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The Mechanical Properties And Stability In The Water Of Clay Mud Blocks Reinforced With Rice (*Oryza sativa*) Straw

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ABSTRACT: Recovering today to earthen construction techniques in many countries has led to the development of various earth block production techniques, including the clay mud block casting technique. Furthermore, the maturation in water is an essential step in developing cementitious matrix materials because it allows an improvement in performance due to the crystallization of a large amount of cement. However, the best maturing method has not been identified for clay-cement blocks produced by this casting technique. Thus, this research aims to revisit this technique and improve blocks' mechanical performance by proposing the adopted maturation method. Clay mud blocks containing 8% cement and rice straw contents varying between 0 and 1% (mass proportion) were made. They were divided into three-part and exposed to three different treatments. The first part was made to mature at room temperature in a room for 25 days. The second part was made to mature in water for 20 days and then dried for 5 days in the same room. Finally, the third part was matured under a tarpaulin for 20 days and then dried for 5 days in the room. These blocks' flexibility was tested under dry and wet conditions. Similarly, their water absorption and swelling were measured. Blocks that have matured at room temperature dissolve totally or partially in the water, while those that have matured in water and under a tarpaulin remain stable. In addition, fibers generally increase water absorption and blocks swelling. They also increase blocks mechanical resistance because of their distribution and adherence to the clay-cement matrix. Finally, the best bending strengths are achieved with 0.8 % fiber with blocks that have matured in water. The maturation in water increases the bending resistance and reduces the swelling of the blocks in water more important than the maturation under a tarpaulin. Similarly, maturation under a tarpaulin allows greater performance improvement than maturation in air.

Keywords: Rice straw, mud block, swelling, mechanical properties, maturation

INTRODUCTION

Nowadays, it's estimated that approximately 30 % of the world's population still lives in earthen houses (Goodhew and Griffihs, 2005; Binici et al., 2005). This reversion to earthen habitats will keep increasing because sustainable development concepts are being more and more considered, and those earth-based constructions contribute to environmental protection. Many techniques have been developed to meet this strong demand for earth-building materials to develop earth-based building products. Thus, rammed earth and compacted earth blocks are greatly improved in their implementation. In addition, processes for incorporating either mineral or plant fiber additives into soil matrix have been considered to increase the mechanical strength, stability, impermeability and durability of earth products (Reddy and Gupta, 2005; Mesbah et al., 2004).

However, these techniques can only be implemented in specific areas and require training because of these improvements. Contrariwise, casting mud into molds, used to produce adobe blocks, has evolved very little. Its implementation is firmly based on empiricism and traditional knowledge. It requires straightforward equipment that is accessible to low purchasing power populations. The adobe production technique is still widely used in Africa and sub-Saharan Africa. But construction from adobe blocks needs continuous maintenance to keep them in good condition. Their significant limitations include water penetration, erosion of walls at the level by splashing water from ground surfaces, attack by termites and pests, and high maintenance requirements. These limitations and the need for sustainable, low-cost buildings have prompted some work on adobe blocks. Dhandhukia et al. (2013) have explained that the physical parameters of the earth (Atterberg's limits and earth grain size) affect the compressive strength of the adobe blocks.

Despite the fact that any type of soil can be used to make adobe bricks, the best results can be achieved with a specific soil composition (clay content between 10-20% and sand content over 50%). Kouakou et al. (2009), in their studies on stabilized adobe blocks, have tried to use varying percentages of cement as a stabilizer. Then they tested them to ascertain the variation of their properties. According to their results, they could obtain a better quality of adobe at a higher percentage of cement. Quagliarini and Lenci (2010) and Millogo et al. (2016) have established that, in general, small amounts of hydrated lime or natural fibers are added to the earth matrix to improve the mechanical strength, impermeability and durability of locally produced adobe. However, all of this investigation was generally limited to earth with less than 30% clay particles.

Nevertheless, they confirm that adobe blocks' physical, mechanical, and durability properties can be improved by incorporating stabilizers and plant fibers. However, during the drying operation, after shaping adobe blocks, a part of the mixing water retires in the form of vapor. This generates contraction forces which are the origin of drying shrinkage (tightening of the constituent elements). When it is not under control, this shrinkage can have severe consequences for the dry product: deterioration of mechanical behavior, deformations, embrittlement, and the appearance of cracks and micro-cracks (Scherer, 1990; Mihoubi, 2004; Chemkhi, 2008). In addition, uncontrolled drying shrinkage can lead to poor quality of adobe blocks even if they were made with the ideal earth.

Furthermore, le ciment portlande demande environ 25 % de son poids en eau pour hydrater complètement sous réserve de problèmes de floculation et d'expansion (Monkman et al., 2018). Les réactions du ciment Portland avec l'eau produisent des silicates de calcium hydraté (C-S-H) et des portlandite (CH). Elles s'accompagnent d'une modification des propriétés mécaniques du mélange. Ces modifications résultent de la superposition de trois phénomènes : phénomène chimique (hydratation), phénomène physique (cristallisation) et phénomène mécanique (prise et durcissement) (Scrivener et al., 2019). Ainsi, l'observation au microscope électronique à balayage (MEB) des composés à matrice cimentaire hydratée permet de constater que, les grains anhydres de ciment se trouvent recouverts d'une couche hydraté. Cette couche peut s'épaissit de plus en plus s'il y a encore de l'eau dans les capillaires et qu'elle arrive à diffuser à travers les pores des C-S-H (Marchon and Flatt, 2016). A la suite de cette diffusion, les pores des C-S-H se remplit progressivement, les dimensions des capillaires contenant l'eau diminuent et la résistance augment Land and Stephan (2015). Pour obtenir des blocs d'argile-ciment par coulage présentant des performances physiques et mécaniques acceptable, l'humidité interne doit être maintenue assez longtemps. Il faut donc trouver une méthode de maturation qui leur soit la mieux adapté. Thus, the objective of this study is to propose maturation method for blocks produced by the casting technique in order to improve their mechanical properties and their stability in water. For this, we produced clay mud blocks containing 8% of cement reinforced with rice straw by casting and kept in three places: at room temperature, under a tarpaulin and in a water basin. These samples were subjected to tests after 24 days of maturation, to check their water stability and their mechanical performance. This article investigates results of this study.

MATERIALS AND METHODS

Raw material

The clay used for this study was collected in the Dabou area, near the Agnéby village (SW of Abidjan). It was ground to powder using a ball mill. This clay is composed of 52% clay, 47% silt and 1% fine sand. It mainly consists of two-grain types 0.02 µm and 2µ and is made of illite, mainly kaolinite and quartz. In chemical words, clay mainly consists of three oxides: SiO_2 (56.20%); Al_2O_3 (27.75%) and Fe_2O_3 (6.60%) (Kouadio, 2010). Cement used for this study is a Portland cement compound (CEM II) distributed by the Société des Matériaux d'Abidjan (SOCIMAT) under the brand "BELIER". The cement is composed of particles less than 100 µm in diameter. It mainly consists of two-grain types with 9 µm and 68 µm diameters. The rice straw used in this study was obtained after the rice harvest in a field near the Dabou area in southern Côte d'Ivoire. Dry rice stalks are stripped of their leaves. This rice straw thus obtained is stored in a room at the temperature of 25 °C. It looks like a hollow tube whose external diameter varies between 1 and 4 mm. Table 1 displays the characterization results of rice straw.

Table 1: Rice straw Characteristics (Kouakou et al., 2018)

Characteristics	Rice straw
Density mass	0.33
Water absorption at saturation (%)	300
Tensile strength (MPa)	145

Block elaboration

There are several stages in this development. First, 8% cement and 30 mm long rice straw in mass proportions of 0 ; 0.2 ; 0.4 ; 0.6 ;0.8%; 1% are added to the clay powder and all together mixed dry for 30 s. Then, according to the Abrams Slump test, we add some amount of water necessary to obtain a paste with normal consistency that corresponds to 32 mm. This refers to the different water-to-material ratios contained in Table 2. The whole is mixed until obtaining a homogeneous mixture. Finally, this paste is cast into 4 x4 x 16 cm³ molds and then stored in a room at a temperature of 26°C and constant humidity (70%). Previous studies (Djohore, 2020) indicate that blocks containing 0.8% rice straw give the best compressive strength. Therefore only the test pieces compound of 8% cement and 0.8% rice straw of 30 mm length will be used for the rest of the work. Three (3) days after shaping, test pieces are unmolded and divided into three groups. The first group of test pieces is stored in the same room at 25°C room temperature and relative humidity of 70% up to 28 days of age. The second group is dry under a tarpaulin for up to 20 days and then dried at room temperature for 5 days. The third group is immersed in water until the 20th day, and then the tubes are removed from the water and dried at room temperature for 5 days. These three groups of samples thus treated will be subjected to various tests.

Table 2: Experimental test results

Mature method	Sub-group	Dry density (g/cm^3)	Drying shrinkage (%)	flexural strength (kPa)	
				Dry	Wet
Air	Without rice straw	1,391	47,600	104,28	-
		1,441	46,511	104,31	-
		1,462	47,458	103,78	-
		1,427	47,794	104,56	-
		1,435	47,399	104,18	-
	With rice straw	1,215	29,224	145,42	-
		1,182	29,579	144,37	-
		1,191	28,983	144,21	-
		1,192	29,691	145,49	-
		1,200	28,213	145,51	-
under a tarpaulin	Without rice straw	1,414	7,159	110,52	87,59
		1,431	7,617	109,91	88,11
		1,384	6,182	111,01	89,81
		1,406	6,363	109,81	89
		1,414	8,729	110,75	88
	With rice straw	1,238	6,609	151,43	86,95
		1,090	6,424	152,01	87,15
		1,225	6,632	151,82	87
		1,180	6,555	150,97	88
		1,188	6,291	150,77	86,82
In water	Without rice straw	1,260	2,406	113,24	98,71
		1,334	2,894	112,24	99,5
		1,377	2,488	113,28	100,1
		1,320	2,088	114,19	99,1
		1,328	2,298	112,55	98,1
	With rice straw	1,060	1,301	153,41	90
		1,148	1,829	152,62	91,54
		1,266	1,346	154,23	92,16
		1,154	1,474	153,21	91,22
		1,162	1,379	152,53	90,59

Testing techniques

- **Mechanical bending test**

Specimens were submitted to a three-point bending strength test according to standard NF P 15-451. Bending strength (σ) is calculated from the formulae:

$$\sigma = 3Fl / 2b^3 \qquad (1)$$

These tests were performed on dry and wet blocks. Average values recorded are obtained from three blocks.

- **Absorption and swelling test**

Two 0.5 mm diameter pins are first inserted into each test pieces, a short distance from each other (l_0), and then the mass (M_0) of each test pieces is determined using a 0.01 precision balance. After that, each test piece was immersed in water for different periods (15; 30; 60 min and 24 hours). Then specimens are taken out of the water and the distances between the two pins (l_t: I_{15}; l_{30}; l_{60}; l_{1440}) corresponding to each different periods are measured with a 0.02 mm precision caliper and their mass (M_t: M_{15}; M_{30}; M_{60}; M_{1440}) is determined. These formulae obtain swelling (G) and absorption (A):

$$G = 100(l_t - l_0) / l_0 \quad (2)$$

$$A = 100(M_t - M_0) / M_0 \quad (3)$$

nd density

Specimens' dimensions decrease while drying. To assess this shrinkage, the drying shrinkage is calculated from the measurements (length (L), width (l), and height (h)) determined on specimens from day 1 and after 28 days of drying with a 0.02 mm precision caliper. The formula gives the shrinkage:

$$R = 100(V - V_0) / V_0 \quad (4)$$

nal volume, V_0 as the test tube's volume after 28 days of drying and maturation (V=L*l*h).
In addition to the 28 days of drying, some test tubes are put in an oven for 24 hours at 105°C temperature. Then their mass (M_1) is determined using a 0.01 precision balance. Finally, their dry density is calculated.

Statistical analysis

The data subjected to analyses are taken from the tests carried out on test pieces. The statistical analysis was performed on 30 test pieces in which 3 parameters were determined in each test pieces (table 2). These 3 parameters are flexural strength, density and drying shrinkage. Given that these variables are quantitative, the statistical methods adopted in this study are descriptive statistics and a t-test using the STATISTICA version 7.1 software. The means, maximum and minimum values, standard deviations (SD), and standard error of the mean (SEM) were performed on 3 parameters of 5 test pieces (Table 3). The aim is to describe the dispersion of data points (SD) and the precision of the study means (SEM). The t-test was carried out on means of the blocks flexural strength values from each mature method. The test aim was to identify the statistical signification of the difference between these means. Therefore, the t-test was used to determine if there is a significant difference between the mean of the two groups, which may be related to certain features.

Table 3: Statistical summary of parameters

Mature method	Sub-group	Statistics	Dry density (g/cm^3)	Drying shrinkage (%)	flexural strength (kPa)	
					Dry	Wet
Air	Without rice straw	Mean	1,431	47,352	104,22	-
		Minimum	1,391	46,511	103,78	-
		Maximum	1,462	47,794	104,56	-
		SD	0,025	0,494	0,283	-
		SEM	0,011	0,221	0,126	-
	With rice straw	Mean	1,196	29,138	145,00	-
		Minimum	1,182	28,213	144,21	-
		Maximum	1,215	29,691	145,51	-
		SD	0,012	0,588	0,651	-
		SEM	0,005	0,263	0,291	-
under a tarpaulin	Without rice straw	Mean	1,409	7,210	110,40	88,50
		Minimum	1,384	6,182	109,81	87,59
		Maximum	1,431	8,730	111,01	89,81
		SD	0,017	1,031	0,523	0,893
		SEM	0,007	0,461	0,234	0,399
	With rice straw	Mean	1,184	6,502	151,40	87,18
		Minimum	1,090	6,291	150,77	86,82
		Maximum	1,238	6,632	152,01	88,00
		SD	0,058	0,142	0,531	0,471
		SEM	0,025	0,063	0,237	0,210
In water	Without rice straw	Mean	1,323	2,435	113,10	99,10
		Minimum	1,260	2,088	112,24	98,10
		Maximum	1,377	2,894	114,19	100,10
		SD	0,041	0,297	0,755	0,760
		SEM	0,018	0,132	0,337	0,340
	With rice straw	Mean	1,158	1,466	153,20	91,10
		Minimum	1,060	1,301	152,53	90,00
		Maximum	1,266	1,829	154,23	92,16
		SD	0,073	0,212	0,687	0,836
		SEM	0,032	0,095	0,307	0,374

RESULTS

Blocks stability in water

Blocks absorption

Figure 1 shows variation in block absorption over time. It shows that blocks matured in the air completely dissolve in water while those matured under a tarpaulin and in water are stable. The way blocks mature improves their stability in water. Anbukarasi and Kalaiselvam (2015) also show that the water absorption capacity of epoxy composites reinforced with the luffa fiber increase with the time

This figure also shows that those matured under a tarpaulin absorb more water than their counterparts matured in water for the same block type. This is because blocks maturation under tarpaulin results in a higher capillary absorption capacity than maturation in water. Moreover, straw in blocks promotes high absorption capacity as even in the same maturation mode, partnerships with straw have higher absorption. Therefore, as rice straws have a high absorption capacity, their presence increases block absorption capacity. All the absorption curves have the same shape. The slope of these absorption curves, from 0 to 15 min, corresponds to the speed of absorption. Therefore, they are identical, whatever the maturation method and whether there is rice straw or not. The speed of absorption being a function of the size of the pores, blocks could therefore contain the same types of pores. However, the maturation model causes specific capillary pores to close, resulting in the variation in block absorption capacity.

Blocks swelling

By absorbing water, blocks can increase in volume. Figure 2 shows block swelling as a function of time. This figure shows that those matured under a tarpaulin are more swollen than their counterpart matured in water for the same block type. Blocks matured in water have a low swelling capacity than those developed under a tarpaulin. Maturation in water results in the blocks less swelling water. When the block swells, its volume increases. This is only possible if the water osmotic pressure in the pores becomes more significant than the bonding forces between the particles. Maturation so favors the formation of bonds between particles, which reduces swelling. When they contain straw, the blocks that have undergone maturation have a higher swelling capacity than those that do not include straw. But, the blocks that have undergone maturation in water, those with no straw, swell more than those with straw. During maturation in water, blocks and rice straw they contain are saturated with water, unlike maturation under a tarpaulin where blocks are in a space with high humidity. In this water-saturated environment, cement gel can quickly crystallize around rice straws, preventing them from swelling. According to Bachir et al. (2014), block swelling increases with decreasing cement content and improving the fibers of palm content. These results show that it is possible to reduce the swelling of blocks content through a ratio of cement and fiber by maturation in water

Blocks mechanical flexural strength

According to their maturation mode, blocks mechanical properties are displayed in Table 4. The results of the t-test applied to the flexural strength means gave in Table 5. Using the degree of freedom value 4 and a 0.05 level of significance, a look at the t-value table gives a value of 2.132. Comparing this value against the computed values in table V indicates that the theoretical t-values are greater than the table value at a significance level of 0.05. Therefore, it is safe to reject the null hypothesis that there is no difference between means. Therefore, the flexural strength set has intrinsic differences and is not by chance.

Table 4 shows that in the dry or the wet state with the absence or presence of rice straw, blocks flexural strength is higher when water is performed and decreases when maturation is performed under a tarpaulin and is lower when maturation occurs in the bear air. The same observations are made in the wet state. Blocks maturation favors cement crystallization better in a very humid environment, hence increasing flexural strength. This table also shows that when blocks are dry, the presence of straw in blocks strengthens their mechanical resistance to bending. The gain in resistance compared with the blocks without a straw is more than 35%, whatever the maturation mode. However, when blocks are wet, we can notice a loss of flexural strength by less than 8% compared with the blocks without straw.

The blocks physical properties

Blocks density

Blocks density variation is displayed in figure 3. It indicates that block density varies with their maturation mode and whether or not rice straw is present. From the same maturation mode, the thickness of blocks with straw is lower than that of the blocks with no straw. This is because the straw makes the blocks lighter. In addition, the density of blocks with or without a straw is greater when ripened in air and decreases from ripening under a tarpaulin to ripening in water. This can be explained by shrinkage during drying.

Drying shrinkage

Blocks drying shrinkage varies with their maturation mode and with or without the presence of rice straw (Figure. 4). The shrinkage of blocks with straw is lower than that of blocks without straw from the same maturation mode. Straw limits block shrinkage.

Blocks shrinkage in the absence or presence of straw is more critical when their maturation takes place in the air and decreases from maturation under a tarpaulin to maturation in water. During blocks hardening phase, the way the blocks mature affects their shrinkage. Indeed, three days after shaping, blocks are rigid. However, cement hardening continues and requires continuous hydration. When maturation takes place in water, blocks are saturated with water. This promotes hydration and formation of cement gel which crystallizes binding particles hence low shrinkage. When maturation occurs under canvas, blocks are in a humid space with water in vapor form. This water vapor hydrates the cement and crystallizes it. But the reaction of water vapor with the anhydrous grains of cement reduces the amount of free water, resulting in more shrinkage than when maturation occurs in water. When maturation occurs in the bear air, the water contained in blocks evaporates faster, resulting in a significant shrinkage compared with blocks matured under a tarpaulin.

DISCUSSION

For the development of earth-based materials, when the quantity of mixing water is high and is close to the plastic limit, drying is an important step that guarantees the quality of the blocks. According to Nowamooz et al. (2013), solid particles come together during drying. They reorganize and the porosity of the material changes. This causes cracks and deformations in the material. Cement is incorporated into the blocks to reduce and/or limit these effects (Kouakou, 2005). Other materials of plant origin, such as fibers can perform this same function and serve as reinforcement in earth materials (Merzoud, 2007). Bouhicha et al. (2005) showed that adding barley straw to the soil reduced shrinkage and hardening time and improved compressive, flexural and shear strengths.

Phung (2018) confirms the reduction of the hardening time by arguing that the incorporation of fibers (flax and wheat straw) in the soil allows obtaining a higher (rapid) drying kinetics by the water transport ease the inside to outside of the sample through the straws. After three days, the blocks developed in this work were put in different environments. These three days correspond to when the evaporation of the water produces normal shrinkage (the evaporation of the water is accompanied by an equal decrease in the volume of internal pores). The pores remain saturated with water (Haines, 1921 in Thi, 2017) under changes in temperature and/or humidity. When put under a tarpaulin where humidity is maintained at a high level, the drying kinetics are slow. Therefore shrinkage is low, so the risks of cracking and deformation become small. As the density becomes more down, however, the resistance is higher. In addition, when soil-cement composites containing fibers are immersed in water, the humidity level is 100 %. Thus, the hydration of the cement is better and the cement gel formed crystallizes in the pores to promote improvements in the characteristics of the blocks (Zhou et al., 2016). The maturation of blocks under a tarpaulin and in water improves performance compared with blocks in the air kept. Rigassi (1995) has compared Compressed Earth Blocks (CEB) stabilized with Ordinary Portland Cement produced in four conditions: exposing to direct sun and wind, sheltering from direct sun and wind, covering with wet clothes and conditioning in relative humidity approaching 100%. He has demonstrated that the last method is most effective when the dry compressive strength at 28 days is concerned. Likewise, Ouedraogo et al. (2020) have shown that the effect of the curing method was most notable on the wet compressive strength, which was not possible to be measured before 7 days of curing. Our results conform with those of these authors and they show that the maturation in water gives the highest resistance

On CEB made at 18 MPa pressure, containing bamboo fibers without cement, Abessolo et al. (2020) obtained flexural strengths, which vary between 0.4 and 2 MPa. Similarly, Ntom Nkotto et al. (2020) obtained CEB containing 0.8% of coconut fibers without Portland cement and CEB containing 8% of Portland cement without fibers, respectively, with flexural strengths of 1.17 MPa and 0.33 MPa. The high values of the resistances compared with the results obtained in this work are explained by the compression of blocks. Indeed, earth compaction leads to densities varying between 1.43 to 1.53, while the densities obtained in this work vary between 1.15 and 1.43. In addition, Mostafa and Uddin (2016) obtained CEB containing banana fibers flexural strengths varying between 0.56 and 1.02 when the fiber length increased from 0 to 100 mm. The differences between the results of all these authors are also related to the nature of the used fibers.

CONCLUSION

In this investigation, the contribution of maturation environments to improving the mechanical properties and stability of mud blocks reinforced with rice straw containing 8% of Portland cement is addressed. The focus is made on evaluating the effect of the liquid and vapor water on the conservation space of blocks, consisting of sample maturation in a room (25°C, 65%RH), under a tarpaulin (25°C, ~100%RH) and water (25°C, water immersion). It permits us to understand that incorporating rice straw into a cement clay mixture improves its resistance to bending when dry and wet. However, resistance acquired when dry by the blocks with straw is more than 35% compared with those without straw.

Blocks maturation under tarpaulin or in water makes them stable and limits their water absorption capacity and swelling thanks to an improvement in cement crystallization. It also increases bending strength. The hydration process of cement is strongly affected by the presence of clay, notably due to its specific solid surface area and its affinity with water molecules and the fact of the straws because of their affinity with water molecules. Under a tarpaulin, the water molecules (vapor water) don’t arrive to hydrate all the cement grains. The capillary pores are partially saturating water due to clay and straws' attractive effect on water molecules. Contrary, when blocks are saturated in water, the capillary pores are full and empty of water. This free water can move easily and hydrates all the cement grains. Cast clay-cement blocks maturation in water is the optimal method to increase their performance and stability. It lets us look at maturation as an "ecological" method to reduce the use of cement.

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The authors confirm no conflict of interest.

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