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Contribution to the Study of Paleoproterozoic Materials for the Improvement of Social Housing in the Kedougou Region: Case of Mako Andesitic Meta-Tuffs

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Abstract

The objective of this project is the valorization of Mako andesitic volcanic tuffs for use in social housing in the Kedougou region. To achieve these objectives, a geotechnical characterization of the tuff samples was carried out and the geopolymerization stabilization was adopted for the manufacture of bricks. These bricks stabilized by an alkaline activation offer compressive strengths that exceed the threshold value (2.9 MPa) set by the standard (NF P14-304). The best compressive strengths (12.14 MPa) and flexural tensile strengths (5.43 MPa) are obtained in the series of bricks made with 35% of the mass of a solution of caustic soda at 12 molars concentration with a curing temperature cooking of 185˚C and an average absorbance of 13.21%.

Keywords

Mako, Volcanic Tuffs, Geopolymerization, Alkaline Activation

1. Introduction

Senegal, a country located on the extreme western part of the African continent, has diversified natural resources. It recorded volcanic activity almost two (2) billion years ago. The region of Kedougou is marked by this phase during which several outcrops of volcanic rocks of different natures were formed. The volcanic formations of Mako and Bafoundou are evidences of this period with the massive presence of volcanic tuffs of several varieties.

On the one hand, Kedougou is home to one of the poorest and most vulnerable populations in the country who are struggling to have decent housing. On the other hand, in this eastern part of the country, more precisely in the districts of Mako and Bafoundou, there is a massive presence of gigantic deposits of volcanic tuffs that are outcropping everywhere.

With the notice of this contrast, we decided to bring solutions to this real problem through a study aiming at the valorization of these volcanic tuffs in order to use them as building material in civil engineering.

Located in the eastern part of the country, the Kedougou region does not have a cement factory and the transport of cement from Thies to Kedougou is still very expensive. It is with this in mind that we will try to manufacture bricks offering good resistance and without cement.

2. Geological Setting

In Senegal, the Paleoproterozoic outcrops in the Kedougou-Keniebainlier, which together with that of Kayes form the westernmost part of the West African Craton. The Kedougou-Kéniébainlier is unconformably covered by the Neoproterozoic and Paleozoic geological formations of the Mali and Segou—Madina Kouta series (in the South), the Faleme (in the West) and those of the Taoudeni Basin (in East and North) [1] [2].

The Paleoproterozoic formations of the Kedougou-Keniebainlier are classically divided into two large lithostratigraphic units [3]: to the west, the Mako Super-Group with predominantly mafic volcanic formations and to the East, the Diale-Dalema Super-Group that is essentially sedimentary and volcano-sedimentary (**Figure 1**).

The predominantly mafic volcanic unit of the Mako Super-Group is composed of basalts with varied textures (in pillow lava or massive) surmounted by a calc-alkaline volcanism constituting a volcano-sedimentary complex with andesitic tuffs that can evolve towards rhyolitic tuffs. At the top, lies a sedimentary complex [1] [4].

The sedimentary and volcano-sedimentary formations of the Diale-Dalema Group, to the East of the Mako Group, consist mainly of carbonate rocks, schists, pelites, sandstones, arkoses, greywackes, conglomerates and tuffs. They are intersected by an intermediate volcanism of calco-alkaline nature ([1] [5] [6] her, 1987 [7]) dated around 2081 Ma [8]. The formations of the Foulde Group in the northwest of the Mako Group are essentially detrital [9].

All volcanic, volcano-sedimentary and sedimentary formations are affected by regional metamorphism of green schist facies and are intersected by magmatic suites consisting of calc-alkaline plutonic rocks of various types [1], whose age extends from 2158 [10], to 2050 Ma.

The andesitic meta-tuffs formations were first mapped by and they constitute the essential of the volcanism to the East of the meta-basalts and appear either in massive flows or in the form of tuffs generally in volcano-detritic bases. The massive rock has a characteristic color with a thickness of about fifty meters and a microlithic-porphyritic texture and an abundance of plagioclase. These andesitic

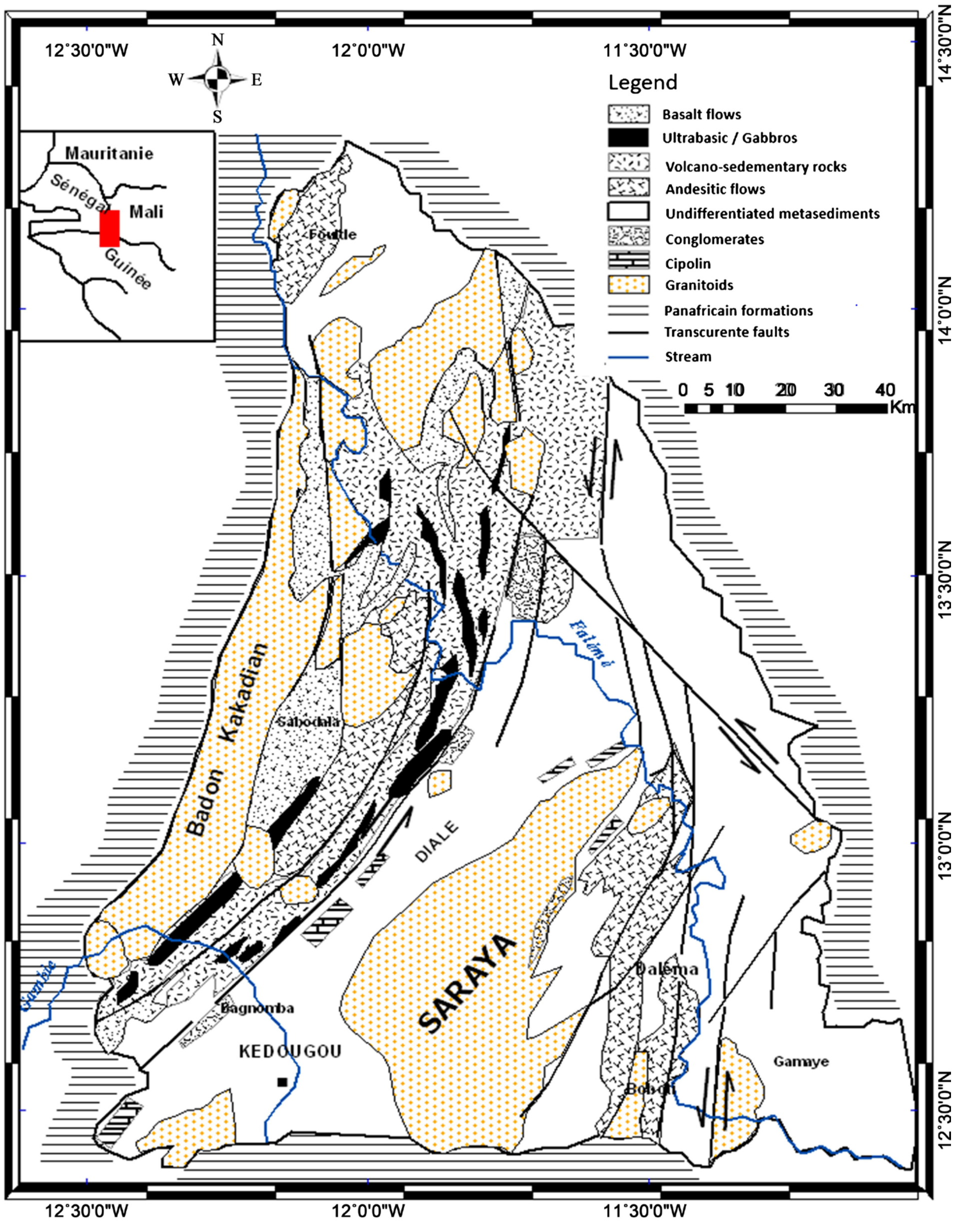

Figure 1. Localisation calco-alkaline of volcanic complex in Mako and Foulde [3].

meta-tuffs can be foliated, mylonitized and even folded.

3. Background

Several studies have been carried out on Mako volcanic tuffs [11] [12] [13].

[12] shows that the region of Mako (Eastern Senegal) has a large quantity of volcanic tuffs. These volcanic tuffs are felsic (with nearly 70% SiO_2). This high content of silica and aluminum (13%) gives to the mixture of tuff and binder pozzolanic properties. Bricks of high resistance (3 MPa) from 72 hours of conservation at 80˚C can be made with the tuffs that are treated with lime (2.5%). Moreover, Ndiaye (2000) shows that the tuffs have pozzolanic characters and can enter into the composition of CEM II A-P 32.5 R pozzolanic cements type.

These types can be used to improve the performance of materials. In addition, further studies were conducted by [10] using the geopolymerization process on mine tailings.

Stabilization by geopolymerization with alkaline activation (soda solution) with or without pozzolanic activation has been applied to Sabodala tailings. Thus, the effect of several parameters such as the concentration of the sodium hydroxide solution, the percentage by weight of the solution and the cement and/or the lime, the curing temperature and the type of drying were studied in order to define formulation and preparation protocol that delivers the best results. This enabled to understand the effect of each parameter on improving the performance of the stabilized material but also to be able to predict its resistance as a function of the values of these parameters and the method of preparation.

4. Methodology and Experimental Study

The methodology adopted consists first of all in a thorough literature review, to evaluate the state of knowledge on the stabilization of the materials by geopolymerization method, but also to define protocols to follow to lead to satisfactory results. Laboratory studies will also be carried out to characterize the volcanic tuffs of Mako and build a database, which will allow us to draw graphs and interpret the results obtained. An attempt to implement the results obtained will be made, in order to appreciate the impact of the different parameters involved.

Being a friable and very particular material, the Mako andesitic volcanic tuffs have to meet a certain number of criteria to be used as building materials for the manufacture of bricks for walls and paving bricks. Parameters such as compressive strength, bending tensile strength and good resistance to water should be checked after the chosen treatment option has been applied. They must exceed the thresholds set by the standards in force.

4.1. Making Bricks from Tuffs

The bricks must be good quality products and at a lower cost. We used the geopolymerization stabilization method to achieve these objectives but also to guarantee the stability of the material. Geopolymerization is the addition of an alkaline solution (NaOH or KOH) to alumina silicates. These results in an oligomer-linked polymerization process that results in inorganic polymers similar to zeolites that are able to withstand the most adverse weather conditions.

4.2. Brick Manufacturing Process by Geopolymerization

The manufacture of bricks made from volcanic tuff of Mako by the geopolymerization method consists in mixing the previously dried material with a solution of soda prepared at a defined concentration. The making of bricks is done using steel mold.

4.3. Principle and Procedure

The principle and the procedure of briquette making include the mixing of the different materials and products used, the molding and demolding of the briquettes, the drying and finally the thermal activation. A first series of tests was done, initially, and allowed to frame some parameters and to set consequently the number of briquettes necessary for the study.

4.4. Preparation of Volcanic Tuffs

The volcanic tuffs are dried in an oven at 105˚C for 24 hours to remove all interstitial water. The formed blocks are then disintegrated in large basins. The cement is already in the state of powder. Each formulation of the mixture is obtained by fixing the percentage by weight of each constituent and consequently its mass. That of the tuffs is always fixed at 1.4 kg, the mass corresponding to the quantity of material necessary to fill a mold with three briquettes. The tuffs and the cement are then poured into the container and homogenized before adding the soda solution. The paste obtained is placed in the mold and is compacted using an iron bar to eliminate voids. The compaction is manual. Refining of the top surface of briquettes finishes their preparations. Table 1 presents the first series of formulations.

5. Results

First series of test formulation was made to define where we can obtain high

Table 1. Composition of different formulations.

formulation N˚	Cement (%)	Tuff (%)	Water (%)	Molar concentration
F1	0	100	30	5
F2	3	97	40	5
F3	3	97	35	5
F4	5	95	30	5
F5	7	93	30	5
F6	7	93	35	5
F7	0	100	40	8
F8	3	97	35	8
F9	5	95	35	8
F10	7	93	35	8
F11	0	100	45	5
F12	0	100	35	5
F13	0	100	30	5
F14	0	100	45	8
F15	0	100	35	8
F16	0	100	30	8
F17	0	100	45	12
F18	0	100	35	12
F19	0	100	30	12

strengths with or without addition of cement but also low concentration of soda at relatively low cooking temperatures. For this, the following 05 parameters have been subject to variation:

- The percentage of cement;
- The percentage of tuff;
- The percentage of mixing water;
- The concentration of the soda solution;
- The cooking temperature of the briquettes.

Table 2 and Table 3 show that the values of the compressive strengths vary

Table 2. Results of few formulations of prime tests for 5 molars concentration.

Formulation (n˚)	Cement (%)	Tuff (%)	Water (%)	Concentration (m)	Temperature. (˚C)	Rc 28 (MPa)
1	0	100	30	5	40	2.117
1	0	100	30	5	60	2.29
1	0	100	30	5	150	2.98
2	3	97	40	5	40	2.591
2	3	97	40	5	60	2.667
2	3	97	40	5	150	6.997
3	3	97	35	5	40	2.42
3	3	97	35	5	60	2.63
3	3	97	35	5	150	6.73
4	5	95	30	5	40	3.046
4	5	95	30	5	60	3.871
4	5	95	30	5	150	4.308
5	7	93	30	5	40	2.716
5	7	93	30	5	60	4.153
5	7	93	30	5	150	4.487
6	7	93	35	5	40	2.855
6	7	93	35	5	60	3.529
6	7	93	35	5	150	14.172
7	0	100	40	8	40	2.179
7	0	100	40	8	60	2.997
7	0	100	40	8	150	17.735
8	3	97	35	8	40	1.472
8	3	97	35	8	60	1.923
8	3	97	35	8	150	7.758
9	5	95	35	8	40	2.109
9	5	95	35	8	60	2.845
9	5	95	35	8	150	6.266
10	7	93	35	8	40	3.472
10	7	93	35	8	60	4.923
10	7	93	35	8	150	8.758

between 1.472 and 17.735 MPa. The minimum value (1.472 MPa) of resistance is obtained with the category of bricks cured at 40˚C and the maximum value (17.735 MPa) with the category cured at 150˚C. This shows that the temperature parameter is very decisive for the desired results. The evolution of the compressive strength as a function of the curing temperature is illustrated in Figure 2.

Figure 2 shows the evolution of the compressive strength as a function of the curing temperature. It shows that the compressive strength of bricks is strongly influenced by each of the parameters, namely the percentage of cement, the percentage of the mixing water of the soda solution and its concentration. The curve indicates that the curing temperature increases with compressive strength. The best resistance is provided by Formulation 6 (14.17 MPa) for which the composition of the briquettes is 7% cement, 35% water, 5 molars concentration of sodium hydroxide and curing temperature of 150˚C.

The same observation is made for the 8 molars concentration formulations (Figure 3).

The higher the curing temperature is, the higher the compressive strengths. But, the best resistance is provided by the Formulation 7 (17.73 MPa) with bricks made without cement and with 100% tuff, 40% water, 8 molars soda concentration

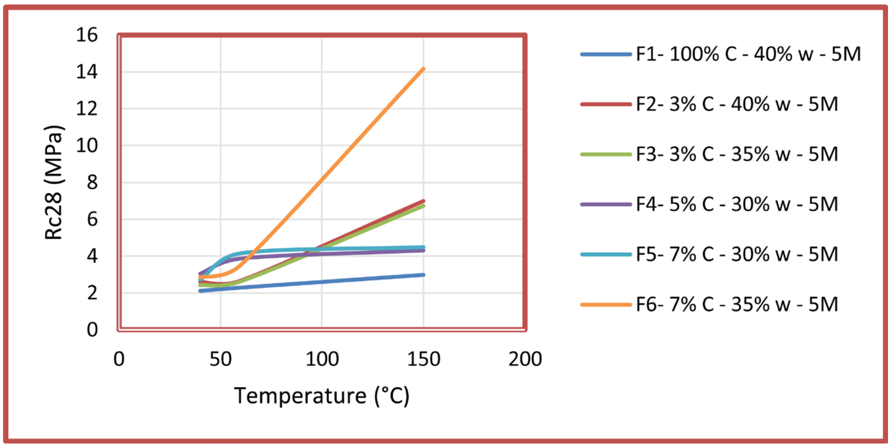

Figure 2. Evolution of compression resistance as a function of temperature for formulations at 5 molars concentration.

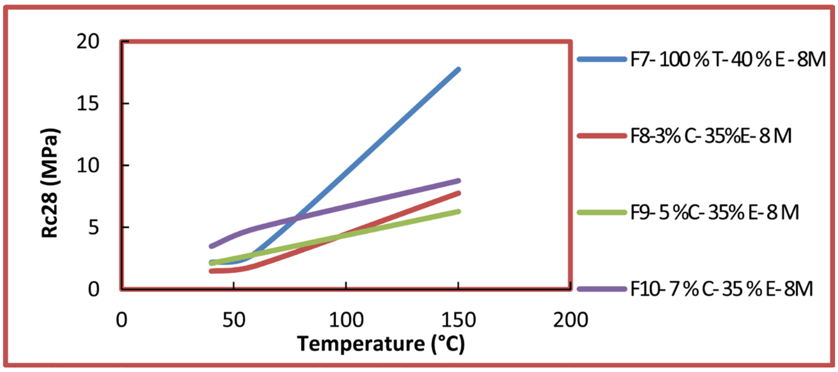

Figure 3. Evolution of compression resistance as a function of temperature for formulations at 8 molars concentration.

and 150˚C curing temperature. This remark gave us the idea of making formulations without adding cement. So for all the formulations that did follow consist of briquettes with 100% Mako volcanic tuff.

5.1. Resistance as a Function of the Concentrations of the Soda Solution

The briquettes were made with 100% tuff, 30%, 35% and 45% sodium hydroxide solution. Relatively low curing temperature of 50˚C for 24 h, tests run on the 28th day and drying under cover have been respected. Figure 4 shows the influence of the concentration on the compressive strength in the manufacturing conditions mentioned above.

The results show that at 50˚C, the best resistances are noted with a concentration of 8 molars for the sodium hydroxide solution with a percentage of mixing water of 35% (Figure 5).

For the curing temperature of 80˚C, the results also show that the best performances in terms of strengths are noted with a concentration of 8 molars for the sodium hydroxide solution with a percentage of mixing water of 35%, the same effect being obtained at 50˚C curing temperature (Figure 6).

A clear difference is observed between the results of briquettes cured at 185˚C

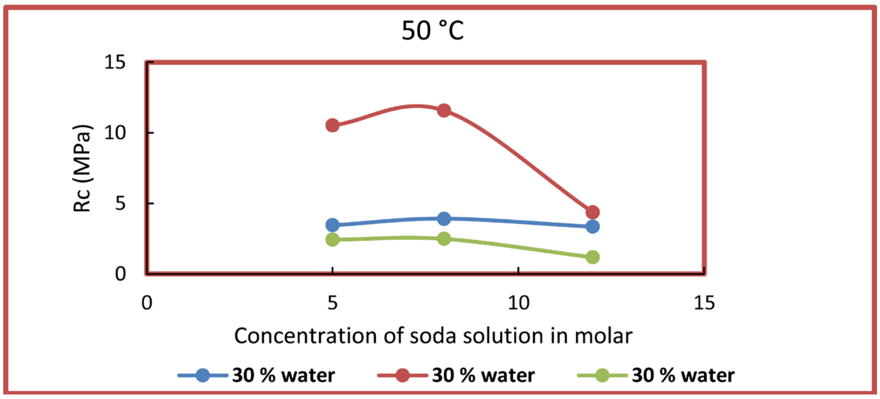

Figure 4. Variation of resistance as function of concentration of soda at 50˚C.

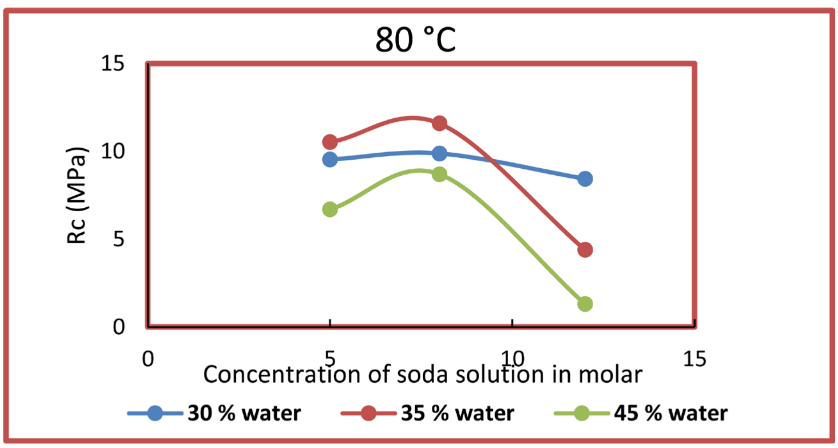

Figure 5. Variation of resistance as function of concentration of soda at 80˚C.

and those at 50˚C and 80˚C. Here, the results show an increase of the resistances with the increase of the concentration of the solution of soda (5, 8 and 12 molars). At 185˚C, the reactions begin. In fact, the pH becomes more and more alkaline with the increase of the concentration of the sodium hydroxide solution thus creating the conditions of more abundant rupture of the bonds of the crystalline structure and thus leading to the formation of new bonds which give rise to the amorphous gel. In addition, an increasingly concentrated solution provides a larger amount of Na+ cations that enter into the constitution of the gel.

5.2. Resistances as a Function of the Percentage by Mass of Soda Solution

The percentages in mass of the soda solution used are 30%, 35% and 45% respectively for the concentrations. Sodium concentrations for each series are 5, 8 and 12 molars. We have three sets of bricks at 50˚C, 80˚C and 185˚C, respectively. The results obtained are shown in Figure 7. The curves show the evolution of the compressive strength as a function of the percentages by weight of the sodium hydroxide solution.

The analysis of the curves shows that a variation of the proportion of the soda solution gives the optimum at 35% for the concentrations of 5 and 8 molars. Too

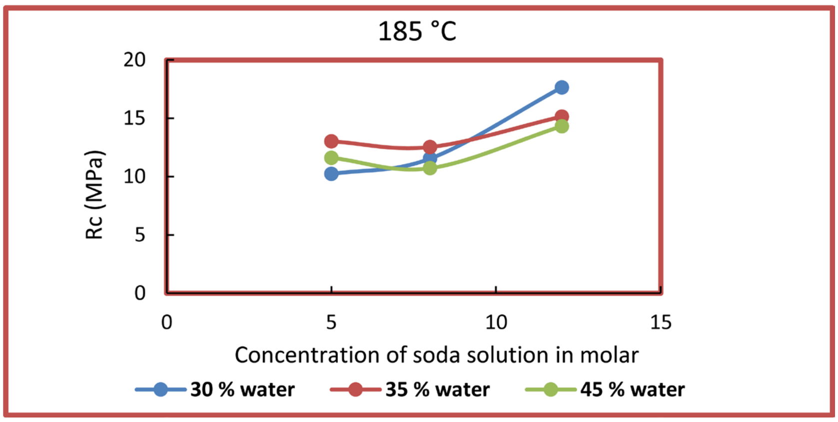

Figure 6. Variation of resistance as function of concentration of soda at 185˚C.

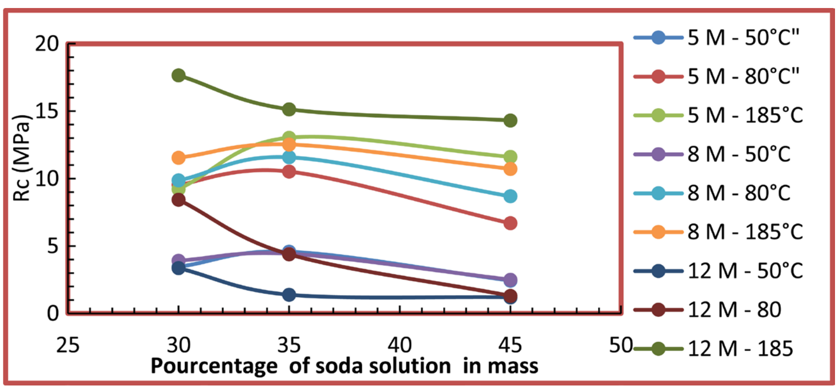

Figure 7. Variation of the compressive strength as a function of the percentages by weight of the sodium hydroxide solution.

little amount of solution does not allow sufficient contact between it and the surfaces of the particles of the tuffs. These results about limitations of the geopolymerization with small quantities of neo-formed gel explain the decrease of the resistances to the left of the optimum. On the other hand, when the solution is too abundant, the liquid/solid ratio which is too high leads to an increase in the porosity and a decrease in the compactness which causes the reduction of the resistances to the right of the optimum. But unlike the concentration of 12 molars, the resistance decreases with the increase of the proportion of the soda solution.

5.3. Resistances as a Function of the Curing Temperatures

The evolution of the compressive strength as a function of the curing temperature has been studied. The results obtained are translated into curves. The different curves are identified with respect to the percentage of the sodium hydroxide solution that served as the mixing water. The results are shown in Figure 8.

Figure 8 shows the evolution of the compressive strength of the bricks as a function of the curing temperature. The shape of the curves for the 5 molars and 8 molars concentrations indicates identical patterns. Note that the resistance increases with the temperature up to 12 MPa at which the resistances remain constant. Unlike for a concentration of 12 molars, curves show a progressive increase in resistance when the temperature increases.

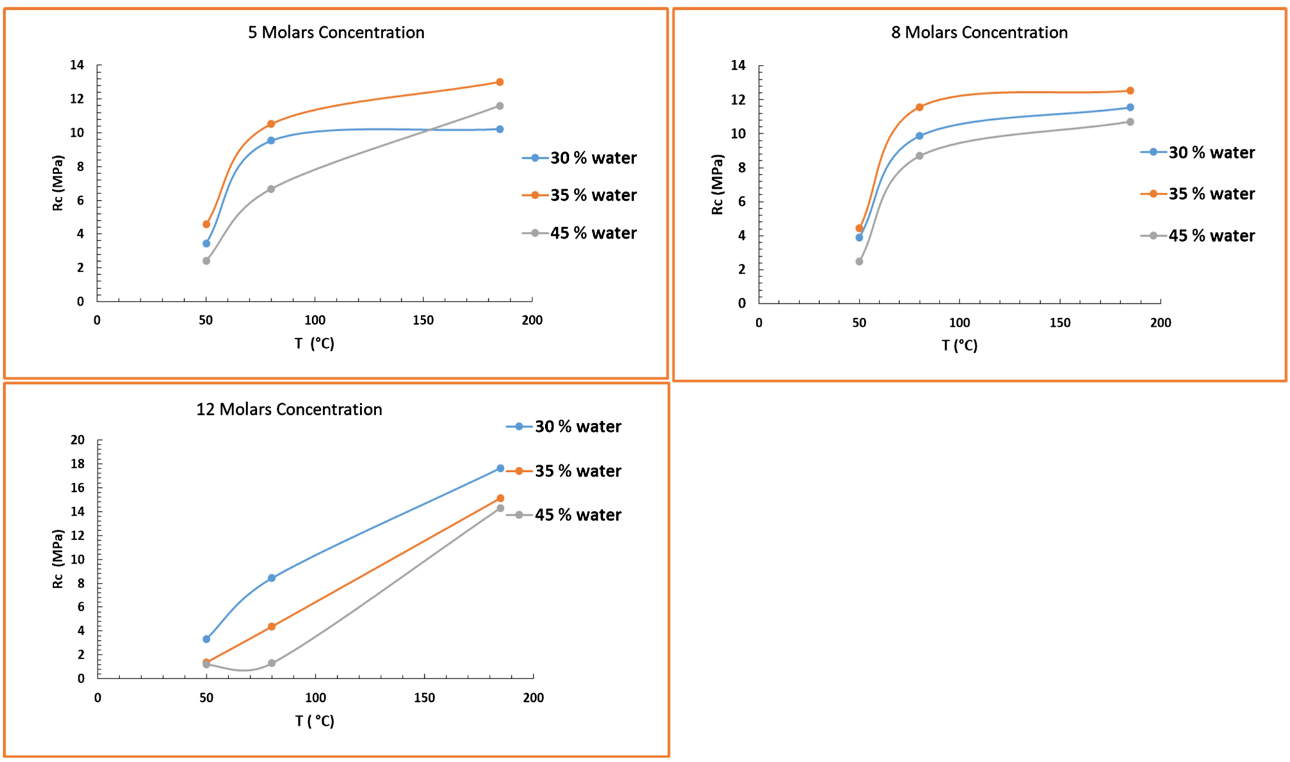

Figure 8. Variation of the compressive strength of the bricks as a function of the curing temperature for the 5 molars, 8 molars and 12 molars concentrations.

5.4. Flexural Tensile Strength of Bricks

The flexural tensile strengths measured vary according to the various parameters involved in the composition of the briquettes. We ranked the results for each set of bricks according to the concentration. The results obtained after testing the briquettes are shown in **Tables 3-5**.

The results of the tensile strength by flexion test for a concentration of 5 molars show that the bricks which are more resistant to flexion are located in the series of bricks treated at 185˚C where the maximum tensile strength reaches 1.865 MPa. The values obtained as a function of the percentage of the water indicate an optimum at 35%.

For bricks made at 8 molars concentration, we noticed the same variations. The results show that the bricks which are more resistant to flexion are located in the 185˚C series of bricks where the maximum tensile strength is 1.442 MPa. The values obtained as a function of the percentage of the sodium hydroxide solution indicate a 35% optimum. Resistances are nil at 50˚C curing temperature.

Table 3. Result of traction resistance for 5 molars concentration.

% Cement	% Tuff	% Water	Concentration (Molar)	Temperature (˚C)	Load (N)	R_t (MPa)
0	100	45	5	50	0.801	0.342
0	100	35	5	50	1.288	0.55
0	100	30	5	50	1.224	0.522
0	100	30	5	80	4.37	1.082
0	100	35	5	80	4.37	1.423
0	100	45	5	80	1.938	1.21
0	100	30	5	185	2.535	1.865
0	100	35	5	185	3.336	1.865
0	100	45	5	185	1.937	0.827

Table 4. Result of traction resistance for 8 molars concentration.

% Cement	% Tuff	% Water	Concentration (M)	Temperature (˚C)	Load (kN)	Rt (MPa)
0	100	45	8	50	0	0
0	100	35	8	50	0	**0**
0	100	30	8	50	0	**0**
0	100	30	8	80	1.996	0.852
0	100	35	8	80	4.137	1.765
0	100	45	8	80	2.535	1.082
0	100	30	8	185	3.176	1.355
0	100	35	8	185	3.38	1.442
0	100	45	8	185	2.054	0.876

The bricks made at the concentration of 12 molars and cured at the temperature of 185˚C have values of tensile strength by maximum traction of 2.318 MPa. We noticed the same variations as the previous table of results. Bricks that are more resistant to traction are located in the 185˚C series of bricks. The values obtained as a function of the percentage of the sodium hydroxide solution indicate a 35% optimum. Resistances are nil at 50˚C curing temperature.

5.5. Results of Measurement of Water Absorption Rate of Briquettes

Measurements of the water absorption rate were made after 6 days after immersing the bricks in basins filled with water (Figures 9-11).

After the flexural tensile test, the brick is split into two parts. The first half of the brick is used to measure the compressive strength and the second half to determine the water absorption rate. The results obtained are recorded in Figure 9.

The results show that the highest absorbance rates are in the series of bricks made at 45% by weight of the sodium hydroxide solution. Bricks made at 35% are the ones with the best results. So, we can remember that there are fewer voids at this level of mixing where the percentage of the solution used is 35%.

Table 5. Result of traction resistance for 12 molars concentration.

% Cement	% Tuff	% Water	Concentration (M)	Temperature (˚C)	Load (kN)	Rt (MPa)
0	100	45	12	50	0	0
0	100	35	12	50	0	0
0	100	30	12	50	0	0
0	100	30	12	80	1.904	0.814
0	100	35	12	80	2.287	0.976
0	100	45	12	80	1.883	0.804
0	100	45	12	185	5.392	2.300
0	100	35	12	185	5.434	2.318
0	100	30	12	185	3.366	2.289

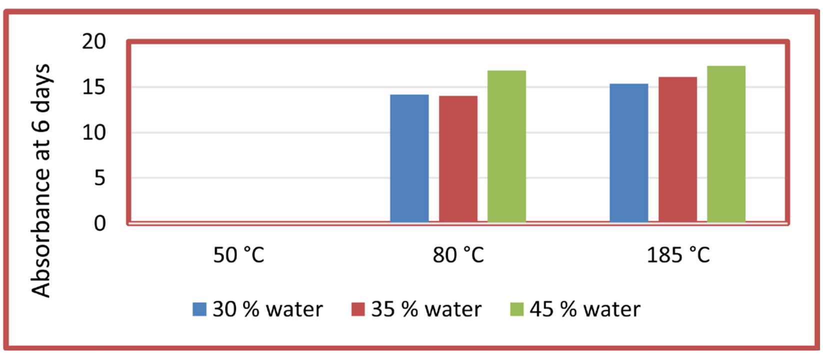

Figure 9. Results for absorbency ratio for brick of 5 molars concentration.

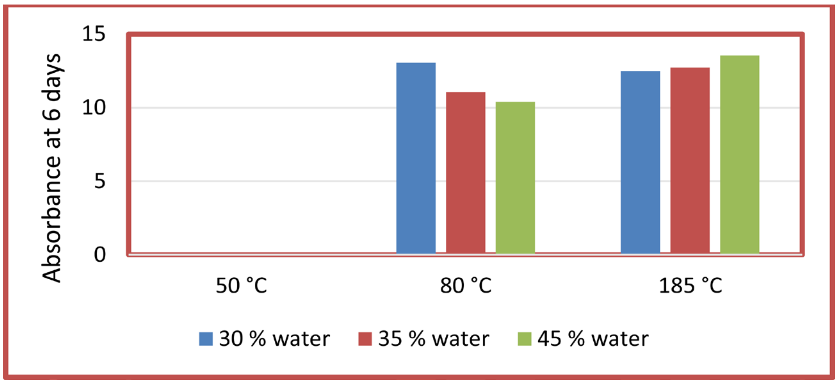

Figure 10. Results for absorbency ratio for brick of 8 molars concentration.

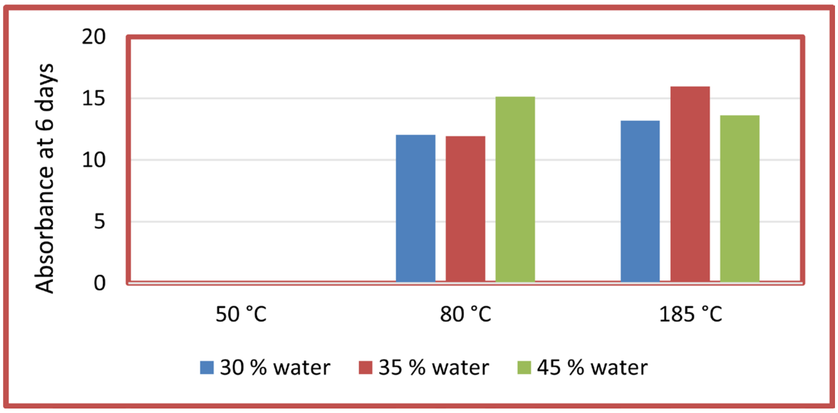

Figure 11. Results for absorbency ratio for brick of 12 molars concentration.

Same remark as for the bricks made with a concentration of 5 molars was done. The results show that the highest absorbance rates are in the series of bricks made at 45% by weight of the sodium hydroxide solution. Bricks made at 35% are the ones with the best results.

For these bricks with a concentration of 12 molars, we noticed an inconsistency in the absorbance levels found. With a cooking temperature of 185˚C, the best absorbance rates are 45% by weight of the sodium hydroxide solution.

6. Conclusion

In general, we can remember that the curing temperature increases with the compressive strength. The best resistances are noted at 8 molars concentration of the sodium hydroxide solution with a percentage of mixing water of 35%. The analysis of the curves shows that a variation of the proportion of the soda solution gives the optimum at 35% for the concentrations of 5 and 8 molars. But unlike the concentration of 12 molars, the resistance decreases with the increase of the proportion of the soda solution. These results in a limitation of the geopolymerization with small quantities of neo-formed gel explain the decrease of the resistances to the left of the optimum. On the other hand, when the solution is too abundant, the liquid/solid ratio which is too high leads to an increase in the porosity and a decrease in the compactness which causes the reduction of the resistances to the right of the optimum. Bricks that are more resistant to bending are located in the 185˚C series of bricks. Bricks manufactured at 35% are the ones with the best results in terms of absorbance.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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