First International Conference on Bio-based Building Materials

June 22nd - 24th 2015
Clermont-Ferrand, France

PERFORMANCE OF CLAY-STRAW PLASTERS CONTAINING NATURAL ADDITIVES

A. Navarro[1], M. Palumbo[1*], B. Gonzalez[1], A.M. Lacasta[1]

[1]Barcelona School of Building Construction, Universitat Politècnica de Catalunya, Av. Dr. Marañon 44, 08028 Barcelona, Spain.

*Corresponding author; e-mail address: mariana.palumbo@upc.edu

Abstract

Earth constructions need to be protected from severe weather conditions in order to reduce their maintenance requirements. Constructive solutions such as overhanging elements play an important role to this intend, but plasters are also crucial. Traditionally, lime and clay plasters are considered to be the most adequate for such structures due to their water vapour permeability and suitable hygrothermal behaviour. The present paper show preliminary results of an ongoing research on clay plasters that may be used to protect earth walls. Barley straw shredded to different particle sizes and natural additives i.e. casein, linseed oil and alginate are added in different proportions to the clay plasters. The hygrothermal performance and durability of the different specimens is evaluated both in laboratory and on-site tests. Water vapour permeability and thermal conductivity are measured in order to evaluate the hygrothermal behaviour of the samples. Erosion and water uptake are also monitored with the aim to investigate the applicability and durability of the different formulations. Fibre size seem to be a driven factor in dimensional stability of the clay plaster, which is reduced in samples with higher fibre sizes. Among the treatments analysed, linseed oil in bulk application yield the best results as significantly increases the resistance to water erosion, reducing the penetration depth about a 60% with respect to the untreated clay plaster. Moreover, it seems to reduce the thermal conductivity of the material. Further work should be done in order to optimise the formulations and confirm these findings.

Keywords:

Clay plaster, barley straw, water uptake, durability

1 INTRODUCTION

In the last years, research on earthen architecture has gained interest mainly due to the low environmental impact associated to this construction material but also as a result of a major concern on the architectural heritage, its renovation and conservation. However, clay plasters have not been studied as much as other earthen construction techniques. Thus, a great part of the present know-how on clay plasters is still based on an empirical knowledge. Such knowledge is handled down through generations in the form of recipes the accuracy of which may vary from case to case.

Nowadays, a large number of such recipes are collected in informative publications, aimed primarily at applicators and/or self-builders [Moréteau 2012]. Moreover, some companies such as Ecoclay, Embarro, Argilus, Akterre, Ecolodeve, The Clay Paster Company among others, have adapted or created their own recipes (adding or not stabilizers) and commercialize them in the form of ready to apply mixtures. However, due to the scarcity of scientific research, any standardised methodology for characterization, comparison and optimization of clay plasters is stablished to date. In this regards, Craterre Laboratory, at the University of Grenoble, in France, is working on the compilation and analysis of some of these recipes [Ashour 2010a]. The results of this research have not been published at the time of this study.

Besides, many of the inherited recipes incorporate vegetable fibres which, as in the case of composites with organic resins matrices, prevent cracking due to drying retraction [Sobral 1990, Ashour 2010, Müssig 2010]. Ashour et. al. [Ashour 2010a, Ashour 2010b, Ashour 2011] characterized and compared ten different formulations of clay plasters incorporating vegetable fibres (i.e. wheat and barley straw and wood chips). Their results show that, under similar environmental conditions, the moisture content of plasters with wheat straw is higher than on the other cases. They determined that fibres have a positive effect on the tensile strength and the ductility of the material.

In the present work clay-straw plasters are analysed. In the first place, the effect of both the amount and fibre size of the straw is investigated. Thereafter, three different waterproofing products are incorporated in one of the previously tested formulations and their hygrothermal behaviour is compared with non-treated clay-straw plasters. Moreover, as no standardised methodology specific for clay plasters is available, the possibility to adopt testing methodologies normally used for other materials for their analysis is investigated. In addition, laboratory tests are compared with on-site observations, as clay plasters are applied on an existing rammed earth wall.

2 MATERIALS

The plasters under consideration are mixtures of clay and barley straw. The clay is classified as a clayey sand (SC) of medium plasticity following the Unified Soil Classification System. It has a maximum aggregate size of 12 mm and a bulk density of 1.30 g/cm^3 (Fig. 1).

Fig.1: Different particle size fractions of the clayey sand used for the plasters.

In the first part of this study the aim is to determine the effect that the amount and fibre size of the straw have on the final properties of the plasters. To this intend barley straw is chopped and sieved in order to obtain fractions of fibres of 1 and 2 mm diametre. These fractions are incorporated to the clay separately or combined (in mixtures of 70% of one size and 30% of the other and vice versa) in order to form the plasters. Moreover, three volumes of straw have been considered: 50%, 40% and 30% with respect to the total volume. These percentages correspond to straw masses (per 100g of earth) outlined in Tab. 1.

Tab. 1: Straw mass used in each clay-straw plaster, per 100 g of earth.

Straw mass (g)			
Particle size (mm)	**Volume straw percentage**		
	30%	**40%**	**50%**
2	2,18	3,05	4,35
1	2,74	3,83	5,47
2+1 (70%/30%)	2,35	3,28	4,69
2+1 (30%/70%)	2,57	3,60	5,13

The appropriate workability of the plasters is achieved by adding a certain amount of water that depends on the volume and fibre size of the incorporated straw. Thus, the amount of water added to the plasters is specific for each formulation and is determined by a consistency test following the EN 1015-3:1999/A1:2004 standard. The water is adjusted in order to achieve a stem flow diameter of 105 ±5 mm which correspond to a soft consistency.

In the second part of this analysis, one of the previously analysed the formulation (50%; 70-30) is aggregated with three different products of natural origin in order to improve its behaviour in front of water. The water-repellents incorporated are of different nature: a protein (casein), a polysaccharide (alginate) and a lipid (linseed oil). They are incorporated in the mixture (bulk application) or applied superficially as a coating. The amount of additives to be incorporated is chosen on the basis of previous work [Milla 2013], [García 2013], [Gubianas 2014], [Cayetano 2014]. Casein is mixed with acetic acid and sodium bicarbonate in equal parts and added to the clay plaster in a proportion of 5% of the clay-straw plaster mass. Alginate is mixed with water to form a 3% solution and added in a proportion of 2% of the clay-straw plaster mass. Finally linseed oil is directly added to the clay plaster in a proportion of 2% in mass.

3 EXPERIMENTAL DESING

In this work laboratory tests are combined with on-site observations. Laboratory tests allow the analysis of the physic-mechanical properties of the plasters: linear shrinkage due to drying, flexural strength and water erosion; and of their hygrothermal behaviour: vapour diffusivity resistance factor, equilibrium moisture content and thermal conductivity and diffusivity. The aim being to evaluate the performance of the different water-repellents, the water erosion test is undertaken only on treated specimens. For the on-site tests, clay-straw plasters are applied on the prototype Casa S-Low. Casa S-Low is an existing prototype built as part of a previous research [Allepuz 2013], [González 2013]. The prototype is built at the UPC Campus in Barcelona using a balloon-frame system made of wood and an envelope of 500 mm with manually rammed earth walls with an interior finishing of OSB boards. The clay-straw plasters are applied on the west wall and cover a surface of 40 x 60 cm^2 each. On-site observations are contrasted with laboratory results on shrinkage. Moreover, a liquid water absorption test is performed in order to complement the data on the durability of the plasters.

As no standardised methodology specific for clay plasters is stablished to date, testing methodologies normally used for other materials are adopted. The methodologies that are found to be more adequate are specific to masonry mortars, to compressed earth blocks (CEB) and to terrazzo tiles. In addition, a standardised work protocol is created in order to determine the behaviour in front of moisture of the plasters.

3.1 Linear shrinkage due to drying

The determination of the linear shrinkage is made following the UNE 83831:2010 EX standard. Three prismatic specimens of 25 x 25 x 290 mm are prepared for each of the different formulations. The specimens are maintained at room stable conditions (20ºC and 50% relative humidity) and measured periodically with the aid of a calliper until a dimensional variation lower than 0.01mm is registered.

3.2 Flexural strength

Flexural strength and deformation modulus of the clay plasters are determined following the EN 1015-11:1999 standard. Three replicates of 40 x 40 x 160 mm of each formulation are produced.

3.3 Water erosion test

The on-site erosion test is performed following the UNE 41410:2008 standard specific for compressed earth blocks (CEB). However, 1-second intervals dripping water is used instead of continuous water flow due to the expected lower resistance of the plasters.

3.4 Equilibrium moisture content

The equilibrium moisture content of the different formulations is determined at 20ºC and 30, 60 and 80% relative humidity following a standardised work protocol. The environmental conditions are controlled with the aid of a climatic chamber. Cylindrical test specimens of 15 mm width and 65 mm diameter are produced for this test. Specimens are oven dried (60ºC, 24hs) before the test and the equilibrium moisture content is gravimetrically determined weighting the samples each 24h until a mass change lower than 0.1% is registered.

3.5 Water vapour diffusion resistance factor

The water vapour diffusion resistance factor "µ" is determined using the wet cup method (EN 1015-19:1998). To this end, triplicate samples of 40 x 40 x 10 mm are produced and placed on the top of a cup containing a saturated solution of Na_2SO_4 which regulates the air humidity at 85%. The cups are placed in a climatic chamber set at 20ºC and 58% relative humidity. Specimens are periodically weight during a week to determine the rate of mass loss.

3.6 On-site liquid water permeability test

The potential durability of the plasters is directly related to its behaviour in front of water. Liquid water permeability test gives an indication on the affection of the material when it is in contact with liquid water. It is determined following the recommendation II.4, RILEM. Once the plasters are completely dried a Karsten tube is glued with silicone to the render. The tub is filled with water and the rate of water absorption is controlled.

3.7 Thermal conductivity and diffusivity

Thermal conductivity and Thermal diffusivity are determined by a transient technique, with a Quickline™-30 instrument, using a surface probe. The method is based on the ASTM D5930 standard.

4 RESULTS

4.1 Linear shrinkage due to drying

Dimensional stability of clay plasters is determined once the sample, maintained in room stable conditions, has reached constant dimensions. Tab. 2 summarizes the percentage of linear shrinkage obtained for each clay plaster formulation.

The most relevant result is that the addition of straw is an effective way to reduce shrinkage produced in plain clay plasters (3.74%). No important differences are obtained for the various formulations, but the general tendency is that shrinkage is lower for higher amount of straw and also is lower for longer fibre length. It's worth noting that, although these laboratory data do not show important differences, the samples placed in the S-Low prototype (40 x 60 cm^2) and thus exposed to weather conditions revealed that the straw mixture 70%/30% in a dosage of 50% is the one that experience the lowest shrinkage.

Tab. 2: Results of the shrinkage test for the different formulations expressed in percentages.

Shrinkage (%)			
Particle size (mm)	**Volume straw percentage**		
	30%	**40%**	**50%**
2	1.41	1.33	1.34
1	1.84	1.92	1.73
2+1 (70%/30%)	1.98	2.29	1.62
2+1 (30%/70%)	2.02	1.74	1.55
Only earth		3.74	

4.2 Flexural strength

Flexural strength and deformation modulus are presented in Tab.3.

Tab. 3: Flexural strength (σ_M) and deformation modulus (E) for the different clay plasters.

	σ_M (MPa)			***E* (MPa)**		
Particle size (mm)	**Volume straw percentage**			**Volume straw percentage**		
	30%	**40%**	**50%**	**30%**	**40%**	**50%**
2	0.65	0.49	0.54	107.0	67.4	45.7
1	0.67	0.55	0.70	100.4	59.5	91.3
2+1 (70%/30%)	0.70	0.70	0.66	100.9	96.6	63.8
2+1 (30%/70%)	0.68	0.72	0.69	93.4	93.4	70.8
Only earth		0.89			170.0	

Compared to plain clay plasters, plasters containing straw fibres show a slightly decreased flexural resistance and a lower deformation modulus.

The flexural strength of clay plasters containing straw is between 20% and 45% lower while their deformation modulus is between 37% and 73% lower.

No significant differences are obtained in flexural strength of the different formulations of clay-straw plasters. Nevertheless, the deformation modulus is reduced when the amount and size of the fibres increases. Thus, results indicate that, in general, mechanical properties are better for high percentage and longer fibres. The reduction achieved in deformation modulus is a very important fact, because it is related with the ability of the material to deform without rupture when subjected to tensions.

4.3 On-site erosion test

The results of the on-site water erosion test are shown in Fig. 2. It is noticeable that alginate and linseed oil applied as coatings are the treatments that better protect the clay plaster against water erosion. Contrarily, alginate in bulk application is the product that has the worst performance. Results for alginate differ significantly depending on the kind of application, probably due to the fact that alginate forms a film when applied as a coating that somewhat protects the clay-straw plaster below. However such film is thin and tends to crack after certain time of exposure to environmental conditions. Water erosion in samples containing casein and linseed oil in bulk present a better behaviour than untreated samples. In both cases the erosion profundity is reduced more than 50%, although linseed oil seem to have a greater protective effect than casein against erosion in both kinds of applications. It should be noted that casein applied as a coating forms clumps that easily desegregate from the surface, which explains that the erosion depth of these samples is similar to untreated ones.

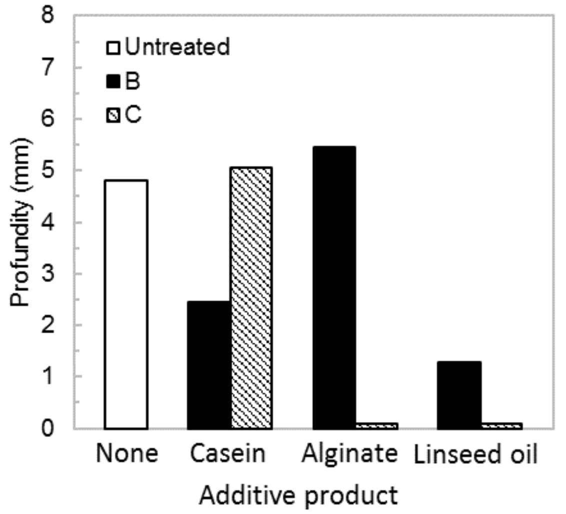

Fig. 2: Water erosion comparative for different clay plaster formulations.

4.4 Equilibrium moisture content

The equilibrium moisture content is expected to depend mainly on the straw mass and not on the fibre size or on the fact that different sizes were combined. Results for the two extreme volume straw percentages (50% and 30%) and the two single fibre lengths are shown in Fig. 3.

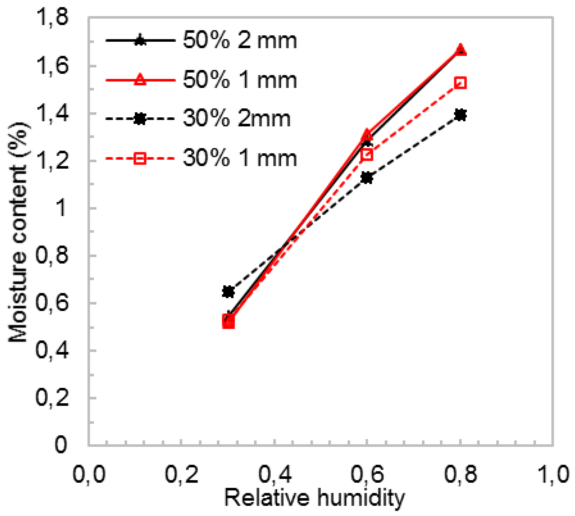

Fig. 3: Equilibrium moisture content at different air relative humidities for clay plasters incorporating a single fibre size.

Results indicate that samples with higher volume straw percentage (50%) absorb more water vapour than the others. For each straw volume, the shorter fibres also absorb more water vapour than the longer ones. This is because a volume of shorter fibres has a higher mass than the same volume of longer fibres (see Tab. 1). Therefore, the samples made with 1 mm fibres actually contain a major quantity of straw (in mass).

4.5 Water vapour diffusion resistance factor

Water vapour diffusion resistance factor (μ) is evaluated for untreated and waterproof clay plasters. In all the cases, the samples are exposed to a relative humidity gap of 27%. Figs. 4-6 show the results.

In clay plasters formulated with one fibre size, a higher resistance is obtained for the samples with less fibre percentage and shorter fibre length. In other words, plasters with higher amounts of barley straw of larger sizes are more permeable to water vapour diffusion. In clay plasters with two combined fibre sizes, μ also increases with fibre percentage but no significant differences are observed caused by fibre length.

All the treatments reduce the water vapour permeability of the plasters, although this reduction is more noticeable for those samples treated with a linseed oil coating. Results are similar for either in bulk or as a coating treatments.

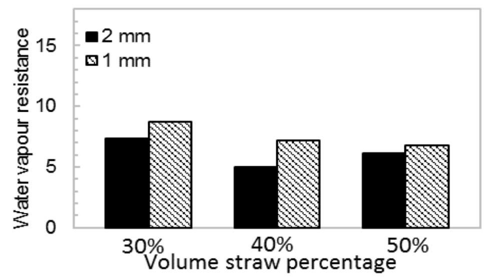

Fig. 4: Water vapour diffusion resistance factor of clay plasters with one fibre size.

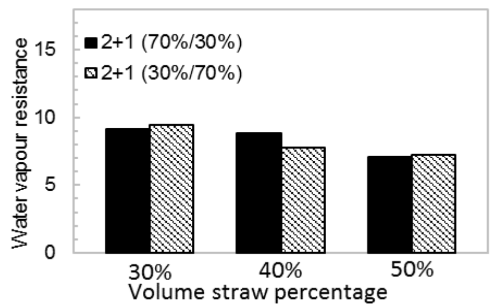

Fig. 5: Water vapour diffusion resistance factor of clay plasters with mixtures of two fibre size.

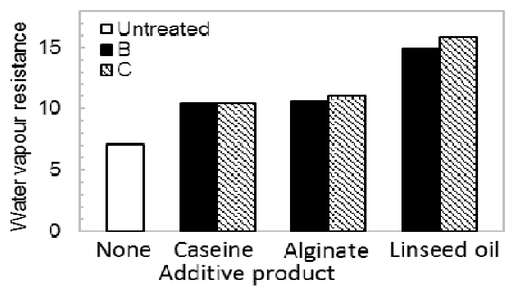

Fig. 6: Water vapour diffusion resistance factor of clay plasters with mixtures of two fibre sizes and waterproof treatments in bulk application (B) or applied as a coating (C).

4.6 On-site liquid water permeability test

The liquid water absorption velocities, obtained on-site with Karsten tubes are shown in Tabs. 4 and 5.

Tab. 4: Liquid water absorption velocities (ml/min), with Karsten tube for the different dosages.

Absorption velocity (ml/min)			
Particle size (mm)	**Volume straw percentage**		
	30%	**40%**	**50%**
2	0.08	0.08	0.08
1	0.08	0.09	0.10
2+1 (70%/30%)	0.10	0.10	0.08
2+1 (30%/70%)	0.11	0.09	0.10
Only earth		0.07	

Tab. 4 compares the results for the different dosages. The liquid water absorption velocity values are similar in all the cases and do not seem to be dependent on the fibre percentage nor their size. Regarding the behaviour of the samples treated with natural additives, Tab. 5 shows the results obtained with respect to the untreated sample. Casein, both applied in bulk and as a coating, and linseed oil in bulk do not change the absorption velocity. Alginate applied as coating causes that the clay plaster has the higher absorption velocity.

Tab. 5: Liquid water absorption velocities (ml/min) with Karsten tub for the clay plaster treated with natural products.

Treatment	Natural additive	Absorption velocity (ml/min)
None	**None**	0.08
Bulk	**Casein**	0.07
	Alginate	0.15
	Linseed oil	0.07
Coating	**Casein**	0.09
	Alginate	0.23
	Linseed oil	0.16

4.7 Thermal conductivity and diffusivity

The addition of fibres greatly reduces the thermal conductivity (λ) and therefore increases the thermal insulation. Tab. 6 shows that λ is lower when a higher amount of fibres is added. For the same amount, the conductivity is lower for longer fibres.

Comparing clay plasters with two fibre sizes, it is observed that the coating "2+1 (30%/70%)" has the best thermal performance since its conductivity is much lower, both for dosage 100% and 70%.

Thermal diffusivity is also a parameter of great interest as it is related to the thermal inertia. Clay plasters with a lower diffusivity have greater inertia and thus will contribute more to the thermal delay of the wall. Tab. 6 shows that, in general, samples with higher percentage of fibres, of longer size, lead to lower diffusivity values. Regarding the thermal behaviour of samples treated with natural additives (Tab. 7), it is observed that the addition of casein reduces the thermal conductivity only when it is applied as a coating. However, linseed oil and alginate are more effective when applied in bulk. No significant variations are obtained for the thermal diffusivity.

Tab. 6: Thermal conductivity (λ) and thermal diffusivity (α) of the different formulations.

	λ (W/mK)			**α (10^{-6} m²/s)**		
Particle size (mm)	**Volume straw percentage**			**Volume straw percentage**		
	30%	**40%**	**50%**	**30%**	**40%**	**50%**
2	0.84	0.57	0.42	1.21	0.40	0.48
1	0.73	0.72	0.45	1.17	0.99	1.05
2+1 (70%/30%)	0.78	0.52	0.52	0.63	0.51	0.51
2+1 (30%/70%)	0.77	0.59	0.50	0.61	0.51	0.62

Tab. 7: Thermal conductivity (λ) and thermal diffusivity (α) for the samples treated with natural additives.

Treatment	Natural additive	λ *(W/m k)*	α *(10^{-6} m²/s)*
None	**None**	0.45	0.51
Bulk	**Casein**	0.457	0.51
	Alginate	0.349	0.51
	Linseed oil	0.375	0.63
Coating	**Casein**	0.343	0.62
	Alginate	0.387	0.51
	Linseed oil	0.415	0.61

5 CONCLUSIONS

Several formulations of experimental clay plasters developed to protect earth walls are analysed. All of them are mixtures of clay and barley straw, in different percentages and for different fibre sizes. In general, significant improvements in physico-mechanical properties are obtained with the incorporation of barley straw. On one hand, as was expected, fibres increase the dimensional stability of the clay plaster. In this sense, it has been found that the use of long fibres, reduces the shrinkage of the plaster. On the other hand, barley straw, as a highly elastic material, tends to contribute to a better deformation in the clay plaster, thus improving the performance in relation to rupture. Accordingly, a lower deformation modulus have been obtained for samples with higher percentages of longer fibres. However, no significant differences have been observed on the flexural strength results.

As expected, samples with higher content of straw are the ones that absorb more water vapour. Equilibrium moisture content was higher for samples containing 1 mm fibres which is attributed to the fact that these samples contain a larger amount of fibres (in mass).

For samples containing longer fibres, it is obtained that the permeability to water vapour is higher and that the permeability to liquid water and thermal conductivity are lower (and therefore more suitable) than when shorter fibres are used.

For one specific mixture of clay with a combination of fibre sizes (70% of 2 mm and 30% of 1 mm) different natural waterproof products are tested. Although the tested treatments do not really work well as water repellents, they do have introduced some changes in the behaviour of the clay plaster. Among the treatments analysed, linseed oil in bulk application yield the best results as significantly increases the resistance to water erosion, reducing the penetration depth about a 60% with respect with the untreated clay plaster. Moreover, it seems to reduce the thermal conductivity of the clay-straw plaster. However, it does not prevent liquid water absorption appreciably and reduces the water vapour permeability of the material. Casein in bulk application also yield promising results and further work should be done to investigate the efficacy of these and other products at different dosages.

6 SUMMARY

This work addresses to the development of suitable materials to protect earth walls against severe environmental conditions. Preliminary but very promising results of an ongoing research on clay plasters obtained as mixtures of clay, barley straw and natural additives are presented here.

7 ACKNOWLEDGMENTS

The authors would like to thank to Generalitat de Catalunya for the quality accreditation given to the research group GICITED (2014 SGR 1298) and for the support under a PhD studentship FI-DGR. We also thank D. García, L. Mila, S. Cayetano and K. Ghazal for their help. The prototype used for the on-site measurements was conducted under the direction of the company Casa S_Low.

8 REFERENCES

[Allepuz 2013] Allepuz, L.; Poza, C.; Informe de las propiedades físicas y mecánicas de la casa S-Low. Barcelona: PFG, UPC, 2013.

[Ashour 2010a] Ashour, T.; Wieland, H.; Georg, H.; Bockisch, F.; et al; The influence of natural reinforcement fibres on insulation values of earth plaster for straw bale buildings. Materials and Design, December, 2010, Volume 31, Issue 10, Pages 4676-4685.

[Ashour 2010b] Ashour, T.; Wu, W.; The influence of natural reinforcement fibres on erosion properties of earth plaster materials for straw bale buildings. Journal of Building Appraisal, March, 2010, Volume 5, Issue 4, Pages 329-340.

[Ashour 2010c] Ashour, T.; Bahnasawey, A.; Wu, W.; Compressive strength of fibre reinforced earth plasters for straw bale buildings. Australian Journal of Agricultural Engineering, July, 2010, Volume 1, Issue 3, Pages 86, ISSN 1836-9448.

[Ashour 2011] Ashour, T.; Georg, H; Wu, W.; An experimental investigation on equilibrium moisture content of earth plaster with natural reinforcement fibres for straw bale buildings. Applied thermal engineering, February, 2011, Volume 31, Issue 2, Pages 293-303.

[Cayetano 2014] Cayetano, S; Ghazal, K; Estudio de revestimientos de tierra con fibras vegetales de cebada. Barcelona: PFG, UPC, 2014.

[García 2013] García, D; Estudio de revestimientos con fibras vegetales. Barcelona: PFG, UPC, 2013.

[González 2013] González, B.; Informe de las propiedades térmicas y mecánicas del sistema modular S-Low de construcción con estructura de madera y envolvente de tapia. Barcelona: PFG, UPC, 2013.

[Gubianas 2014] Gubianas, N.; Anàlisi de formulacions per aïllaments tèrmics elaborats amb residus vegetals i aglomerants orgànics. Barcelona: PFG, UPC, 2014.

[Milla 2013] Milla, L; Desarrollo y estudio de revestimientos con tierra y fibras vegetales a base de cebada y cascarilla de arroz. Barcelona: PFM, UPC, 2013.

[Moréteau 2012] Moréteau, S.; Enduits de terre crue. Terre vivante Editions, 2012. ISBN 978-2360980550.

[Müssig 2010] Müssig, J.; Industrial applications of natural fibres: Structure, properties and technical applications. Wiley & Sons, 2010. ISBN 978-0470695081.

[Sobral 1990] Sobral H.S.; Vegetable Plants and Their Fibres as Building Materials. Londres: Chapman and Hall, 1990. ISBN 978-0412392504.