Quality Control of Compressed Earth Blocks (CEB) on Building Sites.

C. H. Kouakou, M. O. Boffoue, K. C. Kouadio, A. A. Assande, E. Emeruwa

***Abstract*— In Côte d'Ivoire, compressed earth blocks are produced, with manual presses in non industrial factories or directly on the building sites. In these factories, the industrial methods for control of the quality of those blocks worked out in laboratories, such as optimal static compaction or moisture characteristics, are difficult to apply because of lack of appropriate equipment or these are unsuitable. In order to overcome this deficit and predict their performances, according to the characteristics determined on fresh CEB, some blocks have been made of earth extracted at Cocody (Abidjan). Then, the Physical characteristics, directly accessible in buildings sites such as the weight, the volume of blocks and the volume of the mixing water content have been measured on fresh samples. The results show that it is possible to optimize the compaction and control the quality of blocks produced, in the non industrial factories, according to the relationship between the wet density of blocks and the flow coefficient (ratio volume of mixing water /volume of blocks).**

***Index Terms*— Building site, wet density, mixing water, compaction, compressed earth blocks**

I. Introduction

In recent years, the use of earth in construction is becoming more and more important everywhere because earth seems to be an ecological material, and has a high spatial distribution [1]. This idea is supported by many publications and scientific seminars, where the quality and benefits of earth construction are proved. These earth materials can be realized by various techniques, such as the static compaction for compressed earth blocks. The various approaches, proposed for the static compaction, require a press. They all require also an optimization of the water content. Indeed, the mechanical properties of building materials in general are closely related to their dry density [2], which varies according to earth blocks, the amount of mixing water and the nature of the earth.

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In order to optimize the water content, the "drop test" proposed by [3] which consists in dropping a roll from 1.5 m height is recommended. The moisture content is optimal if the roll is fractured into 3 or 4 pieces while dropping. This method is more practical, but it highly depends on the worker and offers a large range of water quantity.

That is why, certain authors like [4] recommend the Proctor test used in road geotechnics to determine the optimum water quantity (optimum proctor) and obtain the efficient mechanical properties of blocks. For sandy soils, the results are satisfactory but, when the ratio of fine particles is important, the optimum Proctor is not significant any more. To correct this insufficiency of the Proctor test, they recommended using the optimum Proctor ± 3 %. Moreover the mode of compaction used in the Proctor test is dynamic which is different from the static compaction used for earth compressed blocks. Then, in regard of the specificity of fine earth, fixing the water content at the optimum Proctor ± 3% is not appropriated.

Other authors [5] recommend the application of a static compaction (or static manual press) to determine the optimal water content. In fact, this water content is highly [1]dependent on the energy of compaction. When the energy of compaction increases, the air in the mixture (earth and water) is under high pressure and is gradually evacuated. The earth approaches the water saturation and its density does not vary enough. The dry density tends towards a limiting value.

A method, usable on building sites, is proposed by [6] [7] with the following steps:

1- Take a quantity (mass) of material (earth with a certain ratio of cement and water content). Introduce it into the mould (of the press) and apply a static compaction to obtain a first quality of block.

2- To the same volume of water, like in the first step, add gradually a quantity of material into the mould until the compaction becomes difficult or impossible.

3- Increase the water content and go back to step 1

4- For each water content, determine the corresponding maximum of dry density.

5- Plot the curves of the maximum dry density of water content. The optimum water content corresponds to the highest dry density.

As the measurements of the water content are based on laboratory tests which require hardware such as an oven that can raise temperatures to 105 °C, therefore, this is impossible on the building sites. And with the oven, the results are only available 24 hours before moving to the production phase. This approach is more useful because it allows a rigorous determination of the optimum water content. But, on building sites, the tasks must be performed in a relatively short time so, waiting for laboratory results is too long. In addition, the earth used for the production of blocks is not always kept under shed. Therefore, its natural water content can vary from one day to another because of bad weather. We would have to determine the new natural water content in the earth, before calculating the amount of mixing water. And the work would be delayed. Moreover, there are no methods to control the quality of fresh blocks. That is why, it seems appropriate to define none empirical method, with fairly fast results and applicable on building sites. This papers so purpose to determine a couple of parameters that can help us control the quality of fresh blocks on building sites or find the optimum proportions of mixing water in earth, for achievement strength compressed earth blocks on building sites.

II. PREPARATION OF COMPRESSED EARTH BLOCKS AND TESTS

Making compressed earth blocks (CEB) requires raw material: the earth taken at Cocody (road of Bingerville) and submitted to the characterization analysis. The results are presented in Table I. By comparing these results to the others, used by [1], [6], [8] we can conclude that it is suitable for compressed earth blocks.
This earth is mixed with some water taken arbitrarily and used to produce blocks. Different amounts of mixing water are used. They are obtained by incrementing the amount of water initially used.

Table I: Identification and composition of Cocody's earth

Sand (10 mm – 0,080 mm)	53 %
Silt and clay (< 0,080 mm)	47 %
Liquid Limit	41 %
Plastic Limit	21 %
Plasticity index	20 %
Grain density	2.65 g/cm^3
Natural water content	6 %

In these different mixtures, the water content of blocks is determined by drying in an oven at 105 °C for 24 hours to attain constant weight. Similarly, the ratio weight of mixing water by weight of natural soil used is calculated.
For each quantity of mixing water, an initial weight of mixture (earth + mixing water) sufficient for filling the mould of the press is determined. Then a series of blocks is made. The initial weight of mixture is gradually increased and at each time, a series of blocks is made until the compaction becomes impossible. The dimensions of each block are measured using a calliper of 300 mm (±0.01 mm) with digital display. Then the fresh density and the dry density of all the blocks are calculated. After 4 weeks (28 days) of drying in the air, the weight and the dimensions of those blocks are measured anew, and their air dry density calculated. Their compressive strength is also determined (Fig.1). This method has been chosen to have aspect ratio 2. A steel ball is put between the sample and the plate of the press to have a homogeneous distribution of stress on the surface of the block. Let's notice that the surfaces of the blocks are not perfectly flat because of the drying shrinkage; to avoid punching, this approach was preferred.

For this study, we use a manual static press CINVA-RAM model with a reduction ratio: hi/hf = $\gamma f/\gamma i$ = 1.68
With h*i*= height of full mould; hf= height of block; γi= density of mixture (earth + mixing water) before compaction; γf= density of block after compaction.

III. OPTIMIZATION OF EARTH COMPACTION

The compaction is an operation that aims at increasing the density of the material. It can be made by mechanical compression. This mechanical compression can also be performed by a dynamic mechanism like the Proctor test or the static mechanism. In this study, the blocks have been made by static compaction with a manual press. The abounding earth is introduced into the mould of the press then, the lever is actuated. The rise of the piston of the press transmits the force developed by the operator to the earth in the mould. The density of blocks obtained by static compression depends upon the quantity of soil in the mould. So, to optimize the compaction, tests are undertaken.

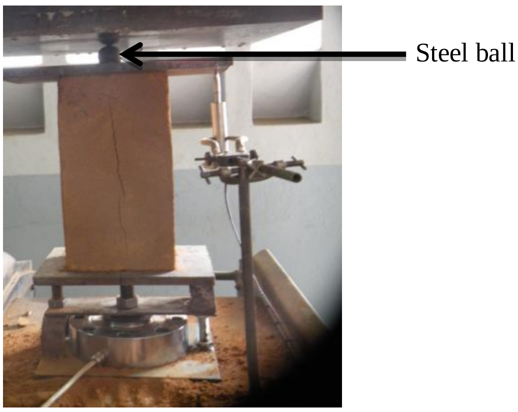

Figure 1 Measurement of compressive strength of blocks.

A- Compaction test

For this test, different weights of earth have been introduced into the mould of the press and compacted. For each block obtained, the dry density and fresh density are measured as well as the compressive strength. The results are presented in the fig. 2.
The graphic (Fig. 2) shows that the dry density increases with the weight of earth in the mould of the press for each moisture content. This increase is related to the increase of the energy of compaction. Indeed, for the same moisture content, the energy of compaction increases with the dry density [5]. But in the context of this work, the volume of blocks is constant (Vt); the dry density (ρd) depends on the total weight of earth into the mould (Mt);

$$\rho_d = (M_t - M_w)/V_t \qquad (1)$$

With Mw: the weight of water in blocks.
So, increasing the total weight leads to an increase of the static energy of compaction. Moreover, according to expression (1), where the volume of compacted blocks is constant, the dry density is a linear function of the total weight of earth molded. This finding is proved in Figure 2, when the total weight is between 9,000 and 11,000 g. According to [9] the linearity observed here corresponds to a gradual decline in the vacuum index:

$$e = (\rho_s/\rho_{di})((H - d)/H) - 1 \qquad (3)$$

Where, d the displacement of the piston, H the initial height of the mould, ρs the density of the grains (skeleton) and ρdi the initial dry density

$$\rho_{di} = M_s/V = (M_t - M_w)/V \quad (4)$$

With V the volume of the mould of the press.
The similarity between the curves, whatever the moisture content of blocks, confirms that stripping, all the blocks have the same volume (constant slope).
When earth in mould is over 11,000 g, the slope of the curve decreases from that of the linear portion because of:
• The mitigation of the stress of compaction caused by the opposition of the hydrostatic pressure of water contained in the pores. As the duration of compaction is very short, about 30 seconds, that water can not escape; hence the slight variation of the dry density.

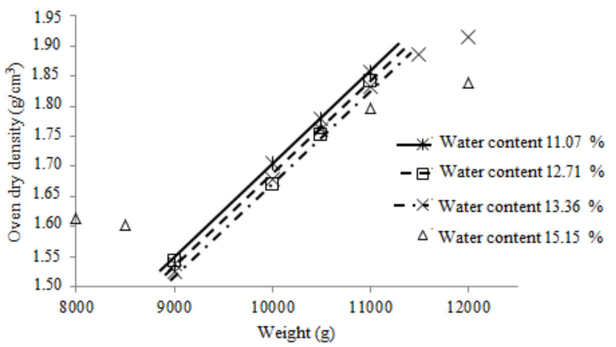

Figure 2: Variation of the dry density according to the weight of fresh earth.

• The increase of frictions between the particles, when the water content is mean. Effective stress, applied on the blocks, is less than the stress performed by the operator.
• The rupture of the particles that form the skeleton of the block when the earth in the mould is very dry.
For less than 9,000 g, the dry densities are rather determined at random because the filling of the mould is not optimum. These densities can only be measured on blocks made of earth with a moisture of 15.15%. This water content allows the particles of earth to be held together grace to the role of cohesion of water.
In sum, the quality of a static compaction achieved with a manual press can be appreciated from the vacuum index, the dry density of blocks or from the weight (quantity) of earth used for compaction. The weight of fresh earth is related to the dry density by the inverse of the volume of compressed earth block. For CINVA-RAM press with empty mould dimensions (29 cm x 22 cm x 14 cm) the weight of fresh earth should be between 9,000 and 11,000 g.
Generally, the blocks should be used in compression. It is important to analyze the relationship between the compressive strength and the dry density of blocks for, according to [10], their mechanical behavior depends on their dry density.

B-Relationship densities and compressive strength

Fig. 3 shows the variation of compressive strength of blocks for different densities:
• The fresh density is obtained by the ratio of the weight of the fresh block and its volume;
• The oven dry density is calculated from the moisture content by the formula: $\rho_d = \rho/(1 + \omega)$
It assumes that there is no drying shrinkage
• The air density of blocks, after drying at room temperature, is calculated from the ratio weight of the block by its volume after drying at room temperature.
Fig. 3 indicates that in general, the compressive strength of blocks increases with whatever density. The volume of the stripping block is constant, the increase in density is due to the increased amount of material, thus to significant contact between the particles forming the skeleton of the blocks. The compressive strength is therefore improved.

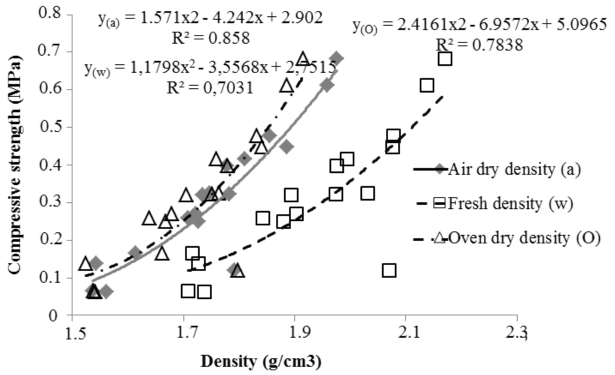

Figure 3: Relationship between the density and the compressive strength of compressed earth blocks

However, the values of the compressive strength, in this study, are low compared to those found in most studies, dealing with the compressive strength of compressed earth blocks [11]-[13]. For this study, the compressive strength was determined on blocks put in width direction (as shown in fig. 1) in order to have a twinge of 2. But for the other studies, the blocks were in length direction. The compressive strength of blocks in length direction leads to a hardening whence an overestimation of the resistance.
Moreover, the compressive strength of blocks, dried in an oven, is higher than that of blocks dried at room temperature, which is itself, more than the compressive strength of fresh blocks. This result is certainly due to the presence of water in the pores of the blocks. The density (ρ) of blocks, whatever their moisture content, is given by the formula :

$$\rho = \rho_d + \rho_w (V_w/V_w) \quad (5)$$

with ρd = the dry density of the earth.
The evaporation of a part of the mixing water, during the drying of blocks, makes their density tend to the dry density ρd. In the oven, blocks are dried at a temperature of 105 °C. All the water has been evaporated. So, $\rho = \rho_d$.
At room temperature (30 °C), a part of the water in blocks is evaporated to a constant weight. So, the ratio V_w/V_t is very low because the residual water content of the blocks is about 3%. ρ is very close to ρd but higher than ρd (Fig. 4). The difference between the compressive strength of blocks dried in an oven and that of those dried at room temperature (Fig. 3) is also due to the drying shrinkage. But, in the calculation of the fresh density, the residual water and the water that could be evaporated (mixing water) [14] must be taken into account. Therefore, the compressive strength of fresh blocks

is quite different from the two others (Fig. 3). That is why, the linear relationship between the density of fresh blocks and that of blocks dried in an oven is maintained, even if, the curves are not co linear, as foreshadowed in the expression (5).

Despite the gap between them, the compressive strength according to the density can be calculated with a polynomial function of degree 2 like $y = ax^2 + bx + c$ (Fig. 3). The correlations are 0.86 with blocks dried at room temperature, 0.78 for blocks in the oven, and 0.70 with fresh blocks.

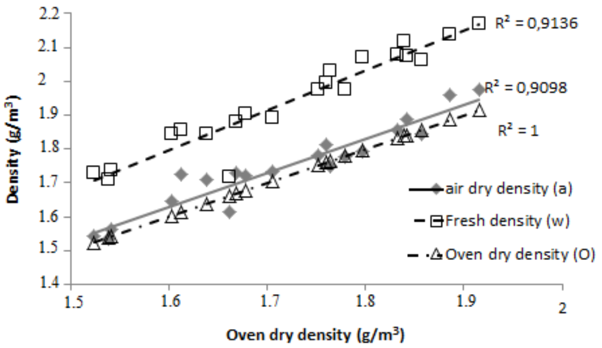

Figure 4: Relationship between different densities

The coefficients of these correlations can be explained by the measurement of uncertainties and distortions generated by the drying shrinkage.

Now, these results confirm, once again, that as the dry density in the oven and at room temperature, the fresh density when the static compaction is optimum (constant final volume of blocks) can be used to predict the quality of fresh compressed earth blocks. But, to reduce impact of evaporation, the evaporable water must be optimal.

IV. OPTIMIZATION OF WATER

Water is always used in the development of building materials. In opposite, all the methods of mechanical characterization of these materials require that they must be dry. During the drying, a portion of the mixing water is removed as vapor. This evaporation causes shrinkage which generates deformations, cracks and microcracks in the material [15]. This depends, on the drying conditions (temperature and humidity in the drier) and the quantity of water able to remove the material. If the evaporation is fast and important, the quality of the material can be deteriorated. Paradoxically, this water has an important role in the compaction theory. So, [16] suggested a relationship to find the water content according to the Proctor compaction energy.

A-Role of water in the static compaction

Fig. 5 shows the variation of the dry density of blocks dried in the oven according to the water content and the different weights of compacted earth.

Overall, the dry density varies when the water content increases. It increases, passes through a maximum before falling. This maximum is reached for a water content of 11% to 11.5%, whatever the weight of compacted earth.

As the plastic limit of earth is 21%, all the earth used for producing blocks are in a solid state (solid consistency). Therefore, when the earth is ruined, the water will wet the surface of the particles. The mass of earth particles forming the skeleton of the blocks is given by the formula:

$$M_s = M_t/(1+\omega) \quad (6)$$

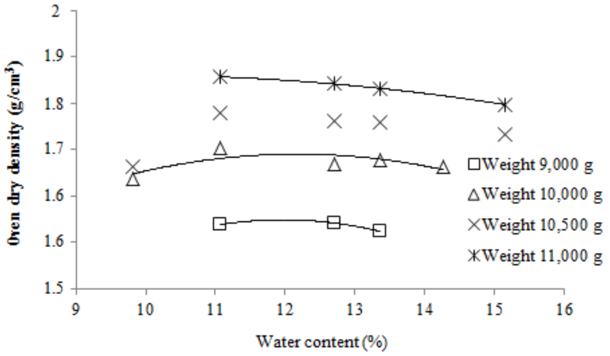

Figure 5: Variation of the dry density of the blocks according to the water content

This expression shows that for a constant weight of compacted earth (Mt), when the water content (ω) increases, the amount of particles in the block decreases.

When the quantity of water around the particles increases, until a water content of 11.5%, the increase of the dry density is caused by the most compact organization of particles facilitated by the water around them. But, when the amount of water around the particles increases for a water content of over 11.5%, the decrease of the dry density is caused by an excess of water in the pores. The Porosity (n) is given by the expression:

$$n = 1 - (\rho_d/\rho_s) \quad (7)$$

With ρs= density of the solid particles of the earth.

This shows that when the dry density decreases, the porosity increases. And water:

• Firstly, lubricates the contact between the particles and is trapped in the pores between them. This accumulation of water in the pores was highlighted by [17] by determining the degree of water saturation of earth during the compaction. They even recommended the Proctor compaction theoretical relations between the degree of water saturation and the liquid limit.

• In a second step, water is pressurized. This pressure is opposed to the effort provided by the operator. Thus, the effective stress on the block is reduced as indicated by this law (Bishop law) $\sigma' = \sigma - u_a + (u_a - u_w)x$

σ' and σ effective stress (respectively provided by the operator), u_a, u_w gas pressure (liquid respectively) and x an empirical coefficient that depends on the degree of saturation. It comes out of this analysis, of the role of water, during the compaction that the quality of blocks is influenced by the quantity of the mixing water per unit of mass of the natural ground. It also appears from this analysis that the quality of the block is clearly influenced by the flow coefficient; flow coefficient = weight of mixing water (g)/weight of earth (g).

So, we can examine the variation of this ratio according to the water content of blocks (Fig. 6).

This figure shows that when the water content in earth increases, the ratio also increases proportionally, with a very good correlation ($r \cong 1$).

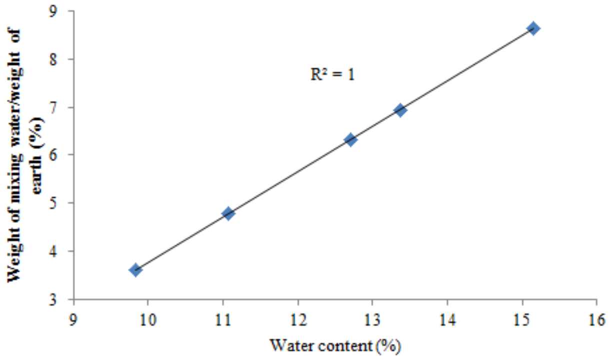

Figure 6: Relationship between flow coefficient and water content

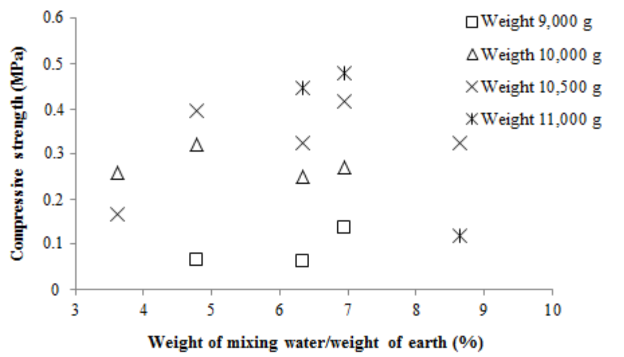

Figure 7: Variation of the compressive strength of blocks according to the flow coefficient

On a building site, to reduce the latency, this ratio can be used to optimize the compaction (in order to avoid the determination of the water content, which requires a drying oven at 105 °C for at least 24 hours). For example, the optimum moisture content for 11 % of the flow coefficient is 5 %.

B-Relationship compressive strength-flow coefficient

The variation of the compressive strength of blocks, according to the flow coefficient of different weights of molded earth, is given in Fig. 7.

For a constant weight of molded earth, the highest compressive strength is obtained with a flow coefficient of 5%. And it also corresponds to the highest dry density. This is similar to the results of [2] which showed that the mechanical behavior of a earth depends on its dry density. Increasing the weight of a compacted earth leads to an increase of its compressive strength. For a flow coefficient of 5%, an increase of the weight of earth put into a mould weighing 500 g or 5 % (of the weight of earth), causes an increase of the compressive strength of about 33 %.

Moreover, the optimal weight of earth, to fill the mould of the press used in this study, is 10,500 g because the dispersion of resistance valued at 9,000 g and 11,000 g of earth is due to exaggerated earth filling mould of the press.

V. CONCLUSION

According to the static compaction of earth-water mixture with a manual press (constant course of the piston and compaction degree), we can make the following remarks:

• For an optimal filling of the mould of the press, the static compaction leads to a linear relationship between the dry density in the oven and the weight of earth. Beyond this area, the viscous behavior significantly affects the density of blocks.

• The relationship, density/compressive strength determined on dry blocks, is a polynomial function of degree 2. However the coefficient of a monomial of degree 2 is closely dependent on the considered density (presence of mixing water).

• The relationship, between different types density and dry density in the oven, is linear. But the fresh density is non-collinear with others.

• Water lubricates the contact between grains (particles) accumulated into the pores and creates or generates a liquid pressure that opposes the compaction stress.

• For a constant natural water content of earth, the quality of the static compaction depends on the ratio mass of mixing water/mass of natural earth.

And from both parameters fresh density and the flow coefficient of the earth, it is possible to control the production of compressed earth blocks on building site and determine the optimum mixing water. This prevents the loss of time but also ensures the quality and compliance of the produced blocks.

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