimens. Contrary, with "flakes" short fibres a gradual increase of the secant elastic modulus has been found. In particular, an increment of this modulus equal to 119.5%has been attained with a percentage of fibres of 1.5%.

Table7. *Analysis of the secant elastic modulus at the maximum force value*

Specimen acronym	Amount of hemp fibres[%]	Fibre type	W_{ul} [mm]	f_{cf} [MPa]	E_{el} [MPa]	$E_{el,m}$ [MPa]
P0.1	-	-	5,95	1,305	23,242	23,53
P0.2	-	-	7,56	1,656	22,775	
P0.3	-	-	6,85	1,588	24,569	
P1.1	-	-	5,950	1,339	24,747	25,21
P1.2	-	-	7,560	1,699	24,716	
P1.3	-	-	6,850	1,629	26,159	
P2.1	0,5	SF	6,390	1,436	24,273	25,35
P2.2	0,5	SF	5,320	1,110	22,530	
P2.3	0,5	SF	5,720	1,550	29,261	
P3.1	1,0	SF	6,370	1,783	30,787	36,51
P3.2	1,0	SF	3,760	1,596	47,554	
P3.3	1,0	SF	6,870	1,984	31,196	
P4.1	1,0	LF	5,200	1,291	26,814	27,99
P4.2	1,0	LF	4,930	1,548	35,172	

P4.3	1,0	LF	7,550	1,482	21,982	
P5.1	1,5	SF	3,250	2,174	74,905	52,39
P5.2	1,5	SF	8,000	1,958	26,440	
P5.3	1,5	SF	5,110	2,547	55,822	
P6.1	2,0	SF	4,510	2,704	67,156	42,58
P6.2	2,0	SF	6,740	1,892	31,440	
P6.3	2,0	SF	7,140	1,857	29,137	
P7.1	2,0	LF	5,240	1,440	31,329	26,76
P7.2	2,0	LF	7,110	1,204	18,973	
P7.3	2,0	LF	5,830	1,561	29,981	

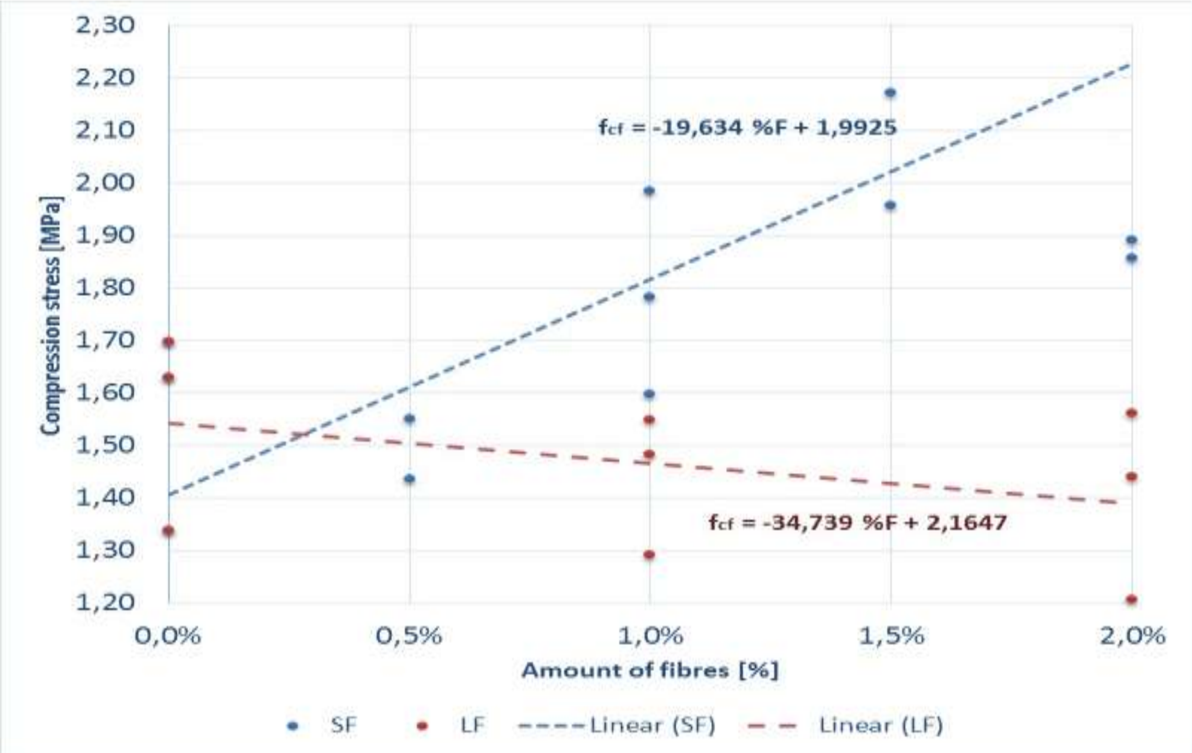

Figure18. *Compression tests: ultimate strains trend vs. percentage of fibres*

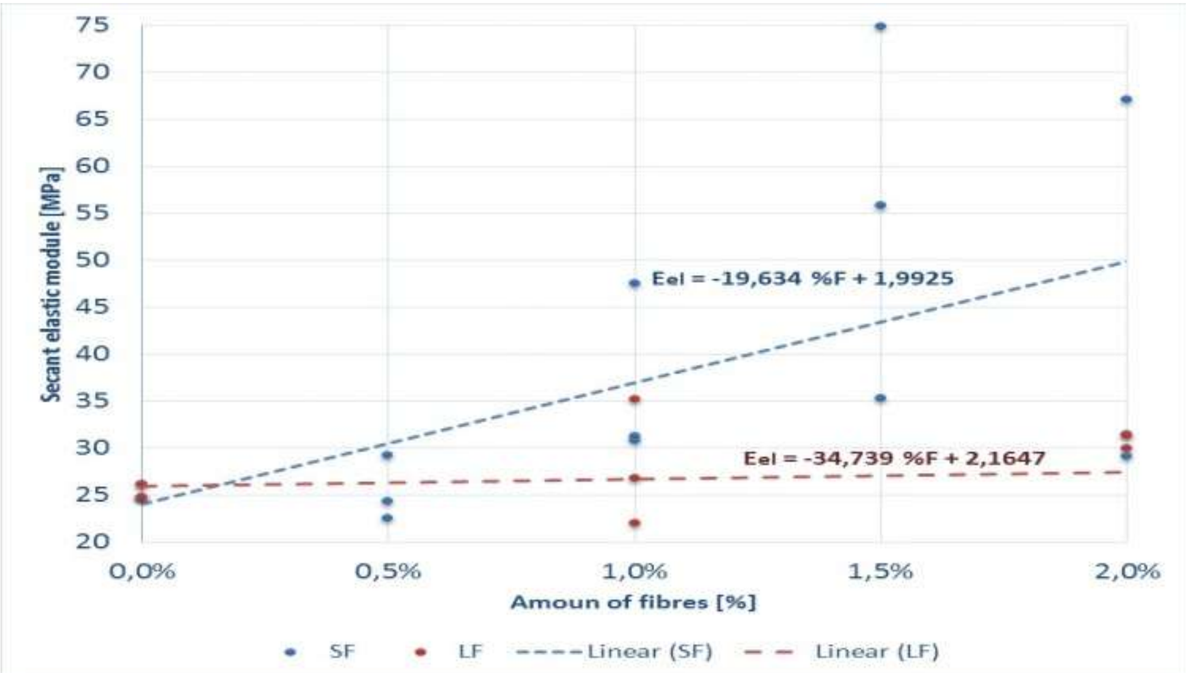

Figure19. *Compression tests: secant elastic modulus vs. percentage of fibres*

CONCLUSIONS

With the aim of rediscovering, in a modern way, techniques that are no longer used but that could be used in the next future in order to recover and protect existing historical heritage, the experimentation herein presented aims at assessing the improvement of properties of raw earth bricks thanks to the innovative use of hemp fibres. The used adobe samples were packed by using raw earth, predominantly made oflime-free clay soil free from vegetable humus, water, having a fix weight percentage of 25% based on the Atterberg limits, and hemp fibres, with weight percentages ranging from 0.5% to 2%. In particular, the adobe bricks were manufactured witheither short fibres, having lengths between 0.5 and 1.0 cm, or long fibres, resulting from hemp combing, having lengths between 1.0 and 2.0 cm. The adobe bricks were hand-manufactured into timber formworks, where the reinforced ground was before put in subsequent layers and then constipated. The seasoninghad a duration of 28 natural and consecutive days. After about seven days, the adobe bricks assumed a good consistency so that they did not lose their configuration. Therefore, they were disarmed and placed in a dry and ventilated room for the subsequent seasoning. By periodically evaluating the change in weight of bricks, it was seen that, after about four weeks, they reached a suitable degree of dryness, showing an equilibrium balance with the outside environment. It was observed that adobe bricks, due to the shrinkage produced by the water evaporation, had significant lengths reduction, with an average value of 1.7cm both on the long side (L = 25cm) and on transverse one (L = 12cm). In general, it was observed that the presence of fibres tended to reduce much more the shrinkage phenomena as the fibre percentage increased. After the seasoning phase, bending and compression mechanical tests were carried out. In bending tests, a gradual reduction of tensile stress was observed, with a slow, but continuous, increase of ultimate displacements and the transition from a brittle behaviour to a ductile one. Since the fibres were placed in the matrix in a chaotic way, a dispersion of results was observed with the increase of the fibre percentage. For manufacturing of specimens to be subjected to bending tests, some corrective measures with respect to the UNI standard provisions for normal bricks were taken. As a result of the tests, it was noticed a remarkable increase of the mechanical performance of reinforced adobe bricks both in terms of compression resistances and elastic modulus. Moreover, short fibres showed performances greater than those of long fibres. The increase of the fibre-reinforced brick resistance was certainly attributable to the presence of hemp fibres, which, at a microscopic level, hindered or prevented horizontal slips among clay sub layers, performing a sort of nailing function among them. This behaviour justified also the observed crushing failure type. Finally, the presence of short fibres dispersed within the raw earth matrix helped to improve the mechanical performance of the base material, making it more suitable for restoring existing heritage assets through a fully sustainable intervention. However, further studies and analyses, even at a microscopic level, will be required to validate the achieved results.

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