

MECHANICAL STRENGTH, MASS LOSS AND VOLUMETRIC CHANGES OF DRYING ADOBE MATRICES COMBINED WITH KAOLIN AND FINE SOIL PARTICLES

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Abstract

Earthen construction represents almost 30% of the housing in developing countries, partially because of its low cost compared to steel and concrete construction, and also because the raw materials are available almost everywhere. One of the biggest disadvantages of earthen materials is the lack of information and variety on their constitutive materials, specifically their soil type. This work addresses the physical and mechanical prop-
15 erties of adobe matrices containing different concentrations of kaolin, which is a specific type of clay, as well as different proportions of fine particles of the original soil of the adobe matrix. In this work, all adobe matrices were manufactured with a SM-SC soil obtained from Santiago, Chile. The mixtures tested had concentrations of 0, 10, 30, and 50% of kaolin and 0, 10, 20, and 30% fines of the original soil content. It is concluded that the
20 compressive strength of the studied earthen mixtures improves when kaolin is added to the mixture. The drying shrinkage of adobe matrices with kaolin compared to plain adobe matrices was reduced during the first days of age and stayed stable after that. This work shows that the inclusion of fines from the original soil (other than kaolin) did not significantly affect any of the studied properties. It also shows that the Unified Soil Classification System is not sufficient to characterize soils for adobe matrices, as the latter have different physical and me-
25 chanical performances.

Keywords: Earth blocks, kaolin, mechanical characteristics, physical changes, clay addition, adobe matrix.

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1. Introduction

Sustainable cities and communities are one of the United Nations seventeen sustainable development goals to be achieved by 2030. Currently, 3.5 billion people reside in cities, but projections estimate that this number will increase up to 5 billion by 2030, which creates a necessity for more housing development in the areas mentioned earlier [1]. In order to reach that increasing demand, but ensuring safe, economic, and sustainable housing development new techniques, new strategies and the use of new materials should be explored. The most common solutions available today are concrete, steel and wood (in a lower proportion compared to the first two). Concrete and steel, ensure safe and economic structures but contribute with approximately 12% (7% to 9% for the steel industry and 5% for only the cement industry approximately) to the global carbon dioxide emissions due to their manufacturing process [2,3]. Wood can comply with the requirements stated before, but the forests where wood is produced must be certified with a Forest certification which guarantees the origin of the production. There are also geographic zones, like the Middle East, where access to wood is scarce and most of the construction wood is imported [4]. Another suitable solution could be to return to earthen materials. This technique dates approximately from the agrarian revolution and used the straw residues from the crop fields to mix it with the soil and water [5].

Adobe blocks are a traditional building technique that consists of mixing a clayey soil with water and a type of fibre, usually straw, and depending on the location, sand and coarse aggregate can also be added to the mixture [6]. After mixing the components, the mixture is left to settle for a few days (between 20 to 30 days), adding water and mixing accordingly. After this period, the soil mixture is placed in moulds, cast and let dry in the sun, rotating the blocks to the adjacent side every 7 days approximately, to promote an even structure and drying of the block. After this process is completed, adobe blocks are ready to be used [6–9].

In terms of improving the mechanical strength of adobe blocks, an option is to add a binder to its matrix. Typically, a binder is an addition to earthen materials which improves the bonding of the soil used to produce them. Portland cement (PC) has been used as a binder for adobe blocks matrices [10–16], due to its ability to react with water and produce calcium silicate hydrate (CSH) [17]. The reaction of PC with water to create CSH occurs mainly in rich quartz clayey soils, as observed by Millogo *et al.* [12]. The use of PC has been already studied previously, proving its ability to increase the compressive strength of adobe blocks between 50% and 5900% [17]. The flexural strength of adobe was addressed using three-point bending tests, where adobe mixtures stabilized with PC increased its flexural strength at least by 50% with respect to plain adobe [17]. As PC proved to be a good binder for adobe blocks, augmenting its compressive and flexural strength, its high energy demand and the CO₂ emissions of its manufacturing process fails to keep adobe as a sustainable material [18]. Lastly but not least, adding PC to adobe mixture eliminates the possibility of recycling the soil.

Lime has also been used as a binder of adobe mixtures, enhancing the compressive strength of the latter [14,15]. Soils with higher plasticity indices (>15%) and also higher clay content [17] have been recorded to react better with lime, due to pozzolanic reactions occurring between them. However, Millogo *et al.* [19]

observed that CSH is mainly obtained in adobe blocks, by the interaction of lime and fine quartz grains. The use of lime as a binder has been studied by [14,15,19–21] concluding that the addition of lime as a binder, in 2% to 10% of weight by the mass of soil, can increase a minimum of twice the flexural/tensile strength of adobe blocks. Regarding the compressive strength, the addition studied by the previously referred authors yielded improvements of up to 30 times, achieved with proportions of lime (weight by the mass of soil) ranging between 2% to 20%. In comparison to PC, lime production produces less CO₂ emissions because it does not require a calcination process.

Other binder materials have been studied aiming to enhance adobe blocks mechanical properties, such as volcanic ash, bagasse ash, gypsum, coal combustion waste, alginate, mucilage and rice husk ash [14,16,22–24], [25]. However, their mechanical strength tests results do not match the increase of compressive strength reached by lime and PC, and on the contrary, the rice husk ash can even decrease it.

Previous works made comments on the effect on mechanical properties of stabilized adobes, like the use of either fibres or binders, with different concentrations of clay originated from the various types of soils used to manufacture the samples [25–30]. Reman [31] studied alternatives to increase the compressive strength and toughness of adobe blocks with the addition of lime, gypsum and bitumen, as well as different types of clays. In that research, it was concluded that clays from the kaolin group generate adobe blocks with higher compressive strength using the same binders. Other studies [32,33] have added kaolin and bentonites to mixtures of adobe to observe the effects on their earthquake resistance, compressive strength and absorption reduction. Islam and Iwashita [32] observed that blocks manufactured with a particular bentonite clay could lead to higher compressive strength in comparison with adobe blocks mixed with kaolin, the failure strain of adobe blocks with kaolin resulting higher than the failure strain of adobe blocks with bentonite. Unfortunately, the chemical composition of the kaolin and bentonite used was not reported in those papers. The soils in those studies were variable, with different particles size distributions and Atterberg limits, some of the adobe matrices containing Portland cement, lime, straws, jute fibres and other additions. The use of additions and different types of soils could make it difficult to identify the effects of clay on the mechanical strength of adobe mixtures.

Different particles in the soils have different contributions to their mechanical behaviour. While large particles (sand and gravel) mainly support loading due to the friction between particles, clays and silts contribute to the strength through cohesion, which depends on weak chemical reactions between soil and water. Low [34] studied the mechanism through which clay and water interact. This author reported that, when water is mixed with certain types of clays (like kaolin), the hydroxyl molecules of clay create bonds with oxygen molecules of water, and that the oxygen molecules of the clay create bonds with the hydrogen molecules of water. The new mixture results in a microstructure with fewer voids than the original, creating a more stable and compact structure. However, if excessive water is added to the mixture, the soil cannot revert to a solid-state, and the mixture saturates, turning into a liquid state. In order to maintain the original constituents of adobe matrix that makes it sustainable by nature, we need to assess how its mechanical response and volumetric instability could be modified by changing the proportion of its natural fines content and the addition of clay. To address the isolated

effect of clay and fines from the original matrix (as defined by the Unified Soil Classification System, USCS [35,36]) in the mechanical and volumetric changes of the mixtures, in this work we proposed to use a single type of soil to manufacture all the specimens, adding different proportions of kaolin, and fine soil particles from the original soil, to explore the mechanical and volumetric changes of the mixtures. In this study, no fibres were added to the mixtures, the water proportion relative to the dry constituents was kept constant in all the samples, to report properties from the matrix of adobe only Therefore, the main objectives of this work are: (i) to evaluate the effect of kaolin on the mechanical and physical properties of adobe blocks matrices and (ii) if any, to find and optimum dosage of kaolin for the manufacture of adobe blocks.

2. Materials and Methods

2.1. Materials

2.1.1. Particle size distribution of soil

The soil used for this study was obtained from Peñalolén, a district of Santiago, Chile. This soil was previously used by a construction company that specializes in the restoration of heritage earthen buildings in Chile. Also, Araya-Letelier *et al.* [37–40] used this soil in their studies about the mechanical strength of reinforced adobe blocks. To measure the particle size distribution of the soil used in this work, a sieve analysis was performed in accordance with ASTM D 6913/D 6913M [41], which can be seen in Figure 1 (black dashed-dotted line and square symbols). The sieve analysis showed that the fine (particles smaller than 75 μm) and sand (particles between 4.75 mm and 75 μm) contents were 9% and 91% respectively. In Figure 1 particle distribution results from soils used in previous studies (i.e. red, green, blue and red dashed-dotted lines) that investigated adobe blocks properties are presented as a reference among the particle distribution of the soil of this study [22,42,43]. This plot demonstrates that the particle size distribution of the selected soil is within the range of other soils previously employed in studies of adobe.

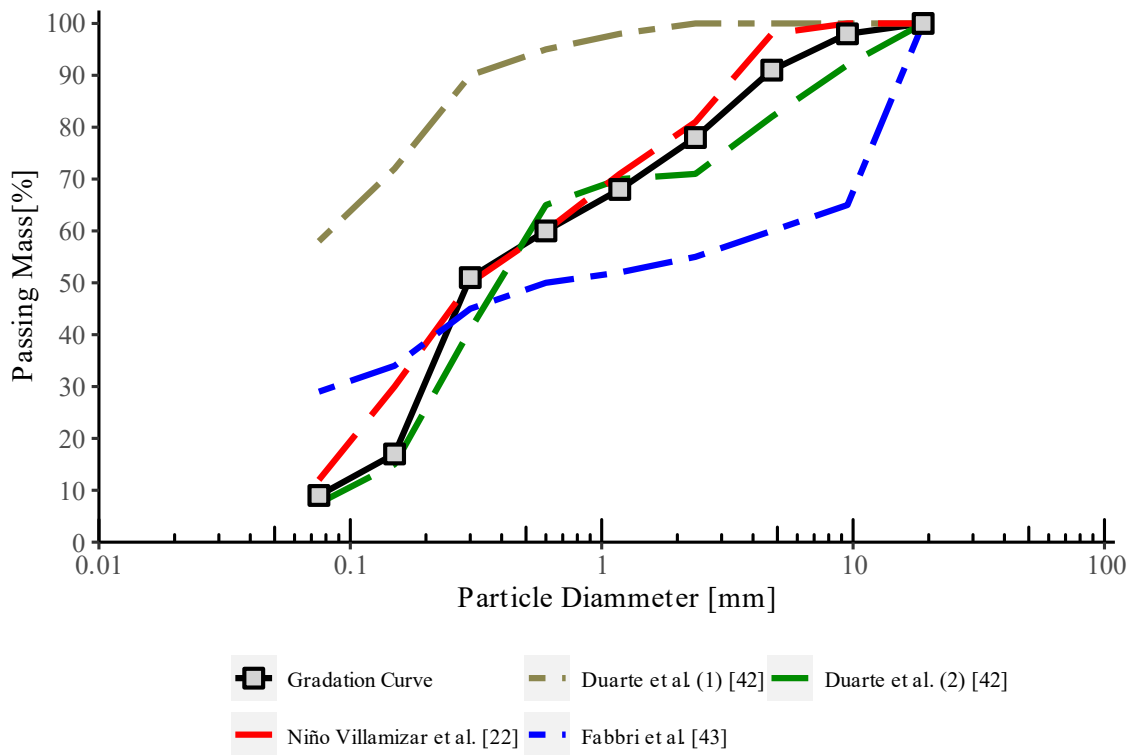


Figure 1: Gradation curve for the soil employed in this research and previous studies [22,42,43].

2.1.1. Clay

The kaolin used in this study was obtained from a clay deposit located in the Coquimbo district, Chile, and was mixed manually with the soil presented in 2.1.1. The chemical name of kaolin is hydrated aluminium silicate ($H_2Al_2Si_2O_8H_2O$) and its main component is silicon oxide, has a specific weight of 2.6 and its colour is white. Table 1 presents a summary of the chemical components reported by the manufacturer, as well as by other authors. Lima *et al.* [33] evaluated the effect of incorporating sugarcane bagasse ash into compressed earth blocks, which is a similar technique as adobe blocks, and due to the high granular soil particles content, they added kaolin to the soil. The difference between both studies is: the type of earth block, the binder used and the tests conducted.

Table 1: Kaolin chemical components

Component	Content in this study (%)	Content in Lima <i>et al.</i> [33] (%)
SiO ₂	51.50	48.33
Al ₂ O ₃	32.30	36.63
Fe ₂ O ₃	2.90	0.87
K ₂ O	2.20	1.99
TiO ₂	1.00	1.10
MgO	0.58	0.32
CaO	0.28	0.06

2.1.2. Dry material of adobe matrices

Three dosages of 10%, 30% and 50% of kaolin (i.e. the percentage of concentration by weight of kaolin respect to the weight of the original oven-dry soil), and three dosages of 10%, 20% and 30% of added fine particles from the original soil by weight respect to the weight of oven-dry soil, were prepared for this study. Two plain soils were the control mixtures (i.e. KF-0, referring to 0% of kaolin and 0% added of the original fines, respectively) for each batch of adobe matrices with different concentrations of kaolin and added fine particles of the original soil. A summary of all the mixtures can be seen in Table 2.

Table 2: Adobe matrices mixtures

ID	w/s %	Solids %		
		Soil	Fine Soil Particles	Kaolin
KF-0		100	0	0
K-10		91	0	9
K-30		77	0	23
K-50	30.7	67	0	33
F-10		91	9	0
F-20		83	17	0
F-30		77	23	0

When working with soil it is important to observe how it interacts with water, and at which moisture content the soil changes to a plastic and liquid mixture. In order to assess those variables, Atterberg limits were tested for each mixture, as each one has a different amount of fines of the original soil and kaolin. Atterberg limits were obtained for all the mixtures in accordance with ASTM D 4318 [44], and the Unified Soil Classification System (USCS) [36]. The plasticity chart in Figure 2 presents the results obtained for the different soil mixtures of this work, and a summary of the mentioned properties is presented in

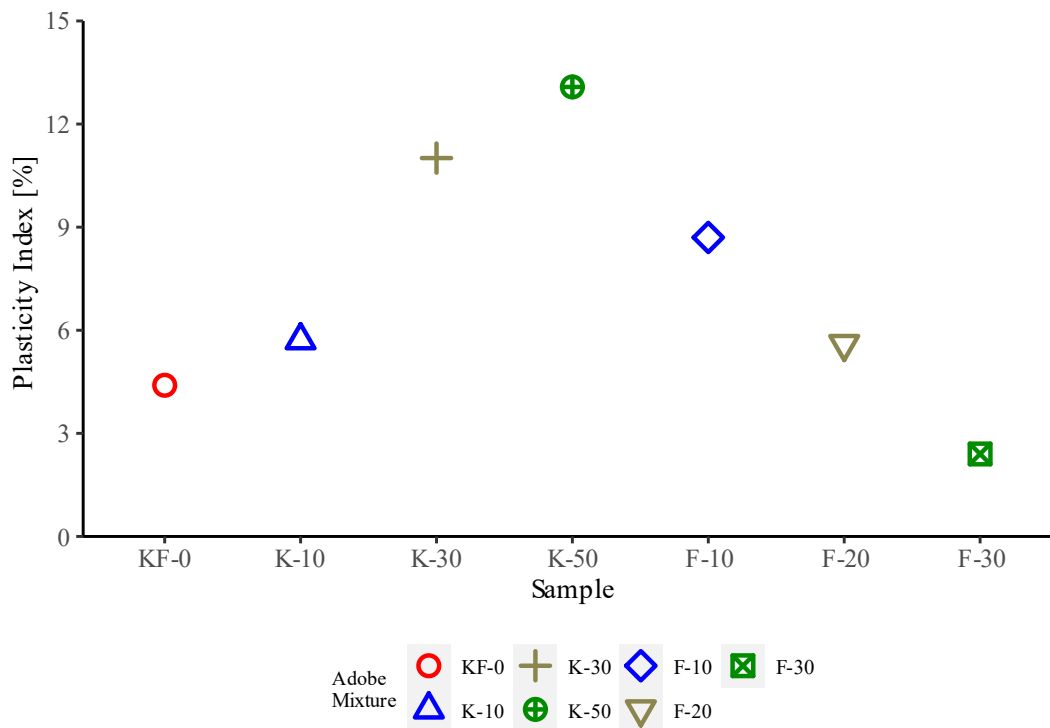


Figure 3: Plasticity index versus fines and kaolin content

Table 3. As can be seen in Figure 3, the kaolin content is proportional to the plasticity index. The latter is associated with the increment of clay minerals in the soil mixture. However, as presented in

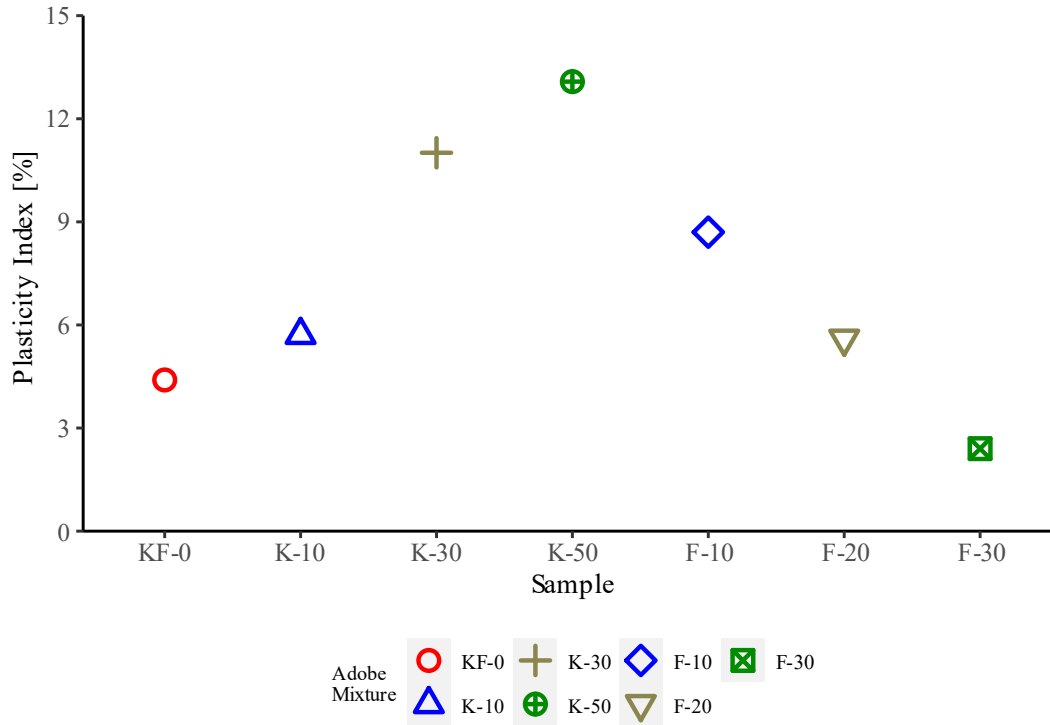


Figure 3: Plasticity index versus fines and kaolin content

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Table 3 no trends were observed for mixtures with fine soil particles where, as the content increased the liquid limit decreased and the plastic limit oscillated around 21%. Due to the lack of information on the particles size distribution of the fine soil particles, no conclusions can be drawn to explain this phenomenon. The plasticity indices values show that neither the soil nor its fine particles have expansive clay minerals, or that its content is too low to influence the adobe matrices behaviour.

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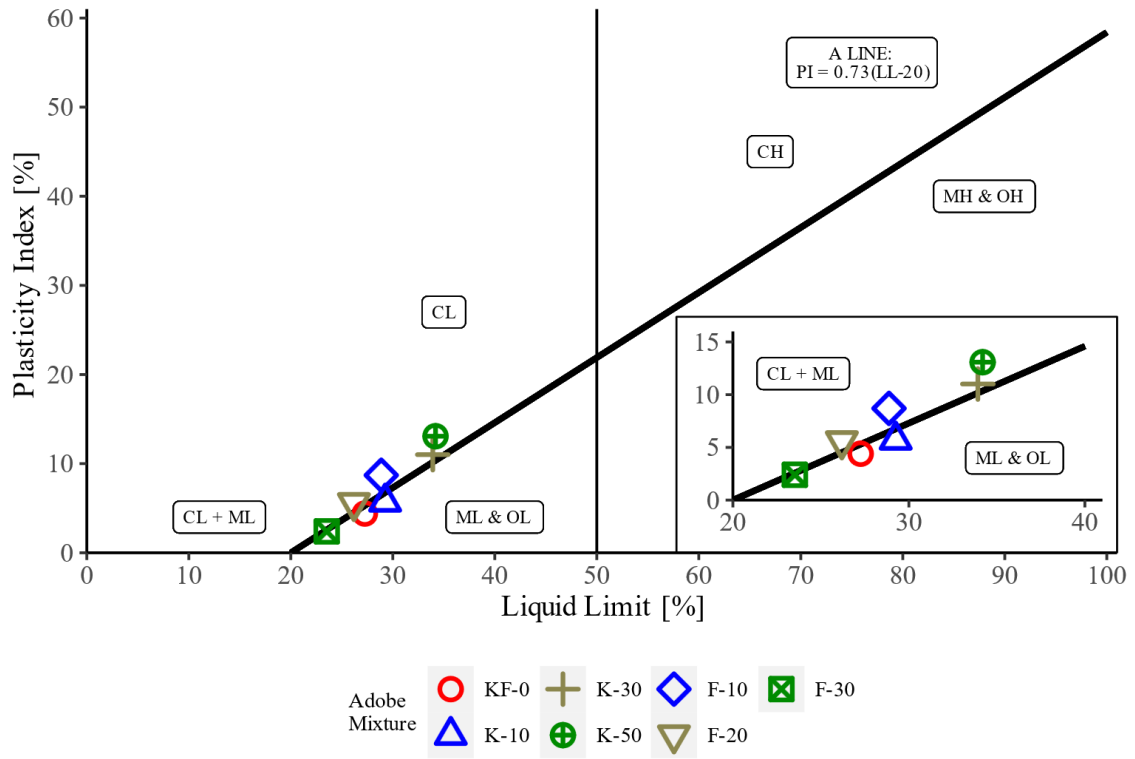


Figure 2: Plasticity chart

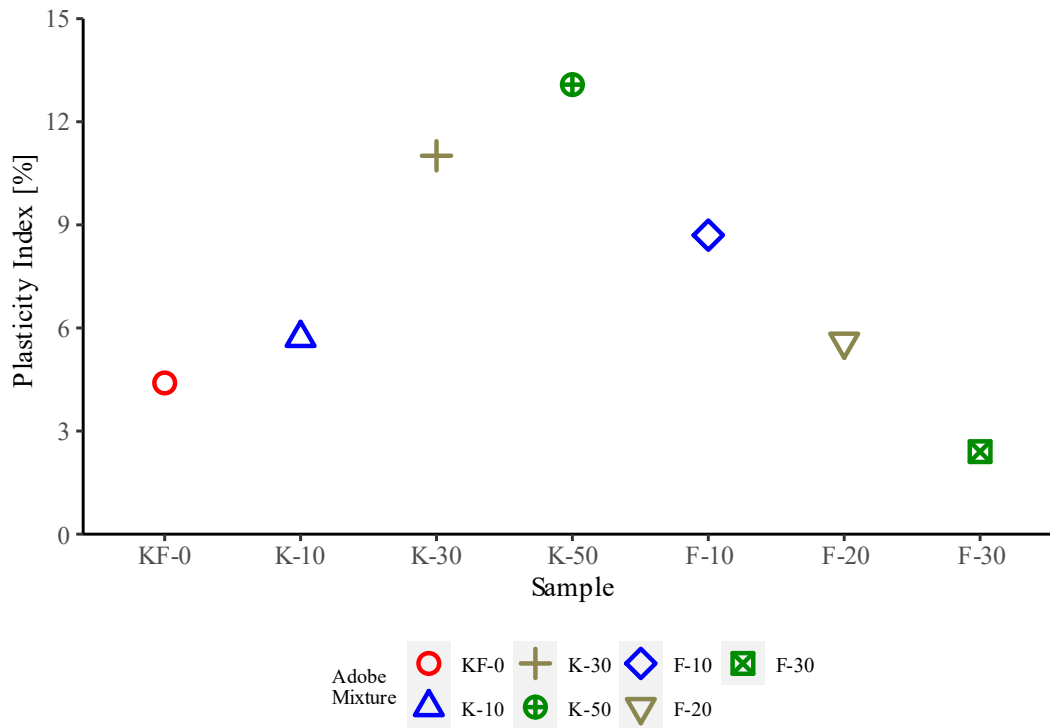


Figure 3: Plasticity index versus fines and kaolin content

Table 3: Adobe matrices mixes USCS classification

Adobe Mixture	Liquid Limit %	Plastic Limit %	Plasticity Index	Classification
KF-0	27.26	22.86	4.4	SM-SC
K-10	29.25	23.54	5.7	SM-SC
K-30	33.92	22.91	11.0	SM-SC
K-50	34.19	21.12	13.1	SM-SC
F-10	28.87	20.12	8.7	SM-SC
F-20	26.19	20.65	5.6	SM-SC
F-30	23.52	21.17	2.4	SM-SC

As it can be seen in

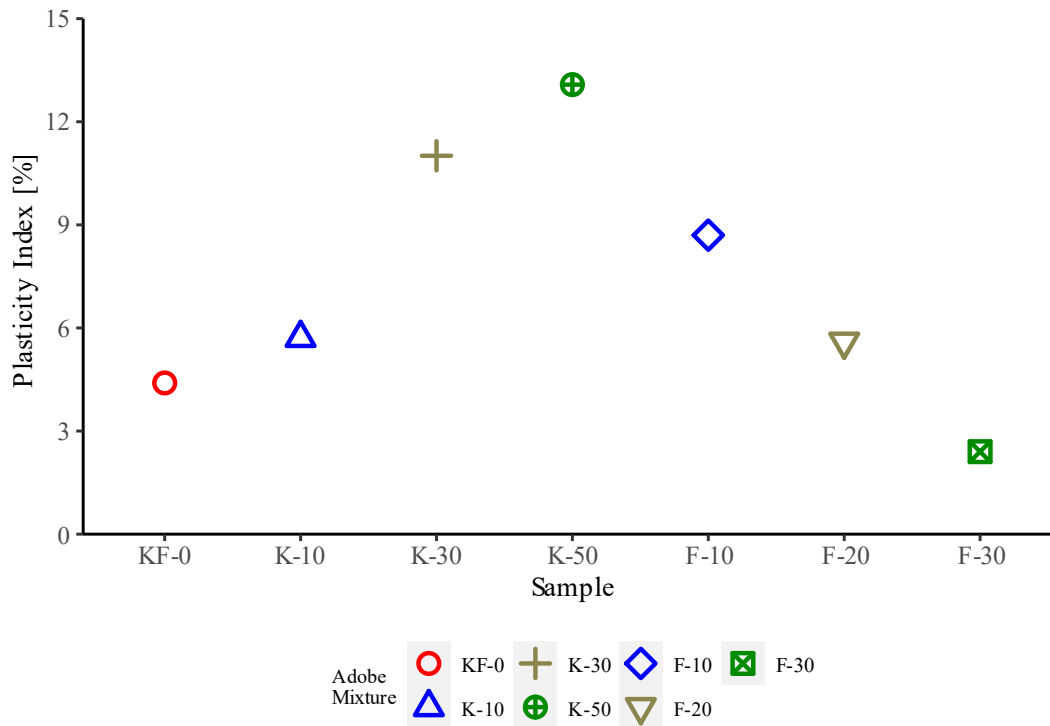


Figure 3: Plasticity index versus fines and kaolin content

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Table 3, mixtures with different fine soil particles (i.e. below 75 μm size) content, as well as mixtures with kaolin content, are classified in the same group, silty sands-clayey sands. To evaluate the effect of fine particles on the mechanical and physical properties, fine soil particles from the original soil were manually mixed with the original soil to obtain the adobe matrices mixtures of this study. The fine soil particles were obtained from the original soil as described in section 2.1.1. using a 75 μm sieve (N° 200) and a vibratory sieve shaker.

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2.2. Earthen mixes and specimen preparation

For this study, water, and soil, were mixed with kaolin and fine soil particles separately to cast adobe blocks matrices. The samples water to soil ratio (w/s), defined as the mass of water divided by the mass of oven-dry solids of the mixture (i.e. soil and binder: kaolin and fines for 24 hours at 110°C) of 0.307 was used (see Table 2). This ratio was adjusted for the soil used in this work in accordance with traditional adobe blocks manufacture and using an adaptation of the Carazas test [40]. To avoid water loss, the components were mixed in plastic containers. After casting, the different adobe blocks matrices specimens were left to settle at laboratory conditions (i.e. 45% of ambient relative humidity and 22 °C room temperature) for two hours. To prevent variations in the temperature and humidity of the adobe blocks matrices, they were not exposed to direct sunlight at any time. The different specimen geometries and purpose are presented in Table 4. A reference sketch for the

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160 geometry of each specimen is presented in Figure 4. Beam specimens were cast in metallic moulds, whereas prismatic specimens were cast on wood moulds wrapped in aluminium foil on the inside, to prevent moisture exchange between the wood and the adobe mixture. It should be noted that test results in this work with less than 12 samples are plotted with only one standard deviation, whereas for those tests, where 12 samples were employed are plotted with two standard deviation error bars. The latter is due to the overestimation of the variance for samples with a low number of subjects if more than one standard deviation is used [45,46].

Table 4: Specimens information

Specimen	Dimensions mm	Test	Number of tested specimens
Beam	160 x 40 x 40	Flexural strength	6
		Compressive strength*	12*
		Ultrasonic pulse velocity*	12*
		Length change**	3
Prism	140 x 75 x 75	Area reduction	3
		Water loss	3

*Obtained from the flexural strength test

**Prism with metal treads

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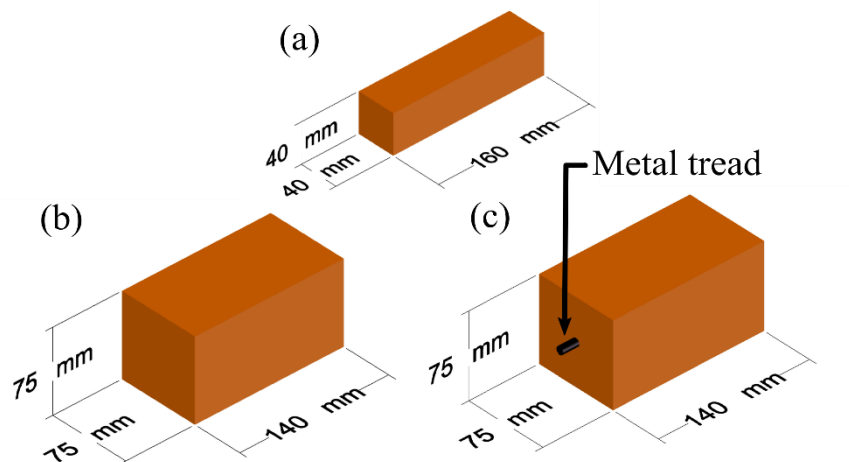


Figure 4: Dimensions of the specimens: (a) Beam, (b) Prism and (c) Prism with metal treads

2.3. Experimental testing

2.3.1. Compressive strength

The procedure stated in ASTM C 109/C 109M [47] was followed to evaluate the compressive strength of the adobe blocks matrices specimens. Due to the difference in the compressive strengths between mortar and adobe blocks, a strain rate control protocol of 1 mm/min was applied. Twelve halves of beam specimens, obtained after the flexural strength test, were tested at an age of 28 days. The testing age for compressive strength was selected because traditionally adobe blocks are left to dry for four weeks before using them [7]. Compressive strength average and standard deviation values were computed. The compressive strength was calculated as follows:

$$\sigma_c = \frac{F}{A} \quad (2)$$

where σ_c is the compressive strength, F is the peak load applied to the specimens and A is the cross-section where the force was applied ($40 \times 40 \text{ mm}^2$). Figure 5 (a) shows a picture of the test setup.

2.3.2. Flexural strength

The procedure stated in ASTM C-348 [48] was followed to evaluate the flexural strength of the adobe blocks matrices. Beam specimens were demoulded seven days after casting and turned 90° to their adjacent side every 7 days until tested, to ensure even moisture distribution on the surfaces of the specimens. A strain rate control protocol of 1 mm/min was used to provide a quasi-static load to the sample. Six beam specimens were tested at an age of 28 days, and the strength was computed as the mean value of the six samples. The flexural strength of each specimen was computed as follows:

$$\sigma_f = \frac{3FL}{2bd^2} \quad (1)$$

where σ_f is the flexural strength at peak load, F is the peak load of the specimen, L is the span length (90 mm), b is the width of the specimen (40 mm) and d is the depth of the specimen (40 mm). Due to the high variability on the materials cast specimen form, nominal widths and depths were used. Flexural strength standard deviation values were also calculated. Figure 5 (b) shows a picture of the test setup.

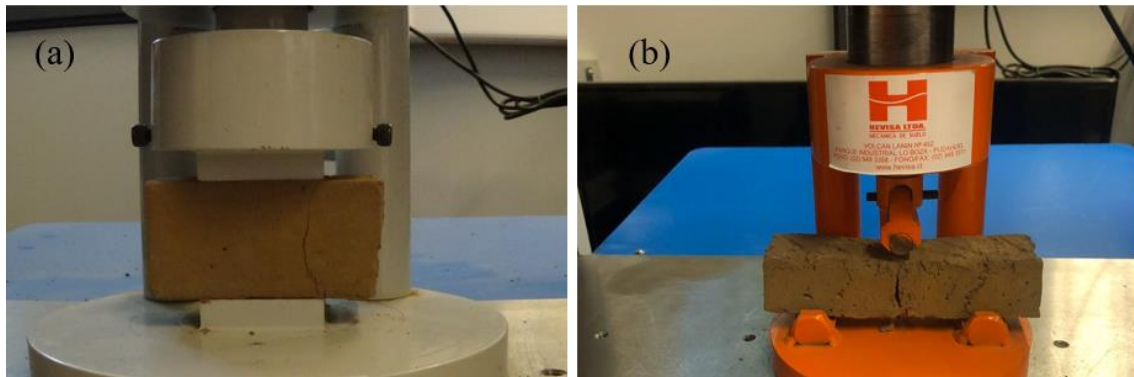


Figure 5: Test setup for (a) compressive and (b) flexural strength

2.3.3. Ultrasonic pulse velocity

Ultrasonic pulse velocity measurements were taken from the matrix of adobe at an age of 28 days, in accordance with the ASTM C 597 standard [49], and the recommendations noted by Araya-Letelier *et al.* [39,40]. This test has been used to evaluate the macroscopic homogeneity of concrete and mortar [50]. Regarding earthen materials, it has been reported that the ultrasonic pulse velocity measurements are proportional to the dry density of compacted clayey soils [51]. As for the knowledge of the authors, ultrasonic measurements were performed previously on large scale soils but not on adobe blocks. Therefore, in this study, we performed ultrasonic pulse velocity measurements of adobe blocks matrices to explore possible relations with its homogeneity.

2.3.4. Mass loss

Previous studies have shown that the mechanical strength and the loss of water of adobe blocks are related [52,53]. To evaluate if kaolin mixed in the adobe matrix affect its water loss [34], measurements of mass loss were taken in this work. The mass loss of adobe matrices gives an indirect measurement of the moisture content of the mixture. Due to the plastic behaviour of the adobe blocks matrices at early ages, the specimens used to measure mass loss were kept inside the moulds up to the age of seven days. The weight of the moulds was previously recorded to estimate the mass loss of the sample at any time. To compute the water loss of the adobe blocks matrices, the mass of the prismatic specimens was measured from the casting day up to an age of 28 days. The average and standard deviation values were obtained from three prismatic specimens for each mixture. The mass change was calculated as follows:

$$ML_t = 100 - \left(\frac{Mass_t}{Mass_{ini}} \right) \cdot 100 \quad (4)$$

where ML_t denotes the mass loss for the age t in percentage, $Mass_t$ is the measured mass of the specimen at any day t after casting and $Mass_{ini}$ is the measured mass of the specimen at the casting day.

2.3.5. Length change

To evaluate the effect of kaolin on the volumetric instability of adobe matrices, defined as the changes in the volume of the block as the water dries out of the material, a length change test was undertaken. An adaptation of the length change test (ASTM C 157 [54]) for cementitious mortars was performed. Specimens of 75 x 75 x 140 mm, with a metal rod inserted on both of its ends were prepared for this test. The use of these dimensions (ASTM C 157 as for a concrete sample) was chosen because the mortar specimen dimensions when manufactured with earth, broke at 24 hours. However, due to the materials volumetric instability [39,40], the results obtained had high variation and several samples broke between 48 and 64 hours after casting. The length of the specimens was therefore changed to 140 mm, and a metal rod was inserted at both ends of the specimen. The length of the samples was adopted to prevent samples from cracking during the testing period. Given the high

plasticity of the samples at early ages, the first measurements were taken at an age of three days, and up to an age of 28 days. The length change was calculated as shown in Equation 3.

$$\Delta L_x = \frac{CRD - CRD_{initial}}{G} * 100 \quad (3)$$

where ΔL_x is the length change of specimen at any age in percentage, CRD is the difference between the comparator reading of the specimen and the reference bar at any age, $CRD_{initial}$ is the CRD obtained at the first day of the measurements and G is the gage length (110 mm). For each adobe mixture, average and standard deviation values were calculated. Figure 6 presents a sample being tested in the length comparator apparatus.



230 *Figure 6: Length change testing apparatus and specimen using 75 by 75 by 140 mm samples*

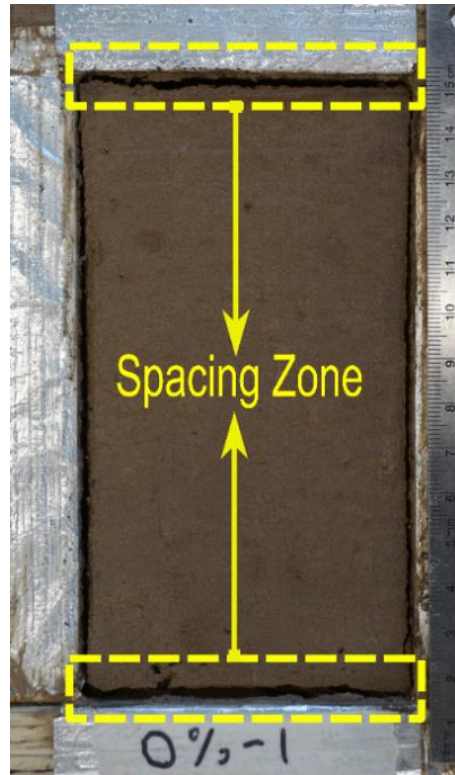
2.3.6. Surface change

In this work, a new approach was implemented to evaluate the volumetric instability due to mass loss of the inner water and chemical reactions of adobe blocks matrices [55]. The purpose is to complement the adapted test of length reduction from ASTM C 157. 75 x 75 x 140 mm specimens left inside the moulds for the entire duration of the test to enforce drying from the upper face of the block. Also, these conditions were identical to the ones used in the mass loss specimens at the early ages of this work. The upper surface of the specimens was photographed periodically every 12 hours up to an age of seven days as adobe blocks matrices mass loss stabilizes approximately at an age of seven days. Using the image processing software ImageJ [56], the photographed surface of the spacing generated between the mould and the specimen was measured both on the upper and

240 lower section of the specimen, as seen in Figure 7. The shrinkage of the specimen was estimated considering the shrinkage of the shortest faces of the specimen using equation 5.

$$AR = \left(1 - \frac{CA_t}{TA}\right) \cdot 100 \quad (5)$$

where CA_t is the surface of the spacing between the mould and both short faces of the specimen at age t and TA is the initial surface of the specimen.



245 *Figure 7: Schematic of surface variation specimen*

3. Results

3.1. Mechanical properties

3.1.1. Compressive strength

250 Figure 8 (a) shows average compressive strength, and its two standard deviation error bars, for the adobe matrix mixtures with different fine contents at an age of 28 days. The average values varied from 1.43 to 1.79 MPa (20% difference) for mixtures F-20 and KF-0 respectively, whereas standard deviation values vary from 0.35 to 0.44 MPa (mixtures F-10 and F-30 respectively). Figure 8 (b) presents average compressive strength values, and two standard deviation error bars of the first batch of adobe matrices with kaolin content at 28 days tested for this work. The last digit in the ID of each mixture represents the number of the batch (1: first batch
255 and 2: second batch). Average values vary from 1.09 to 1.92 MPa (176% difference) for mixtures K-10-1 and

K-50-1 respectively, whereas standard deviation values vary from 0.20 to 0.37 MPa for mixtures KF-0-1 and K-10-1, respectively. Specifically, plain mixtures KF-0-1 had a 155% difference in comparison with the K-50-1 mixture. Figure 8 (c) shows average values and two standard deviations of compressive strength at an age of 28 days of the second batch of adobe matrices mixtures with kaolin. Average values vary from 0.76 to 1.85 MPa (243% difference) for mixtures KF-0-2 and K-50-2 respectively, whereas standard deviation values vary from 0.17 to 0.31 MPa for mixtures KF-0-2 and K-50-2, respectively. Average values of compressive strength at 28 days of plain mixtures from the first and second batch (KF-0-1 and KF-0-2) are in the same order of magnitude as values of compressive strength at 28 days reported in previous studies [39,40], with values ranging between 1.0 and 2.0 MPa for reinforced and plain adobe respectively with a W/S ratio of 30.7% and the same mixing process.

To assess if the addition of fine and kaolin had a statistical effect on the compressive strength of each mixture, a Welch t-Test was performed to the compressive strength of all mixtures described in Table 2, as well as cross-testing between samples with kaolin from different batches (e.g. K-10-1 versus K-10-2). This test compares samples with different variances and assumes that the data distribution is normal [57]. The Welch t-Test was performed considering a confidence level of 95%. A Shapiro-Wilk test was performed on every result set for each mixture tested in compression for this work, to ensure that the distribution of compressive strength results of each mixture is normal. Ghasemi and Zahediasl [58] propose the Shapiro-Wilk test over the Kolmogorov Smirnov and other tests to evaluate normality because the Shapiro-Wilk test is based on the correlation between the data and the corresponding normal scores without a specific mean and variance. As can be seen from the Shapiro-Wilk test's results in Table 5, there is no sufficient evidence to reject the hypothesis that compressive strength results set for each mixture distribution are normal, considering a confidence level of 95%. Regarding the Welch t-Test, Table 6 is divided into three groups, to illustrate if the comparison between results is statistically different, bold letters indicate that the tests are not statistically different. Table 6 (a) presents the results of the Welch t-Test when the compressive strength of adobe with different contents of the original fines are compared. For these mixtures, the Welch t-Test results showed not enough evidence to prove a difference between the means of the different adobe matrices mixtures, with exception of mixtures KF-0 versus F-20. However, the P-Value obtained for this comparison was near 5%, and mixture F-20 is not statistically different to the other fine content mixes, therefore the compressive strength of all original fines content mixes was considered similar. The latter indicates that the compressive strength of adobe blocks matrices is not significantly influenced by the addition of original fines.

The top part of Table 6 (b) presents the results of the Welch t-Test when the compressive strength of adobe with different contents of kaolin of the first batch are compared; except for the KF-0-1 to K-10-1 results, the average values of the different mixtures of this batch are statistically different. Similar results of the Welch t-Test were obtained for the second batch of kaolin samples presented in the bottom part of Table 6 (b); almost all mean values are statistically different, except for mixtures K-10-2 versus K-30-2 whose p-value is only 0.4E-02 above the alpha level. The latter proves that the content of kaolin in adobe matrices is proportional to the compressive strength. The top part of Table 6 (c) shows the Welch t-Test results for average compressive

strength comparison between KF-0, and KF-0-1 and KF-0-2 mixtures. All plain samples of this study had statistically different average values, although the same raw materials, environmental conditions, proportions, and the procedure was followed to mix and cast all the samples. This is an important finding that shows the need to control the variability of the manual compaction method of adobe. Formerly, González-López *et al.* [59] studied the effect of compaction force on earth blocks with and without stabilizers and observed that as the compaction force increases, compressive strength values also increase (133% average increment for 1 kN compaction force increment for earth blocks without stabilizers). This is also in line with the findings of Park and Santamarina [60], which showed that higher effective stress on finely graded soils improve its load-carrying capacity as the soil skeleton consolidates. This also occurs in fine/coarse mixtures, where the fine particles can help improve the stability of the soil matrix by improving the skeleton and achieving a higher density [61]. On the contrary, if the statistical difference of adobe mixtures with kaolin from the first and second batch are compared (see Table 6 (c) bottom), our results show that the average values are not statistically different regardless of the content of kaolin. The latter proves that adding kaolin to the mixture could help to reduce the variability of the compressive strength of adobe blocks matrices. This lack of difference between the two kaolin content adobe blocks matrices batches could be related to the increase of the liquid limit of the mixture, in comparison to plain adobe matrices samples. It is possible that the liquid limit (see Figure 2), close or higher to the w/s ratio (0.307) of the adobe mixtures with kaolin, reduced the free water available in the fresh mixture during the mixing process. The latter could decrease the voids left in the mixtures as the free water evaporates during the curing process of the material, reducing the heterogeneity of the material and increasing the compressive strength. In addition, the chemical bonds that occur between clay and water [34] inside the matrix of adobe create molecular chains of kaolin that may reduce the voids inside the matrix of the material, as well as increase the friction angle and cohesive strength of the soil. More work needs to be done to address these effects on the variability and increment of the compressive strength of adobe matrices with kaolin.

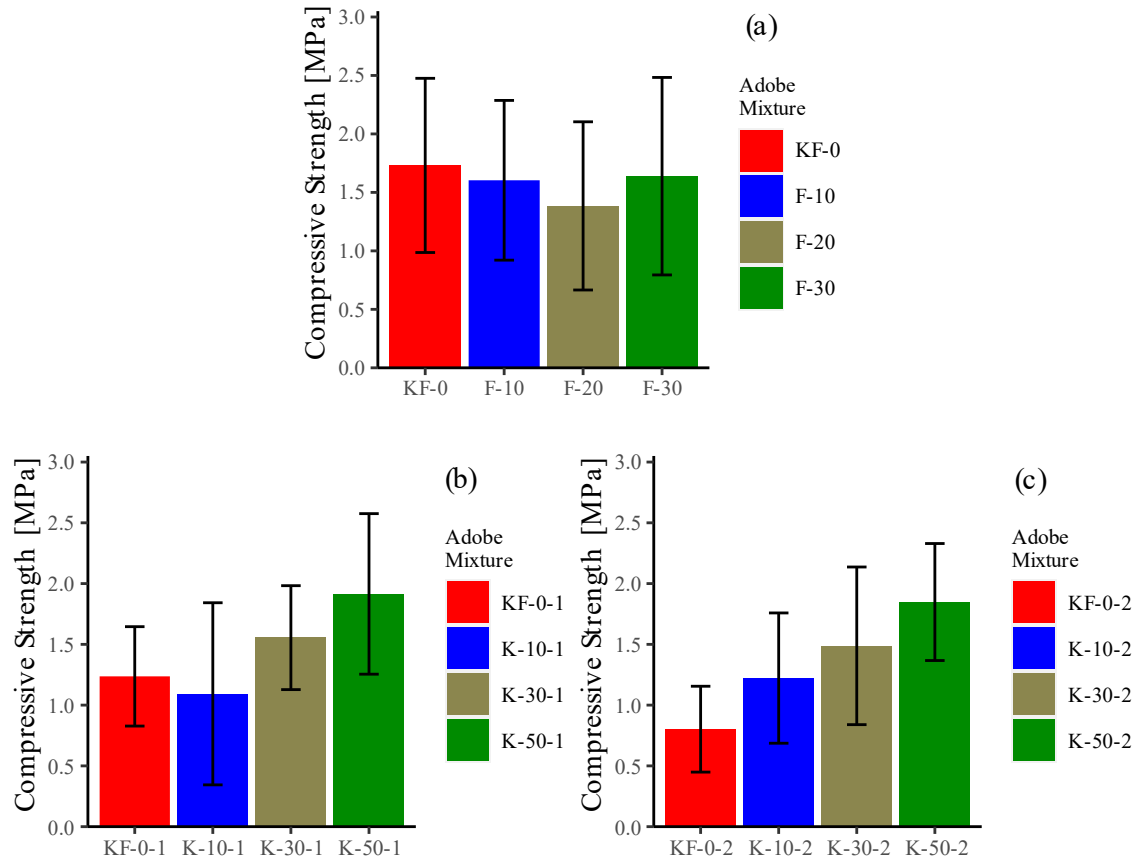


Figure 8: Compressive strength test results of (a) fine content adobe matrices, (b) first batch kaolin content adobe matrices and (c) second batch kaolin content adobe matrices

Table 5: Shapiro-Wilk test results

Sample	W	P-Value	Sample*	W	P-Value	Sample**	W	P-Value
KF-0	0.98	9.6 E-01	KF-0-1	0.92	3.9 E-01	KF-0-2	0.98	9.4 E-01
F-10	0.98	9.9 E-01	K-10-1	0.94	5.2 E-01	K-10-2	0.91	2.4 E-01
F-20	0.92	3.5 E-01	K-30-1	0.96	4.5 E-01	K-30-2	0.90	2.0 E-01
F-30	0.90	1.6 E-01	K-50-1	0.96	7.9 E-01	K-50-2	0.96	7.4 E-01

*Results correspond to Figure 8 (b)

**Results correspond to Figure 8 (c)

Table 6: Welch t-Test results

(a)		(b)		(c)	
Comparison	P-Value	Comparison	P-Value	Cross Sample Comparison	P-Value
KF-0 to F-10	4.3 E-01	KF-0-1 to K-10-1	2.6 E-01	KF-0 to KF-0-1	1.5 E-03
KF-0 to F-20	3.8 E-02	KF-0-1 to K-30-1	1.5 E-03	KF-0 to KF-0-2	2.8 E-06
KF-0 to F-30	5.8 E-01	KF-0-1 to K-50-1	2.3 E-05	KF-0-1 to KF-0-2	1.3 E-04
F-10 to F-20	1.5 E-01	K-10-1 to K-30-1	1.7 E-03	K-10-1 to K-10-2	3.4 E-01
F-10 to F-30	8.3 E-01	K-10-1 to K-50-1	1.5 E-05	K-30-1 to K-30-2	5.8 E-01
F-20 to F-30	1.3 E-01	K-30-1 to K-50-1	6.9 E-03	K-50-1 to K-50-2	5.9 E-01
		KF-0-2 to K-10-2	5.0 E-04		
		KF-0-2 to K-30-2	4.9 E-05		
		KF-0-2 to K-50-2	1.8 E-09		
		K-10-2 to K-30-2	5.4 E-02		
		K-10-2 to K-50-2	4.9 E-06		
		K-30-2 to K-50-2	1.0 E-02		

325 3.1.2. Flexural strength

Figure 9 (a) presents average values and error bars representing one standard deviation of the flexural strength of the adobe matrices mixtures with fine content at an age of 28 days. Average values of flexural strength vary from 0.27 to 0.40 MPa (33% difference) for mixtures F-20 and KF-0 respectively (see Figure 9 (a)). The minimum and maximum standard deviation values were 0.07 to 0.20 MPa corresponding to mixtures 330 F-20 and F-30, respectively. Figure 9 (b) shows the average values and error bars for the flexural strength of the adobe matrices mixtures with kaolin content at an age of 28 days. Average values vary from 0.26 to 0.43 MPa for mixtures K-50 and K-0, respectively. Standard deviation values vary from 0.08 to 0.24 MPa for mixtures K-50 and K-30, respectively. The average and standard deviation values obtained for the flexural strength of adobe blocks matrices with fine soil particles and kaolin addition of this study are consistent with values 335 reported previously [39,40]. As it has been previously observed, earthen materials present low average flexural strength, compared to other construction materials like wood or mortar [62,63]. Although the dimensions and

reinforcement of the specimen differ from the previously mentioned studies, the results obtained for plain samples are of the same magnitude. According to the dispersion of the results, flexural strength is not sensitive to the addition of kaolin. Future work should consider testing a minimum of 12 samples to perform a more in-
 340 depth statistical analysis of the flexural strength of adobe. Overall, the flexural strength of adobe did not change with the addition of either the fine particles of the same soil catalogue as SM-SC according to USCS or kaolin.

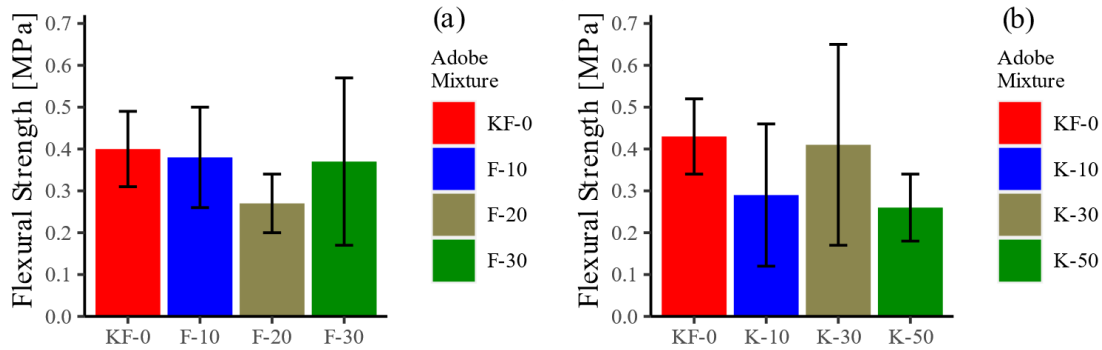


Figure 9: Flexural strength test result with (a) fine content and (b) kaolin content

The increment of flexural strength in quasi-brittle materials is proportional to the increment of the matrix compressive strength. For example, the flexural strength of concrete is approximately 10% to 20% of the compressive strength [64]. For the adobe blocks, matrices mixtures studied in this investigation, average flexural
 345 strength values corresponded to 25% of the average compressive strength.

Maleej and Li [65] observed that for quasi-brittle materials, like concrete, flexural strength is dependent on the materials brittleness ratio, as well as geometric parameters (mostly depth) of the tested specimen. The brittleness ratio influences the relationship between flexural and tensile strength. As a materials brittleness ratio
 350 increases, its flexural strength tends to the tensile strength. As was mentioned by Islam and Iwashita [32], adobe blocks (i.e. adobe blocks matrices with fibres) exhibit brittle mechanical behaviour, therefore its flexural strength is expected to be close to their tensile strength. Araya *et al.* [66] addressed the brittle nature of the adobe matrices used in the present work subject to a three-point bending test. The tensile fracture occurs in brittle materials when initial sub-microscopic flaws in the material extend in an unstable fashion [67]. Following
 355 the generally accepted Griffith's criterion, brittle materials show in general an 8:1 compressive to tensile strength ratio [68]. The latter could help explain that adobe blocks matrices are insensitive to kaolin content for flexural strength tests.

3.1.3. Ultrasonic pulse velocity of adobe mixtures with kaolin

Figure 10 presents average tests results of ultrasonic pulse velocity for adobe blocks matrices mixed with
 360 kaolin. Error bars represent two standard deviation values above and below the average. Average values vary between 1450 and 1550 m/s. This test has been previously used to evaluate heterogeneity of adobe blocks reinforced with pig hair fibres by Araya-Letelier *et al.* [40] and earth-based walls stabilized with lime mixed

mortars by Slávka Andrejkovicová *et al.* [69], however, as for the authors' knowledge, no correlation between strength and quality of adobe and UPV has been currently determined for adobe matrices. The previously mentioned authors obtained UPV values between 1200 and 2200 m/s. Ultrasonic pulse velocity (UPV) has been used in concrete and mortar as a measurement to evaluate the quality of the composite as well as indirect measurements of strength [70]. Gonzalez and Alloza [50] developed a correlation between UPV results and the quality of the matrix, in which as the UPV increases, so does the quality of concrete. For concrete, values above 4500 m/s are considered of excellent quality and values below 2000 m/s are considered to have very poor quality. The measurement of quality correlates with the defects or heterogeneity of the matrix of the composite, in which as more voids or imperfections are present in the material, UPV decreases. If a simile with concrete is made, the values obtained for this study's adobe blocks matrices would indicate an average quality, considering low-quality values below 1200 m/s and excellent quality values above 2200 m/s. Average values of UPV of adobe blocks are expected to be lower than concrete, due to the difference in both materials densities. Araya-Letelier *et al.* did not find any statistical difference between samples of adobe with and without fibres, whereas Slávka Andrejkovicová *et al.* observed that UPV values decreased over time. The adobe blocks matrices of this study are like the mentioned in the previous studies in the type of soil, W/S, compaction method and binders used. Although compressive strength values show differences between plain and kaolin adobe matrices mixtures, no statistical difference amongst the different mixtures can be concluded for UPV test results if error bars are considered. The lack of difference between the adobe matrices mixtures could be related to the scale at which the UPV test performs (macroscopic scale). It has been previously reported that variations in the compressive strength of 40% of concrete cubes, correspond to an approximately increment of only 8% in UPV measurements [71], which could help to explain the absence of sensitivity of this test.

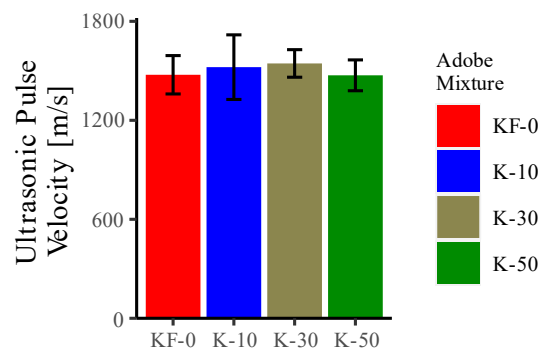


Figure 10: Ultrasonic pulse velocity test results

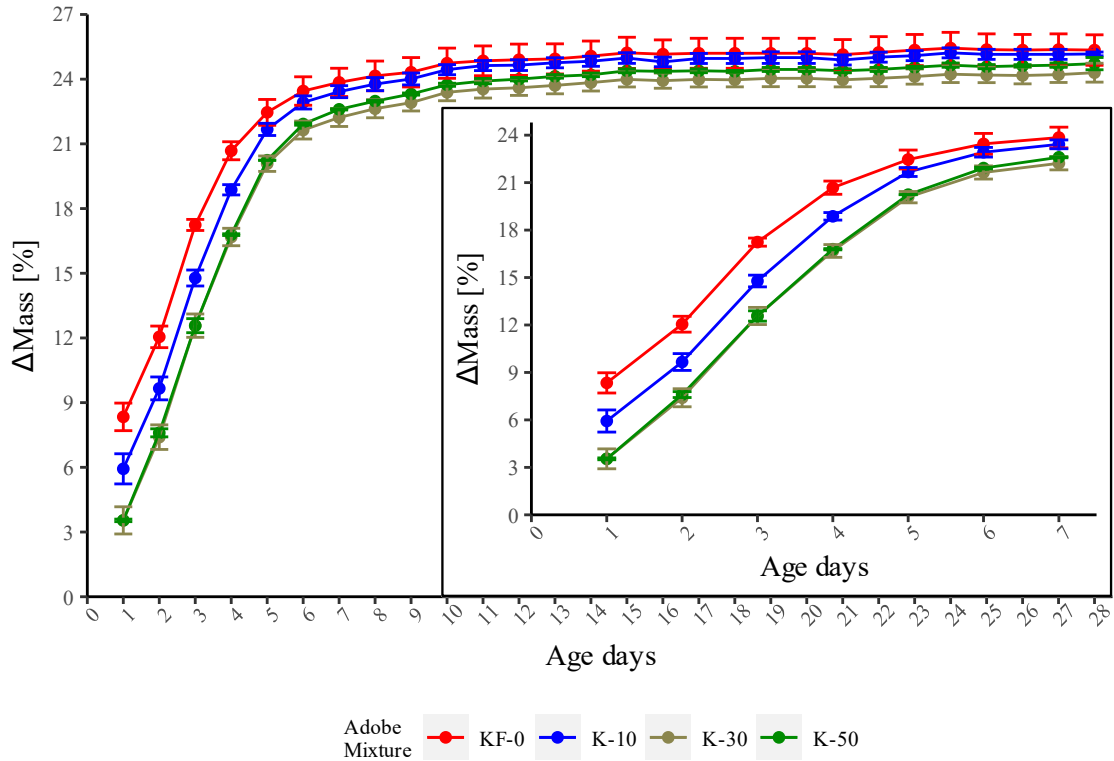
3.2. Physical properties

3.2.1. Mass loss

Figure 11 presents the average values and error bars (one standard deviation) of mass loss for each adobe mixture with kaolin content of the second batch. The inset in Figure 11 shows the values of mass loss recorded from an age of 1 to 7 days for both kaolin mixtures of the second batch, and the mixtures of adobe with fines

390 from the original soil. It can be observed that the mixtures K-30 and K-50 had a 4.80% lower average loss of
mass than the control mixture (KF-0) at an age of 1 day. At an age of 7 days, the latter differences of the mass
of K-30 and K-50 compared to KF-0 are 1.62% and 1.25%, respectively. The lower mass loss of the mixtures
with a high content of kaolin compared to the control mixture occurs only at the early ages of the blocks (from
day 1 up to day 7 approximately). At later ages, the mass loss of the different mixtures is not statistically sig-
395 nificant. As for the authors' knowledge, the latter occurs because water creates hydrogen bonds between the
hydroxyl and oxygen molecules found in typical clays from the kaolinite group [34,72]. Mixtures (K-30 and K-
50) lost 1.72 and 1.39% less mass respectively, in comparison with plain samples. It is important to mention
that for plain adobe samples (KF-0), samples K-30 and K-50 had 95 and 143% higher compressive strength,
respectively. The latter could indicate that the water mixed with kaolin does produce a chemical reaction be-
400 tween the molecules, therefore reducing its mass loss, in exchange for increasing the hydrogen bonds in the
matrix. Yet, internal humidity was also measured for 28 days and proved that at later ages; the internal humidity
of all samples stabilizes with the ambient humidity. Further research must be conducted to evaluate the chemical
effect of kaolin on the microstructure of earth-based materials.

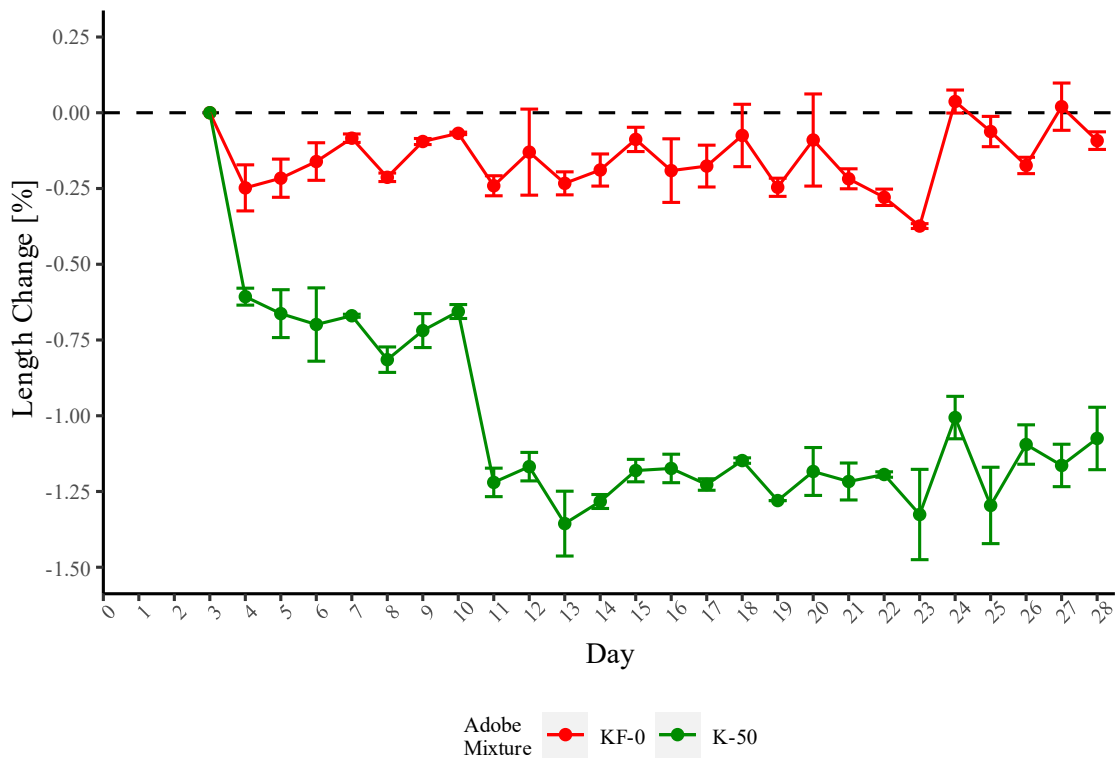
This test was also performed for adobe matrices mixtures with fine soil particles; however, results were
405 obtained from the day after casting and forward. For this reason, no comparison was made between kaolin and
fines of the original soil mixtures. Test results for fines of the original soil showed no difference between them
and plain adobe. The latter supports the statement that fine soil particles do not behave similarly to clay particles
when used for adobe blocks matrices manufacture, even if the added fines correspond to SM-SC by the USGS
classification.



410 *Figure 11: Mass loss of samples with kaolin*

3.2.2. Length change

Figure 12 reports the average length change of samples KF-0 and K-50 and error bars (one standard deviation) from 3 to 28 days of age. K-10 and K-30 test results showed high variance, masking the effect of the length change. Therefore, only KF-0 and K-50 mixtures are presented which stresses the difference in a length change of samples with and without kaolin. On average, the length change test results vary from 0% to -1.075% for samples K-50 and 0% to -0.092% for samples KF-0, respectively. A negative length change indicates shrinkage of the sample, whereas positive values indicate their expansion. Dispersion of the data varies from 0.029% (KF-0) 0.103% (K-50). As can be observed in Figure 12, both mixtures shrank, where KF-0 and K-50 reached equilibrium at an age between 7 and 10 days. The equilibrium of the length change of adobe matrices is consistent with the approximate age at which mass loss reaches equilibrium (see Figure 11). Other tests have been proposed to evaluate the volumetric instability of adobe plasters, but the authors have found that replicability of the method is hard to achieve [39,40]. The length change of mixtures containing fine soil particles was also measured, however no differences between plain adobe and fine soil particles adobe matrices mixes was observed.



425 *Figure 12: Length change of samples with kaolin*

3.2.3. Surface change

430 Considering the dispersion of the adapted linear change test described in the previous section to evaluate the volumetric changes on partially saturated soils (i.e., soils that have both water and air entrapped inside), the authors of this work proposed a new technique to evaluate drying shrinkage of adobes by measuring its surface change. One of the main benefits of this methodology compared to the adapted test of ASTM C157 is that this test does not require removing the specimens from its mould to perform measurements; allowing to take measurements from the first day of age. The latter feature of this test provides completeness to the history of deformation of the adobe matrices at early ages that otherwise with the length change test is incomplete as it requires samples to be hardened. Figure 13 presents two horizontal lines showing the underprediction of the steady-state linear shrinkage, at an age of 21 days of adobe mixtures KF-0 and K-50 using the length change method in comparison with the measured linear shrinkage using the surface change method proposed in this section. Figure 13 shows average surface reduction values of all adobe matrices mixtures presented in this study, from day 0 to day 7. Error bars present one standard deviation of each adobe mixture.

440 Between 1 to 3 days of age, no statistical variations were observed between the mixtures with different contents of kaolin, with all samples having a steady increase, of approximately 0.5% / day. Between 5 and 7 days of age, samples with kaolin increased their surface change in comparison with earlier ages, whereas plain adobe samples maintain a surface change close to 2.5%. At these ages, the mixture with the lowest percentage

of kaolin, namely K-10, has 1.0% more surface change on average in comparison with KF-0 adobe samples. Adobe matrices mixtures K-50 have an average difference of 2.5% with respect to KF-0 at an age of seven days. The difference of surface change between adobes with kaolin and plain samples after an age of six days is related to the initial mass loss of the mixtures as reported in Figure 11. As mentioned in previous sections, this could be explained by the fact that clay particles are reorganized at a molecular level when they interact with water [34,55], hence reducing voids of the adobe blocks matrices, and increasing its volume change. Adobe blocks matrices with and without kaolin, show an average trend to stabilize its area reduction at later ages (day 7), which is consistent with the results obtained for length change and mass loss reported previously.

As for the knowledge of the authors, few studies have researched the volumetric instability of adobe blocks and earthen materials [73]. Some authors have shown that these materials develop volumetric changes at early ages due to the loss of water [6–8,52]. Typically, fine soils, like clays and limes, exhibit larger expansions and contractions when they interact with water than coarse soils like sands and gravels. This occurs due to the capacity of coarse soils to drain water compared to the capacity of fine soils [55].

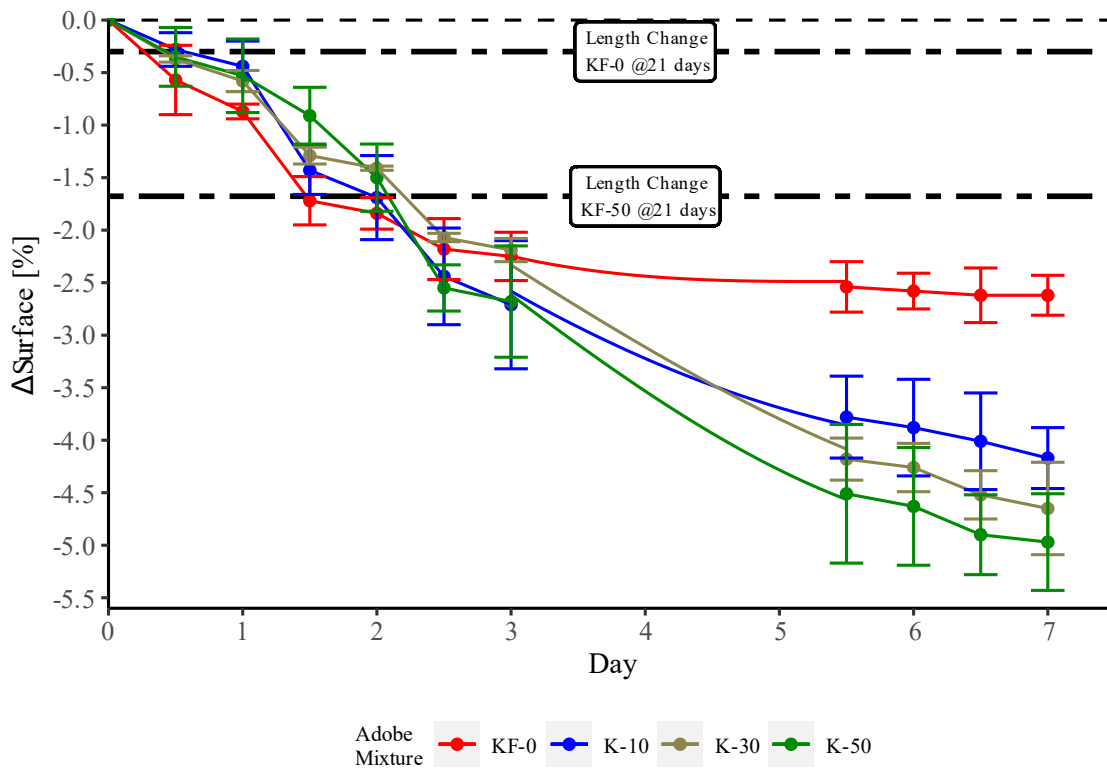


Figure 13: Surface reduction test results, values between days 3 to 5.5 were adjusted using a polynomial regression

3.3. Discussion on the role of moisture content and soil classification

Figure 14 (a) shows values of compressive strength at 28 days versus moisture content of the specimens at an age of 1 day. Moisture content values were obtained considering the initial water content of the samples and the mass loss of water at an age of day 1 for each adobe specimen. Compressive strength error bars show two

standard deviations, whereas moisture content error bars were plotted considering one standard deviation, as was explained in section 2.3. Two observations are worth to be mention: i) as the concentration of kaolin increases, the humidity content of adobe at an age of 1 day is higher (i.e. more water retention at 1 day), and the difference of water content between mixtures persists up to an age of approximately 7 days (Figure 11); ii) mixtures with larger concentrations of kaolin (i.e. adobe matrices mixes K-30 and K-50), and higher initial water content develops statistically higher average compressive strength at 28 days.

A similar correlation can be observed in Figure 14 (b) for compressive strength at 28 days versus steady-state surface change at 7 days of adobe blocks matrices with kaolin. Identically to Figure 14 (a), compressive strength error bars show two standard deviation values, whereas area reduction error bars present one standard deviation. As the surface of the specimens shrank, higher compressive strength values at 28 days were calculated. The latter indicates that higher contractions of the matrix of earthen material, possibly due to the presence of kaolin and its combination with part of the free water in the system, help to obtain a more compact matrix and therefore, higher compressive strength. As Low [34] and Jalal et al. [74] describe, the chemical bonds that occur inside the structure of a kaolinite clay when they interact with water are hydroxyl and oxygen bridges which have medium intensity (0.16 kcal/mol [75]). This interaction creates a stable molecular structure with fewer imperfections as the voids between soil particles are filled with clusters of clay particles. These clusters of clay have greater compressive strength than randomly distributed clay particles [55]. The latter confirms our experimental observations that adobe matrices mixtures with higher concentrations of kaolin present higher initial moisture content that induces higher volumetric reduction that ultimately improves compressive strength at an age of 28 days.

Jimenez Delgado and Cañas Guerrero [26] did an extensive normative review on soil selection criteria for earthen construction. In their work, they review properties like texture, compaction, soil classification and others. In general, the soil classification criteria and tests were extracted from soil mechanics, using the USCS or other international classification systems manuals. As was observed in this study, the USCS classification system can help identify soils for adobe matrices manufacture, but it lacks the precision to select suitable ones for the mentioned purpose. Our latter comments are based on the fact that all eight adobe matrices mixtures of this study had identical USCS classification. Yet, had a diverse mechanical and physical performance on the different tests executed. In particular, compressive strength showed differences of up to 199% on average between plain soils and high kaolin content mixtures. Other tests like mass loss and area change had differences of up to 4.8% and 2.5% respectively for the same mixtures (KF-0 versus K-50). For the mentioned reasons, the authors believe that the minimum criteria to select soil suitable for adobe blocks matrices production is the clay, silt and sand content, as well as the type of reactivity of the clay used. An alternative classification system for adobe block manufacturing could be the one proposed by Park and Santamarina [60] which provides further categorization based on the flow characteristics of the soil and also accounts for the roundness of the coarse particles.

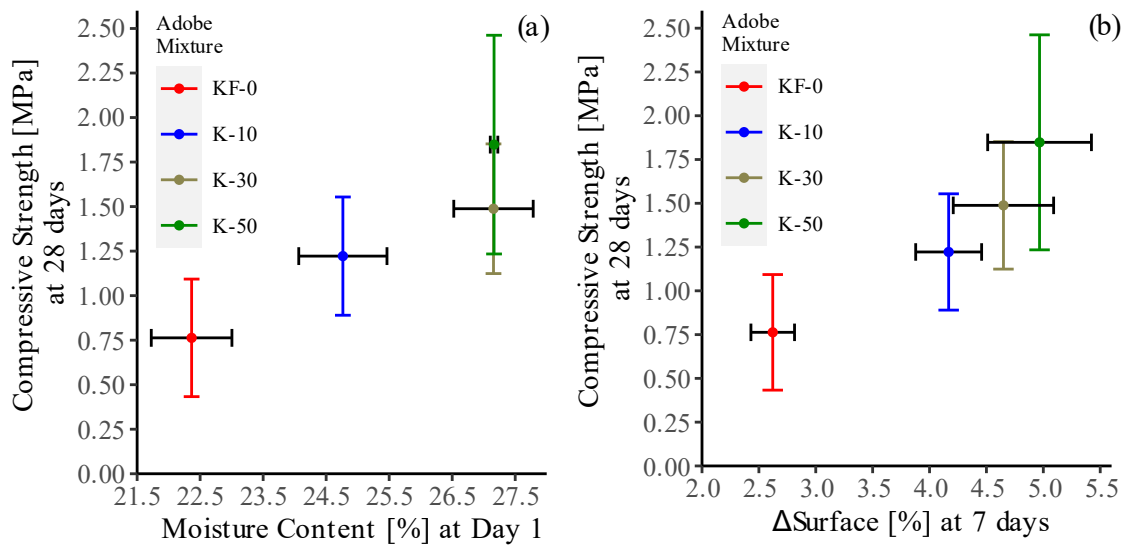


Figure 14: Compressive strength versus (a) moisture content and (b) surface change

4. Final comments and conclusions

This work presents an analysis of mechanical strength and physical changes of earth-based materials matrices with the addition of different concentrations of kaolin and the particles under 75 microns of the original soil. The conclusions of this research are only applicable to the conditions described, soil and clay used but might be indicative of similar behaviours in similar materials. The main findings of this study are stated below.

1. The increase in the concentration of kaolin increases proportionally the drying shrinkage of adobe which increases its compressive strength as a result of denser material.
2. We proved that the adapted ASTM C 157 testing method in adobe underpredicts its length change at early ages. In this work, we proposed a new testing method to address drying shrinkage of adobe at early ages based on the digital image processing of the surface change. We concluded that an important part of the volumetric changes of adobe caused by drying occurs during the first days after casting. Besides, the length change test could incorporate high variability to the results as the adobe samples remain plastic several days after casting. Overall, the bonds created between kaolin and water at early ages may help to reorder the atomic structure of adobe, reducing voids, and therefore increasing shrinkage and compressive strength.
3. The USCS classification for soils does help classifying soil for adobe block manufacturing. Nevertheless, differences between identical classifications have been observed in this study. The authors suggest that further analysis of the characteristics of the soils must be performed for adobe blocks matrices manufacturing.
4. The flexural strength of adobe blocks matrices is not statistically sensitive to the addition of either kaolin or fine soil particles from the original soil. The dispersion of the results suggests that the number of samples tested ($n = 6$) could be increased to develop more statistical sensitivity.

5. The authors of this paper recommend using soils with at least 30% of kaolin content to manufacture adobe blocks matrices. Although no evaluation of the w/s ratio was performed on this study, the authors observed that this ratio must be close to the liquid limit of the mixture to obtain a workable mix. As an initial rule, we suggest using 2% less of the liquid limit as an optimal w/s ratio for adobe. The evaluation of the microscopical effect of the kaolin, on adobe blocks matrices, is left as future work.

5. Acknowledgements

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