COMPRESSIVE STRENGTH TESTING OF EARTHEN PLASTERS FOR STRAW BALE WALL APPLICATION

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ABSTRACT

Straw-bale construction is an emerging building method and many builders choose to plaster the straw bales with earthen plaster to reduce the embodied energy of the structure. A better understanding of the parameters affecting earthen plaster strength is essential for safe and effective use of this building technique. This study investigated the importance of initial plaster moisture content, drying time, clay content and, moisture content at the time of testing. Clayey silt soil, bagged ball clay and lime-cement are compared as plaster binders for straw-bale applications. Compressive testing was conducted on 50-mm plaster cubes and 100-mm by 200-mm plaster cylinders. It was found that as initial moisture content increased, strength and modulus of elasticity was unaffected for the earthen plaster. As the drying time increased between 10 days and 18 days, strength was unaffected but modulus of elasticity increased proportionally. As clay content increased, strength increased proportionally and stiffness was unaffected. As moisture content at the time of testing increased, both the strength and the stiffness decreased proportionally. Plaster made with soil was found to have greater strength than the plaster made with bagged clay or lime-cement plaster.

Introduction

In recent years the traditional practice of building plastered straw bale structures has seen a revival due to its economic and environmental benefits. As of 2004, over 50 permitted straw bale homes had been built in Ontario alone (OSBBC, 2004). This method of building originated in Nebraska in the late 19th century and a number of earthen rendered homes from the turn of the century are still lived in use. Load-bearing straw bale walls typically consist of a sandwich panel of stacked straw bales with plaster skins of Portland cement, lime, gypsum, clay, or a combination of these binders. Portland cement or lime-cement plasters are currently the most widely accepted, especially by building officials. However, the harmful environmental effects of cement and lime production have encouraged many environmentally conscious builders to consider earthen plasters.

Earthen plasters are typically mixed on-site and consist of local clay-rich soil, sand, water and chopped straw. They have been successfully used for centuries but are viewed with skepticism by many building officials. This is due, in part, to the lack of published research pertaining to the parameters that affect the strength of earthen plasters. Past research on earthen plasters has investigated parameters such as chopped straw content and sand content (Lerner et al. 2003; Ash et al. 2003). These tests have provided promising strength values as high as 2.00 MPa (Ash et al. 2003). These strength values are comparable to published values for Portland-cement plaster, ranging from 0.75 MPa to 1.98 MPa (Lerner et al. 2003; Vardy et al. 2005). However, some results are irreproducible due to a lack of proper soil analysis and there are many parameters yet to be investigated. A better understanding of how soil components and moisture content affect the strength of earthen plasters is essential to consistently building safe earthen rendered straw bale structures and allow for more widespread use of this environmentally friendly building material.

Experimental Materials and Methods

Earthen plasters were mixed using either clayey-silt soil or commercially available bagged clay, masonry sand, and water. The soil was excavated to build a foundation on a residential building site in Haliburton, Ontario and subsequently used to plaster the walls of a load-bearing straw-bale building. The bagged clay was Ball Clay #123, a fine grained hydrous aluminum silicate clay with high unfired strength produced by the HC Spinks Clay Company.

The soil was broken up by hand and a mechanical sieve analysis for particles larger than 0.075 mm in diameter was conducted. Hydrometer tests in accordance with ASTM D 422 (2002) were performed for particles less than 0.075 mm.

Table 1 is the testing matrix, which shows the preparation parameters of each batch of plaster. Standard cube and cylinder specimens were prepared for each batch. Soil and sand for each mixture had a volume ratio of 1 : 1.5 (1 : 2.4 by mass), typical proportions for straw bale applications. The exceptions to this were batches R1 with soil to sand ratio of 1 : 1 and batch R3 with soil to sand ratio 1 : 3. Table 2 shows the percent by mass clay contents obtained in batches R1, R2 and R3 and the corresponding plaster strengths.

For plasters M1 … M5, the initial moisture contents (M.C.) were varied from 0.126 to 0.146 by mass. These moisture contents represent the workable limits for straw bale application. The drying time was varied for plasters T1, T2, and T3. Ten days is the earliest that the plaster hardens. Straw-bale builders generally regard 14 days as the time to reach adequate strength. The third drying time, 18 days, was chosen for linearity. Moisture content at time of testing was varied with batches C1, C2 and, C3. These batches were allowed to dry, and then subjected to extreme heat, moisture, or laboratory air. This is intended to simulate plaster subjected to hot, dry weather or a heavy rainfall, with the laboratory air acting as the control environment. Batch C1 was placed in a moisture room with 100% relative humidity prior to testing. Batch C2 dried in a laboratory environment. Batch C3 was placed in a drying oven at 110° C prior to testing. Cubes were left in the oven or moisture room for 24 hours and cylinders for 48 hours to ensure complete drying or moisture penetration.

Batch S1 was made with packaged clay purchased from a local earth-brick manufacturer. Portland-cement and lime plaster cylinders and cubes (P1, P2 and, P3) were cast in accordance with ASTM C 39 (1996) and ASTM C 109 (1998) respectively. The proportions of masonry sand, hydrated lime and Portland-cement were equal to 4.5:1.25:0.25 for all three batches.

To prepare the earthen plasters, the soil or bagged clay (batch S1 only) was massed and mixed thoroughly with water. The contents of the mixing bucket were allowed to soak for approximately two hours. The sand was then added to the mix.

The cubes and cylinders were allowed to dry in a controlled temperature room with a low-speed fan to speed the drying process. The cubes and cylinders were removed from the molds after 4 days. All specimens continued to dry in the laboratory for 10 more days, except for batches T1, T3, C1 and, C3. Specimens from batch T1 were tested after only 10 days and specimens from batch T3 were tested after 18. After 14 days, specimens from batch C1 and C3 were placed in the moisture room and drying oven respectively. Cubes were tested 24 hours later and cylinders were tested 48 hours later.

The cubes and cylinders were loaded until failure at a rate of 0.485 mm/min using an Instron Testing Machine. Due to the relatively low strength of the plaster, soft cork pads were used to cap the cylinders.

Results

The ideal soil for mixing plaster for straw-bale application is predominantly clay-sized particles because they act as a binder for other particles. The hydrometer test on the earthen soil indicates that it consists of 69% silt, 27% clay and 4% sand and can be classified as a clayey silt. The hydrometer test on the bagged ball clay revealed that it contained approximately 80% clay-sized particles and 20% silt-sized particles. Although only 80% of the mass is clay-sized, a larger proportion is likely clay minerals, specifically hydrous aluminum silicate. It is unknown whether or not the clay-sized particles in the soils are clay minerals.

Figure 1 is a typical stress-strain curve for an earthen plaster. The response is similar to that for concrete and cement-lime plaster. At stresses up to 40% of the ultimate stress (in this case about 35 MPa), the response is fairly linear. In accordance with ASTM C 469 (2002), the modulus of elasticity was taken as the slope of the stress-strain curve at 40% of the ultimate stress of the cylinder. Beyond 35 MPa, the response becomes non-linear. The ultimate stress, defined as the strength of the plaster, occurs at 0.89 MPa. The ultimate strain is 0.005.

Table 3 summarizes the average strength results for the cube and cylinder tests and modulus results obtained from the cylinder tests. The strength and modulus for each batch is the average value obtained from the three cubes or cylinders tested. Generally, there is little difference in the strength values obtained from cubes or cylinders for the earthen plasters. However, for the cement-lime plasters (P1, P2, P3), the cube strengths are significantly greater than the cylinder strengths.

Figure 2 shows the variation in strength with moisture content for the earthen plaster. There is little relationship between the initial moisture content and the strength of the plaster. As indicated by the data in Table 3, the modulus of the plaster also did not vary significantly with initial moisture content. This contrasts with cement-lime plasters, for which the ratio of water to cementitious materials was a critical parameter for the strength of the plaster (Vardy et al. 2005). The reason for the lack of sensitivity of earthen plasters to initial moisture content may result from the loss of water from the plasters, which was observed in these tests as visible shrinkage of the cubes and cylinders.

Figure 3 shows the plaster compressive strength obtained at various drying times. Clearly, there is no significant change in strength in the plaster between 10 and 18 days of drying. In contrast, Figure 4 shows the plaster modulus obtained at various drying times. The results indicate a significant increase in modulus between 14 and 18 days of drying. The results for batch T1, T2, and T3 in Table 3 indicate that the average modulus increases 2.4 times between 14 and 18 days of drying. Although the relationship is linear on this timescale, further investigation is necessary to determine plaster behaviour before 10 days and after 18 days of drying time.

Figure 5 shows the effect of increasing clay content on the plaster compressive strength. Batches R1, R2, and R3 as well as the bagged clay batch S1 are shown. For the earthen plasters, strength increases linearly with clay content. The bagged clay, however, does not follow the same trend, and has a much lower strength than earthen plasters with similar clay content. The reason for these differences may be related to the vastly different gradations measured for the two types of soil. The bagged soil is 80% clay and 20% silt, while the earthen soil has 69% silt, 27% clay, and 4% sand. Further research is needed to identify the optimum soil gradation for earthen plasters. This has some important practical implications for builders using clay plasters, since the ideal is to use soil from the building site to reduce the energy needed to transport the building materials. Locally available soil may not have the optimum soil gradation to produce structural plasters.

Batches C1, C2, and C3 were dried in different environments prior to testing. This varied the moisture content of the plaster at the time of testing. The moisture content of each cube or cylinder was measured immediately after the compression test was complete. Figure 6 shows the drastic changes in moisture content and strength resulting from the different environments. Placing the plaster in a 110 ºC oven substantially reduced the moisture content and increased the strength. Leaving the plaster in a humid environment increased the moisture content and resulted in lower strength as opposed to a lab environment. This can be compared with the initial moisture content results of Figure 2, which indicated no relationship between initial moisture content and strength. This suggests that the range of initial moisture contents tested for batches M1,..,M5 did not result in significantly different final moisture contents. This is an area that needs further investigation. Furthermore, these results point to the critical importance of ensuring adequate moisture protection for the clay in building applications. In addition, the exposure of the plaster to hot temperatures during, for example, summer days, is likely to have a beneficial effect on the strength of the plaster.

Three batches of cement-lime plaster, P1, P2, and P3 were tested for comparison with the earthen and bagged clay plasters. The water to cementitious materials ratio (w/cm) ranged from 1.08 to 1.28. As the water to cementitious materials ratio increased, the compressive strength decreased. The results in Table 3 indicate that the average strength and elastic modulus increase as w/cm decrease, a trend noted by Vardy et al. (2005). Figure 11 compares the compressive cube strength of typical soil clay plaster (M3), bagged clay plaster (S1), and three batches of lime-cement plaster (P1, P2, P3). The average strength of the earthen plaster is slightly higher than the cement-lime plasters, and significantly greater than the bagged clay plaster. The average elastic modulus, given in Table 3, of the earthen plaster is 2086 MPa, which is significantly greater than the bagged clay plaster (1731 MPa) and the cement-lime plasters (395 MPa – 839 MPa). It is encouraging that earthen plaster can equal and even surpass lime-cement plaster in strength since earthen plaster has only a small fraction of the embodied energy of lime-cement products.

Summary and Conclusions

This study investigated the effect of moisture content, drying time, drying conditions, and clay content on the strength and elastic modulus of an earthen plaster. The plaster was mixed using soil consisting of 69% silt, 27% clay and 4% sand. The earthen plasters were also compared to a plaster mixed using a commercially available clay, and cement-lime plasters. The specific conclusions of this work are:

1) The stress-strain response of the earthen plaster was similar to that of concrete or cement-lime plaster.
2) The initial moisture content of the earthen plaster had a negligible effect on the strength and elastic modulus. This is in contrast to structural concrete or cement-lime plasters.
3) There is a negligible increase in compressive strength, but a significant increase in elastic modulus with 10 to 18 days of drying of an earthen plaster.
4) Increased clay content significantly increased the strength of the earthen plaster.
5) Placing the plaster in a 110 ºC oven substantially reduced the moisture content and increased the strength. Leaving the plaster in a humid environment increased the moisture content and resulted in lower strength as opposed to a lab environment.
6) The earthen plaster had higher strength and elastic modulus than typical cement-lime plasters used for straw-bale construction. The earthen plaster also had higher strength and elastic modulus than the plaster mixed with commercial clay.

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Table 1. Test matrix describing batch parameters.

Batch	Drying Time	Initial M.C.	Drying Conditions	Sand/Soil	Binder Type/Source
Moisture Content:					
M1	14 days	0.126	lab	1.5	Clay / Soil
M2	14 days	0.132	lab	1.5	Clay / Soil
M3	14 days	0.134	lab	1.5	Clay / Soil
M4	14 days	0.144	lab	1.5	Clay / Soil
M5	14 days	0.146	lab	1.5	Clay / Soil
Drying Time:					
Batch	**Drying Time**	**Initial M.C.**	**Drying Conditions**	**Sand/Soil**	**Binder Type/Source**
T1	10 days	0.14	lab	1.5	Clay / Soil
T2 (M3)	14 days	0.14	lab	1.5	Clay / Soil
T3	18 days	0.14	lab	1.5	Clay / Soil
Drying Conditions:					
Batch	**Drying Time**	**Initial M.C.**	**Drying Conditions**	**Sand/Soil**	**Binder Type/Source**
C1	14 days	0.14	moist room (24h/48h)	1.5	Clay / Soil
C2 (M3)	14 days	0.14	lab	1.5	Clay / Soil
C3	14 days	0.14	drying oven (24h/48h)	1.5	Clay / Soil
Sand:Soil Ratio					
Batch	**Drying Time**	**Initial M.C.**	**Drying Conditions**	**Sand/Soil**	**Binder Type/Source**
R1	14 days	0.14	lab	1.0	Clay / Soil
R2 (M3)	14 days	0.14	lab	1.5	Clay / Soil
R3	14 days	0.14	lab	3.0	Clay / Soil
Clay Source					
Batch	**Drying Time**	**Initial M.C.**	**Drying Conditions**	**Sand/Soil**	**Binder Type/Source**
S1	14 days	0.14	lab	3.0	Clay / Bagged
S2 (M3)	14 days	0.14	lab	1.5	Clay / Soil
Lime-cement plaster					
Batch	**Drying Time**	**W/C.M.**	**Drying Conditions**		**Binder Type/Source**
P1	28 days	1.08	first 7 days moist, lab		Cement-lime / Bagged
P2	28 days	1.18	first 7 days moist, lab		Cement-lime / Bagged
P3	28 days	1.28	first 7 days moist, lab		Cement-lime / Bagged

Table 2. Clay content for batches R1, R2 and, R3

Batch	Sand/Soil (by Vol.)	% Clay (by mass)
R1	1	10.3
R2	1.5	7.9
R3	3	4.6

Table 3. Summary of average compressive strengths and modulii of elasticity

Batch	Initial Moisture Content	Cube Strength (MPa)	Cylinder Strength (MPa)	Modulus (MPa)
M1	0.126	1.5	1.4	1672
M2	0.132	1.2	1.3	1431
M3	0.134	1.1	1.2	2086
M4	0.144	1.1	1.3	1827
M5	0.146	1.0	1.2	1811
Batch	Drying Time (d)	Cube Strength (MPa)	Cylinder Strength (MPa)	Modulus (MPa)
T1	10	0.9	0.8	890
T2	14	1.0	1.1	758
T3	18	1.0	1.1	1848
Batch	Drying Environment	Cube Strength (MPa)	Cylinder Strength (MPa)	Modulus (MPa)
C1	drying oven (110 C)	1.8	2.1	2285
C2	laboratory	1.0	1.1	758
C3	moisture room (100%RH)	0.7	0.9	562
Batch	Sand/Soil by volume	Cube Strength (MPa)	Cylinder Strength (MPa)	Modulus (MPa)
R1	1.0	1.5	1.5	2500
R2	1.5	1.0	1.1	758
R3	3.0	0.7	0.8	1787
Batch	Clay Source	Cube Strength (MPa)	Cylinder Strength (MPa)	Modulus (MPa)
S1	commercial bagged clay	0.8	0.9	1731
S2	clayey silt soil	1.0	1.1	758
Batch	Water/Cementitious Mat.	Cube Strength (MPa)	Cylinder Strength (MPa)	Modulus (MPa)
P1	1.08	1.1	0.8	443
P2	1.18	1.1	0.7	839
P3	1.28	0.9	0.7	395

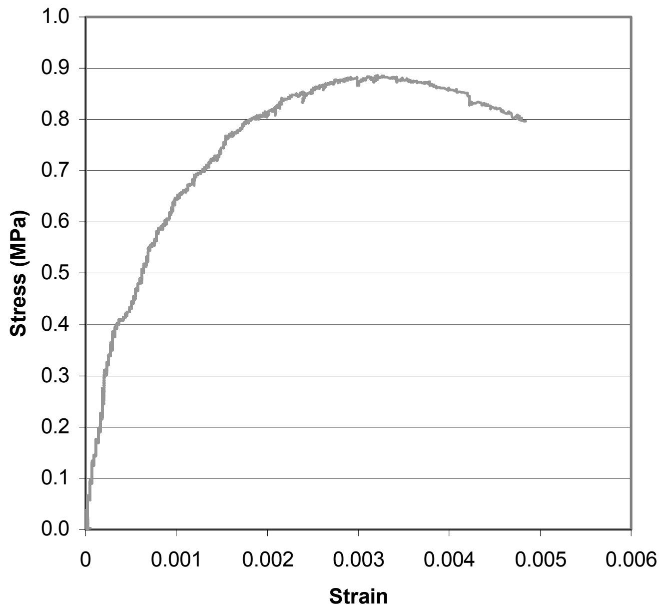

Figure 1 - Stress-strain response of cylinder A of batch C3 of earthen plaster.

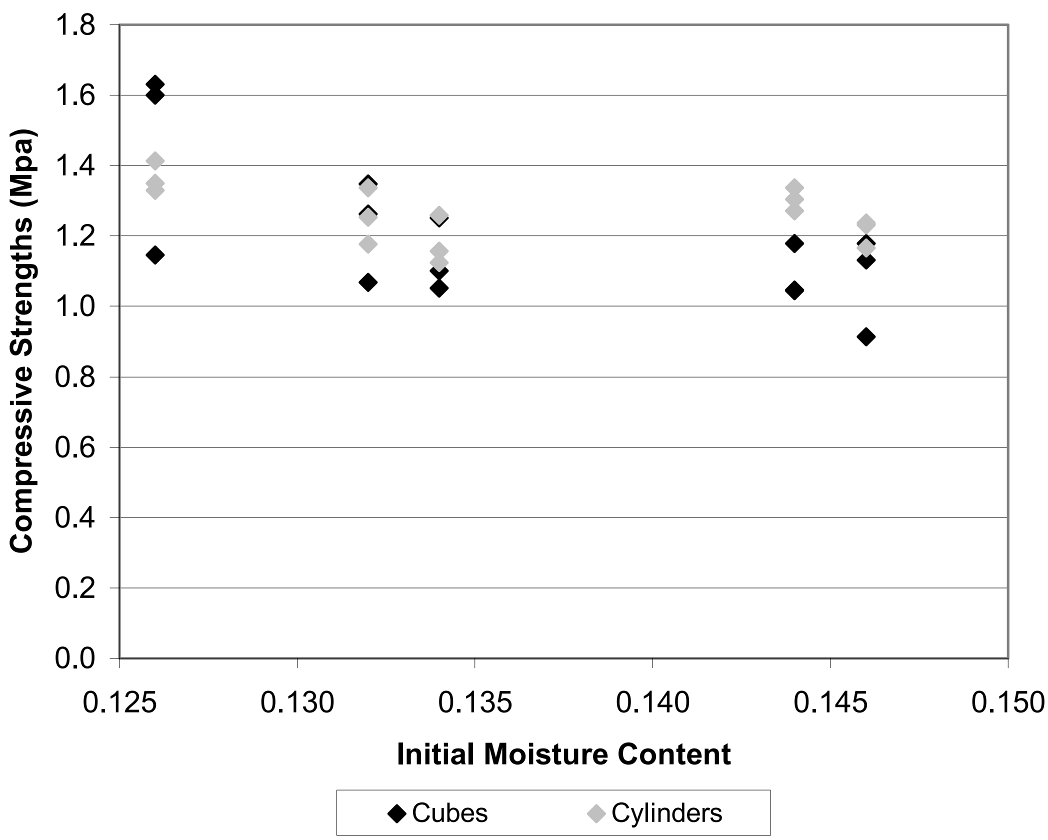

Figure 2. Relationship between initial moisture content and compressive strength of earthen plaster.

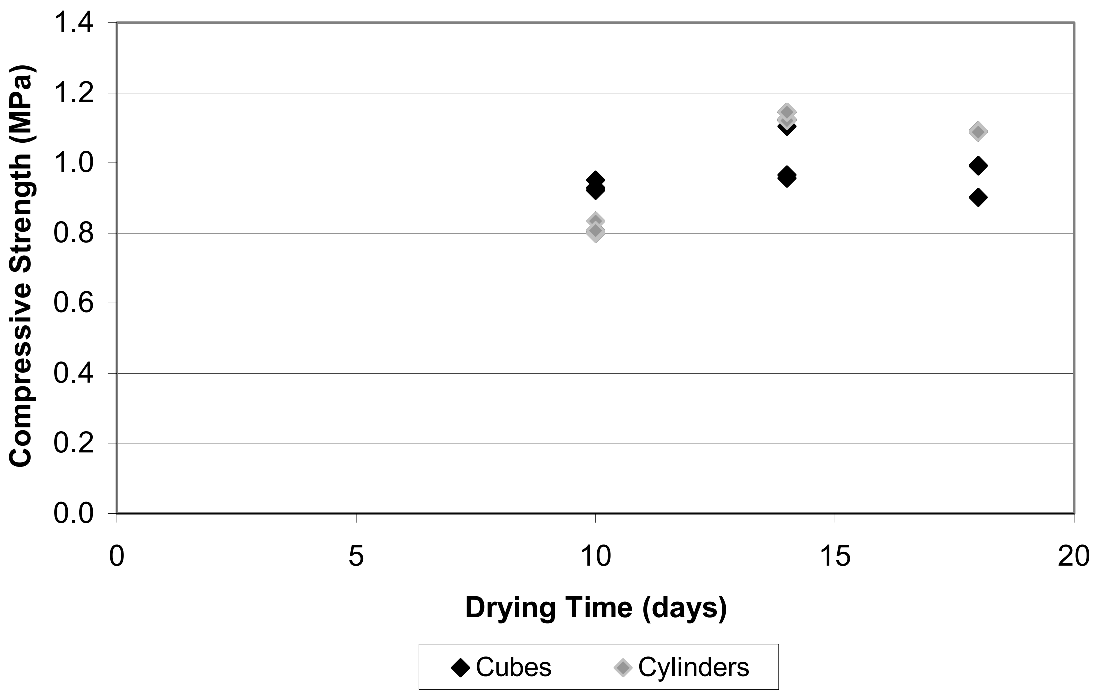

Figure 3. Relationship between drying time and the compressive strength of earthen plaster.

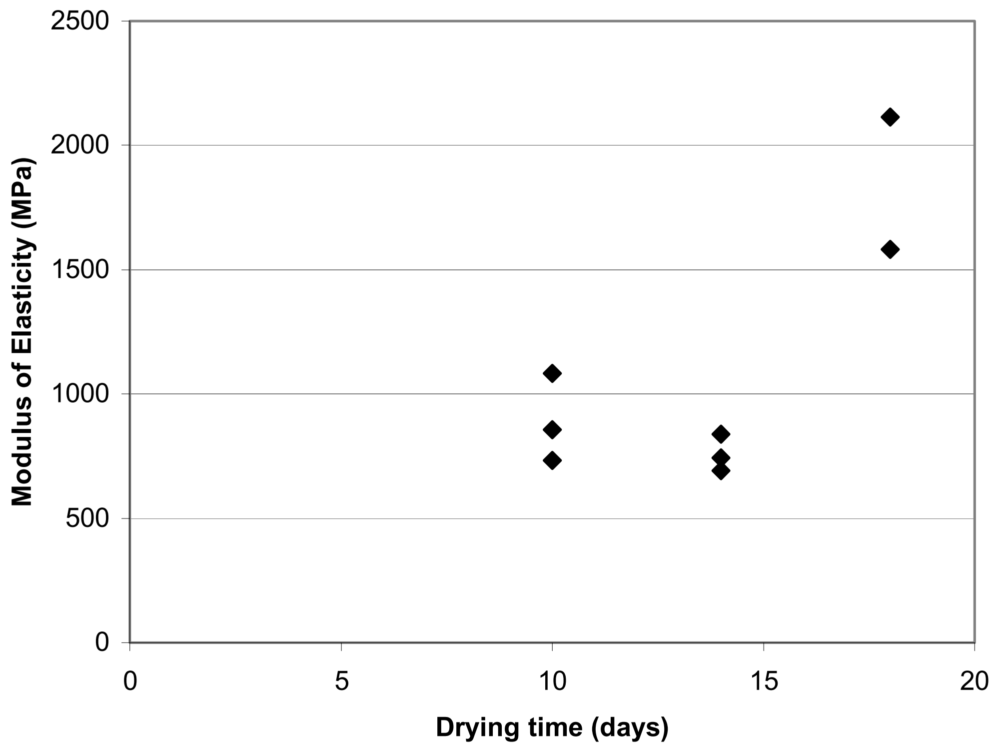

Figure 4. Time dependency of the modulus of elasticity of earthen plaster.

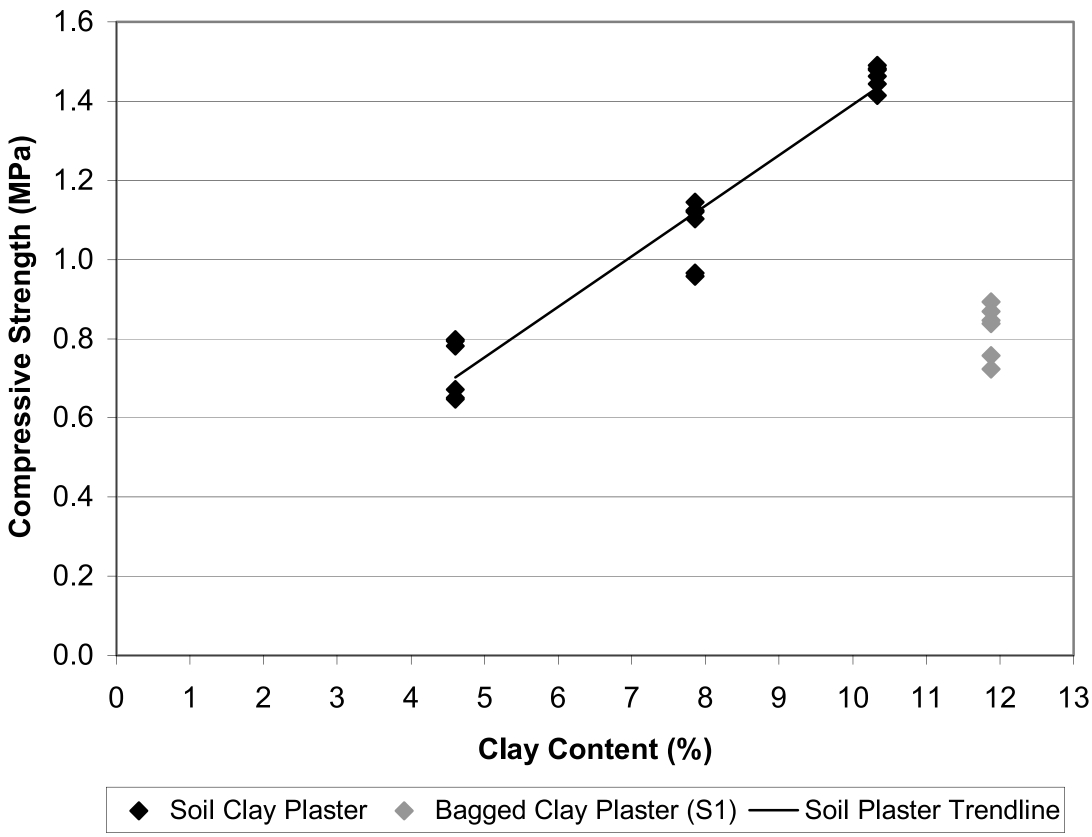

Figure 5. Clay content and strength, including the bagged clay plaster batch (S1).

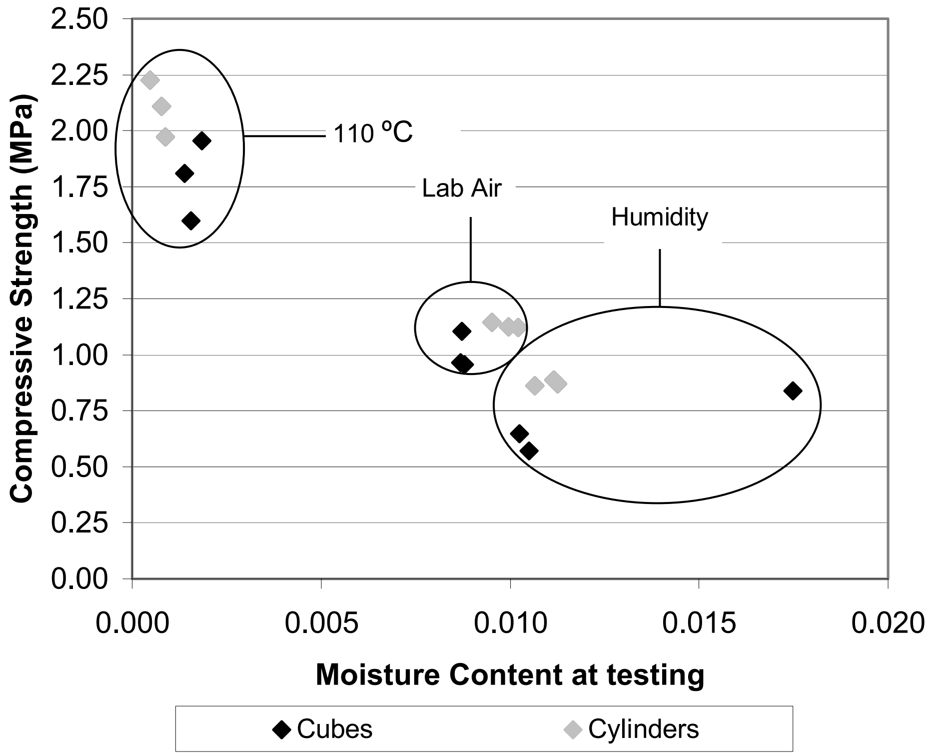

Figure 6. Relationship between the moisture content at time of testing and strength.

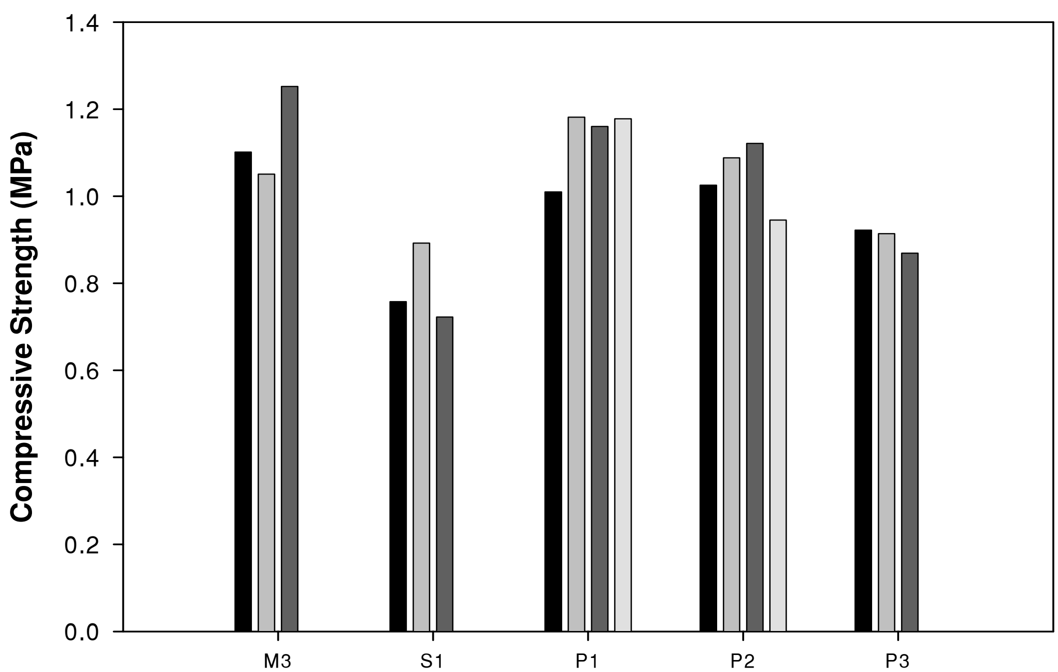

Figure 7. Compressive strength of plaster made with various binder types.