ИННОВАЦИОННЫЕ ПРОГРАММЫ ИНЖЕНЕРНЫХ ИССЛЕДОВАНИЙ

PHYSICAL AND MECHANICAL CHARACTERISTICS OF THE EARTHEN BARNS USED FOR FOOD CROP STORAGE IN THE NORTH-WEST OF BENIN (WEST AFRICA)

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Atacora and Donga are two departments regarded as the barns of Benin. In these two regions, the surplus of food crops harvested by farmers is stocked in earthen barns whose primary construction material is kneaded clay soil with an admixture of vegetable straws (fonio, rice…) pounded beforehand.

The following research is designed to scrutinize the variation of compression strength and/or tensile strength of the used earthen material with respect to the optimum straw content, and the fluctuation of the fracture related parameters.

Laboratory tests have shown that an optimum straw content of 2% provides the highest compression strength with the best mechanical performances in terms of cohesion and internal angle of friction. Tensile strength, however, continues to increase with higher straw percentages with no breakpoint indication. Moreover, the laboratory determination of the composite material's modulus of elasticity has proven that the used soil does not have a linear elastic behavior.

Key words: earthen barns, clay soil, vegetable straws, strength, fracture related parameters.

The use of earthen barns is a very old tradition in the north-west of Benin where it is perfectly integrated in an efficient storage system of cereals (grains of corn, fonio sorghum and others), legumes (voandzou, beans, peas), and cossette (dried yam used to make flour). Compared with other storage structures used for food products (wood storage sheds, barns made of bamboo, etc.), earthen barns are more suitable from a sustainability standpoint (longevity of more than 40 years), in terms of storage capacity (more than 3 m^3), and in regards to the stock protection against parasites and rodents. This article aims at bringing out the physical and mechanical characteristics of earthen barns so as to properly size other food storage structures and integrate them in the other rural areas of north and central Benin where the climate is favorable for their construction. This will enable rural farmers to resolve food conservation problems that engender the poor management of crops during harvest season.

The study area includes the departments of Atacora and Donga (Figure 1). From a geomorphologic point of view, this area covers the depression of Oti-Pendjari, the massif of Atacora and the Dahomeyan peneplain.

Figure 1. Localisation of the study area

The geological formations are shales, silts and fine noticeable sandstones of brown-reddish colour which is due to river sections. Slightly leached and ferruginous, the ground in this area is characterized by sandy-clayey horizons, made of humus, and containing ferruginous concretions.

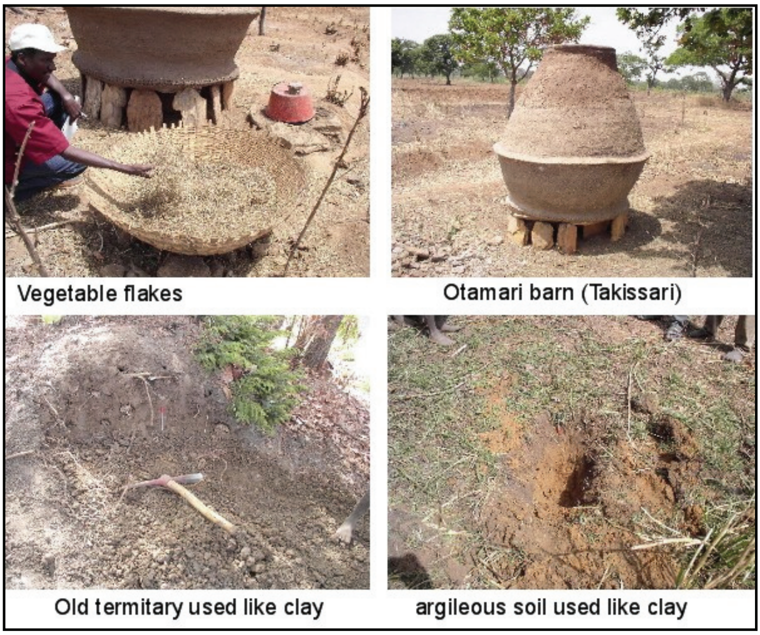
The climate in this region is Southern Sudanese (Sudanese-Guinean) and encompasses two seasons: a dry season from November to the beginning of May, and a rainy season from May until October. The economy is dominated by agriculture in which the major part of the working population indulges. Farmers cultivate cereals, tubers and legumes whose preservation is sometimes subject to challenges.

The main construction material used for barns is clayey soil (outcropping clayey soil and/or termites mound) kneaded with hands and feet until certain plasticity is achieved. Then vegetable straws made of folio, rice or other stalks (which were crushed beforehand) are added as shown on Picture 1 underneath. The straw to be chopped and mixed with clay must be light, flexible, soft, and fibrous when it is crushed.

This mixture is used for building the barn whose wall thickness varies from 4 to 7 cm.

Barns are constructed one piece at a time over a ten-day period. An under floor space with pillars made of stones or wood is used as base support for the barn. The recommended period for barn construction in the north of Benin is between December and March, characterized by the end of the rainy season and the arrival of the dry wind (harmattan) between December-January followed by a long heat spell (February — March).

When the percentage of clay is too high, shrinkage becomes important and the dried material cracks more rapidly. The twigs of herbs mixed with the clayey soil fight against the shrinkage phenomenon. The material stretch is rather slow as the used soil is more or less rich in clay. Laboratory tests show this stretch lasts between 72 and 96 hours (CNERTP, 1999). The stabilization is ensured by vegetables extracts (CNERTP, 1999). The life expectancy of a barn is at least 40 years. Following the study of different types of barns, several tests were carried out. Those included gradation tests, strength tests, and fracture related parameters of the materials used.

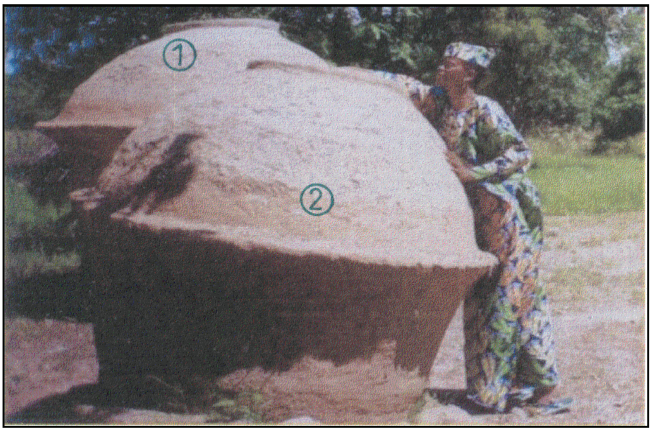


Picture 1. Depiction of clayey soils and vegetable flakes used in the building of barn

Gradation tests. Gradation tests allowed to measure the grain size distribution and to estimate the Atterberg Limits (Plastic Limit, Liquid Limit, and Plasticity Index) of the used soil. The apparent and specific weights of the material were also determined. These particle size classification tests encompass the sieve analysis for grains larger than 80 micrometers, and the hydrometer analysis for grains smaller than 80 micrometers (silts and clays).

Strength tests: fabrication and crushing of cylindrical and prismatic test tubes. Prior to making test tubes, modified Proctor tests were carried out to determine the optimum water content for which the dry density is maximal, based on the proportion of vegetable straws used in the mixture. The fabricated cylindrical brick slips are standardized NF standards P18—400 with a diameter of 10 cm and a height of 20 cm. As for the prismatic brick slips, they are standardized NF standards P 18—401 and measure 4 cm × 4 cm × 16 cm. The constructed cylindrical test tubes were wrapped in wax cloths for 7 days to preclude swift shrinkage. They were then crushed through simple compression and diametrical compression after 28 days of cure. The prismatic test tubes had been kept earlier in a cold room for 28 days before being crushed through bending and simple compression.

Tests for determining the physical and mechanical coefficients. These laboratory tests consist of loading the test tubes to measure the stress and strain, and shearing them in order to determine the material's cohesion and internal angle of friction (C and f). The tests were carried out using test tubes with various proportions of vegetable straws (1.5%; 2%; 2.5% and 3% of vegetable straws). As an investigation of whether the material's characteristics evolve with age, direct shear tests have been run on different types of barns at intermediate time spans. Periods of 3 days, 7 days, and 14 days had been selected for that matter. A barn is comprised of an upper dome and a lower dome connected by a belt which denotes the largest circumference of the barn as presented on Picture 2. A barn is of the Yom type when H/RC = 1/2 (a/3), of the Otamari type when H/Rc = 2 (c/1), and of the Monkolé type when H/RC = 1 (a/1, b/2 or c/3). The Lokpa type has a cylindrical lower dome (a, b or c / 4). No matter what type of barn, the upper opening must be large enough to enable the user to get in and out. The radius R of the barn must be greater than or equal to 60 cm, but always less than the central radius Rc.



Picture 2. Depiction of a few types of barns

The sieve and hydrometer analyses of the used soil yielded the grain size distribution curve shown beneath.

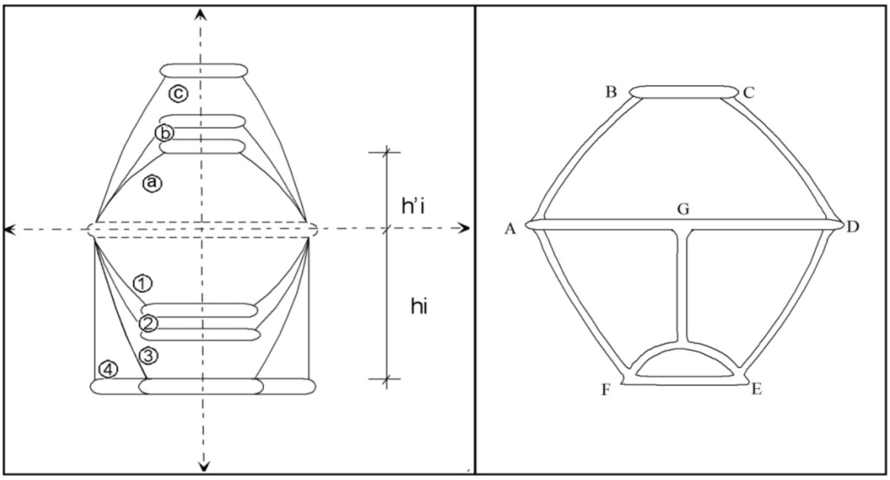


Figure 2. Analysis of different types of earthen barns

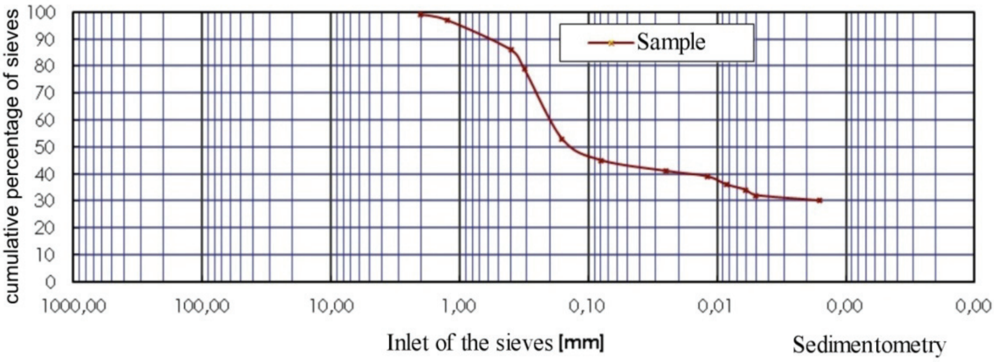


Figure 3. Grain size distribution curve of the used soil

The coefficient of uniformity Cu of the used soil is equal to 200, which indicates that the soil is well-graded. As for the Atterberg Limits, the plasticity index I_p was determined to be 18.11 and the liquid limit w_L 36.

Per Casagrande's Plasticity Chart, these I_P and w_L values classify the used soil as an inorganic clay with average plasticity. According to the Unified Soil Classification System (USCS), the used soil is a clayey sand.

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The apparent density of the soil is γa = 1.09 g/cm3 and the specific weight γs is equal to 2.64 T/m3.

The gradation tests have thus identified the material as a clayey sand with an average plasticity. Strength wise, this material by itself, will not supply good mechanical characteristics. Hence, the customary use of vegetable straws as admixture in barns manufacturing.

Strength tests, compression tests on cylindrical and prismatic tubes. The results of the compression test on cylindrical and prismatic test tubes are recorded in Table 1. These results show that stress values have accrued when the percentage of straws increased from 1.5% to 2%. From 2.5% upward, however, these stress values have dropped as indicated by Table 1. Therefore, the optimum straw percentage for each type of compression test is 2%.

Diametrical compression tests (or splitting tensile tests) and flexure tests. The results of the diametrical compression tests and flexure tests presented in Table 1 show that stress values increase linearly with the percentage of straws. Therefore, the straws used in traditional constructions fulfil the same role as reinforcement bars utilized in concrete constructions. However, this increasing pattern of stress values with the percentage of straws, reaches a stopping point where a reverse paradigm starts occurring. The optimum percentage of straws will be determined by the desired minimum compression stress. Above 2% of straw, the greater the straw percentage is, the lower the compression stress value becomes. As further highlighted by Table 1, compression stress and bending stress values of prismatic tubes are more indicative in terms of determining the optimum straw percentage to be used.

Table 1

Modified proctor characteristic and values of resistances to compression and traction of cylindrical and prismatic test pieces

			Cylindrical test tubes		Prismatic test tubes	
Composite	Optimal water content (W_{op})	Maximal dry density (γdmax)	Simple compression stress (Mpa)	Diametrical compressive stress (or plitting tensile stress) (Mpa)	Simple compression tress (Mpa)	Bending stress (Mpa)
1.5% of straw	12.5%	$1.86T/m^3$	2.292	0.456	2.844	0.487
2% of straw	14.0%	$1.82T/m^3$	2.801	0.491	3.340	0.619
2.5% of straw	13.0%	$1.75T/m^3$	2.546	0.540	2.844	0.712
3% of straw	12.8%	$1.77T/m^3$	1.859	0.583	2.745	0.788

Determination of the physical and mechanical coefficients of the various composites. Determination of the modulus of elasticity *E* and Poisson's ratio *ν*. For the composite material with 1.5 % of straw (Figure 4). The obtained stress vs strain curves are presented on Figure 4 below. The analysis of these curves shows they cannot be assimilated to straight lines. Thus, the composite material with 1.5% of straw does not display a linear elastic behavior and the determination of the modulus of elasticity will be convoluted. The Poisson's ratio for the above specimen was determined to be the average of the coefficients of all the test tubes, that is $\nu = 0.52$.

For the composite material with 2 % of straw (Figure 5). 16 test tubes with 2% of straw had been loaded and the stress vs strain curves were plotted as follows. As illustrated by Figure 5, these curves are not straight lines. Therefore, the composite material with 2% of straw does not exhibit a linear elastic behaviour. The Poisson's was determined to be the average coefficient of the 16 test tubes, which is $\nu = 0.37$.

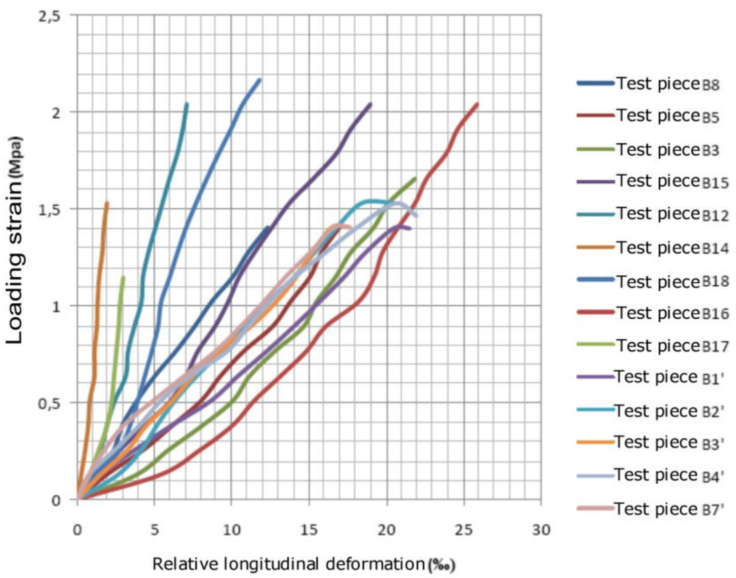

Figure 4. Stress vs strain curves of test tubes with 1.5% of straw

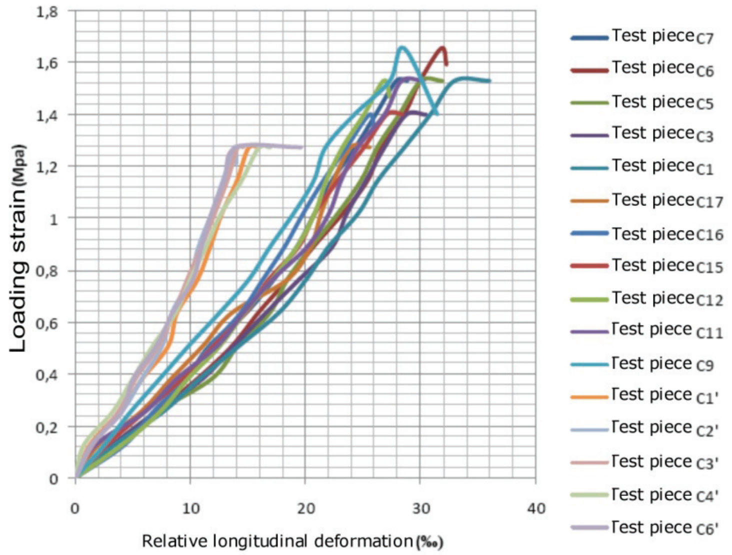

Figure 5. Stress vs strain curves of test tubes with 2% of straw

For the composite material with 2.5% of straw (Figure 6). 16 test tubes of the composite material with 2.5% of straw had been loaded and the resulting stress vs strain curves are presented below.

Figure 6 shows these curves are not straight lines. As a result, the composite material with 2.5% of straw does not have a linear elastic behaviour. The Poisson's ratio was found to be ν = 0.33.

For the composite material with 3% of straw (Figure 7). 17 test tubes of the composite material with 3% of straw had been loaded and the stress vs strain curves appear as follows.

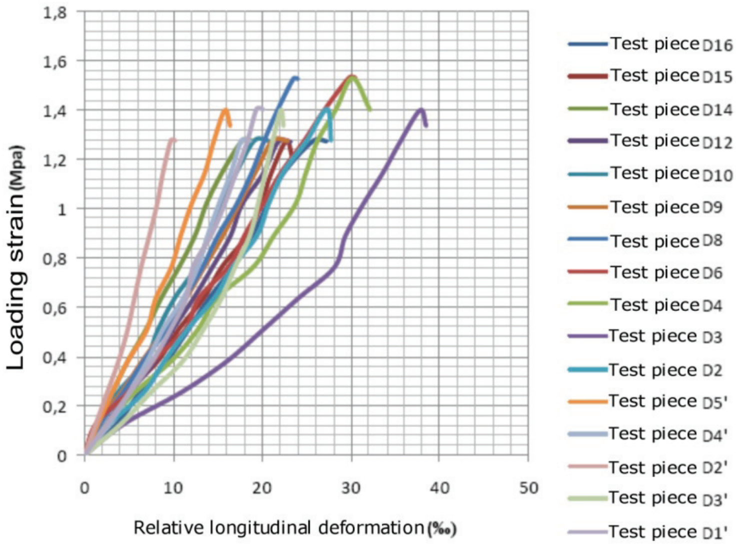

Figure 6. Stress vs strain curves of test tubes with 2.5% of straw

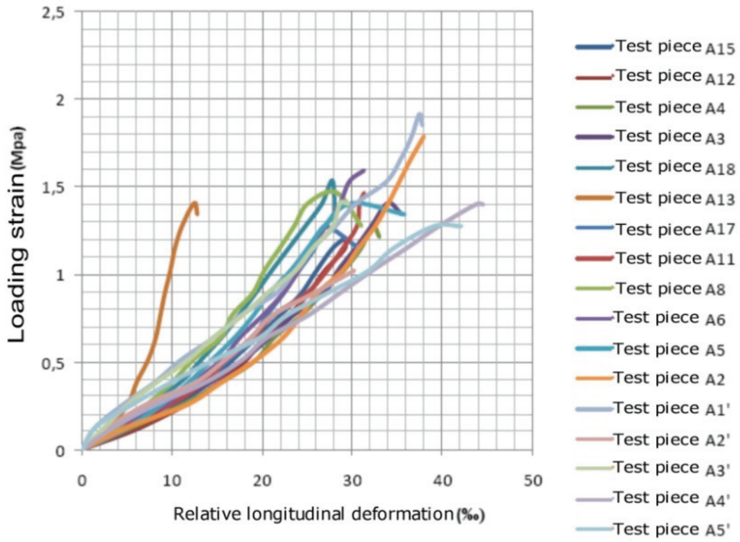

Figure 7. Stress vs strain curves of test tubes with 3% of straw

Just as in the case of the previous composite materials, these curves are not straight lines and the composite material with 3% of straw does not have a linear elastic behaviour. The Poisson's ratio was determined to be $\nu = 0.33$.

In the course of these loading tests, the Poisson's ration went from 0.52 to 0.33. Therefore, the Poisson's ratio decreases as the straw percentage increases.

3.4.2. Determination of the cohesion c and the internal angle of friction φ of the four types of composite material (1.5%, 2%, 2.5% and 3% of straw)

The values of the cohesion and the internal angle of friction based on the cure time are summarized in Table 2.

The results of the Direct Shear Test performed on each composite material indicate that cohesion increases with cure time; even if the internal angle of friction does not have a clearly defined variation pattern. Considering Mohr-Coulomb's Equation: $\tau = \sigma \cdot \text{tg}\ \varphi + C$ and Coulomb's Failure Criterion equation involving principal stresses:

$$\sigma = \text{tg}^2\left(\frac{\pi}{4}+\frac{\varphi}{2}\right)\cdot\sigma_3 + 2\cdot\text{tg}\left(\frac{\pi}{4}+\frac{\varphi}{2}\right)\cdot C,$$

randomly selected values of τ and σ_3 revealed that the global characteristics (C; φ) of all the composite materials have improved between 3 days and 28 days regardless of the variation trend of the internal angle of friction. Therefore, the mechanical coefficients (C; φ) of the composite material improve with cure time in open air.

The results also reveal that at every stage of the cure, the cohesion of the composite material with 2 % of straw is the highest (See Table 2). Furthermore, these results confirm that 2% of straw is the optimum admixture quantity to obtain better performances in terms of mechanical coefficients (C; φ) of the composite material.

The material used for the construction of earthen barns is nothing else but clayey soil displaying useful properties for the construction of structures with complex shapes given conducive weather conditions. Vegetable straws are used as admixture to provide reinforcement for the clayey soil.

Table 2

Values of C and φ per cure time and per composite

Composite	Cure Time (Time between molding and shearing in days)	Cohesion C (daN/cm2)	Internal Angle of Friction (°)
1.5% of straw	3days	0.50	23
	7 days	0.65	14
	14 days	0.70	25
	28 days	0.95	25
2% of straw	3 days	0.60	28
	7 days	0.80	21
	14 days	0.95	20
	28 days	1.15	21
2.5% of straw	3 days	0.60	25
	7 days	0.70	25
	14 days	0.80	20
	28 days	1.10	23
3% of straw	3 days	0.55	19
	7 days	0.60	17
	14 days	0.70	20
	28 days	1.00	17

Not only is this research geared toward improving the compression strength and tensile strength of the composite material by varying the straw percentage, but also at identifying the fracture related mechanical parameters of the used material.

The results of the various tests carried out in this study have indicated that 2% of straw is the requisite admixture for optimum compression strength and shear strength. Optimum tensile strength, however, is achieved with an admixture of 3% of straw.

Compression tests on cylindrical tubes, which have yielded the stress vs strain curves for all the composites materials, show that none of the curves are linear within the elastic region of behavior. Hence, the used soil does not have a linear elastic behavior. As for the results of the Direct Shear Test, they revealed that the use of 2% of straw as admixture provides the material with optimum mechanical characteristics of cohesion and internal angle of friction.

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ФИЗИКО-МЕХАНИЧЕСКИЕ ХАРАКТЕРИСТИКИ ГЛИНЯНЫХ АМБАРОВ, ИСПОЛЬЗУЕМЫХ ДЛЯ ХРАНЕНИЯ ПРОДУКТОВ НА СЕВЕРО-ЗАПАДЕ БЕНИНЫ (ЗАПАДНАЯ АФРИКА)

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Лабораторные эксперименты показали, что оптимальное (2%) содержание соломы обеспечивает максимальное сопротивление изделия сжатию и лучшие механические параметры для его изготовления благодаря сцеплению и внутреннему углу трения. Воспринимаемые напряжения растяжению, тем не менее, продолжали увеличиваться при увеличении процентного содержания соломы без образования трещин. Экспериментальное определение модуля упругости композитного материала доказало, что применяемый грунт ведет себя как нелинейно-упругий материал.

Ключевые слова: глиняный амбар, глинистый грунт, растительная солома, прочность, модуль упругости.