Study of the influence of the intrinsic parameters of charcoal pellets and relative humidity on compressive strength and moisture adsorption.

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Abstract:

In this study, charcoal fines were used to produce pellets by applying wheat starch and arabic gum. The moisture content and calorific value of charcoal fines were respectively 3 % and 30.02 MJ/kg. Two levels of binder rate were used (6 % and 10 %). Binders of wheat starch and arabic gum were obtained by mixing wheat starch or arabic gum with water. Compaction pressures of 20 MPa, 30 MPa and 50 MPa were applied for briquetting. Temperature of 30 °C and relative humidity values of 30 %, 65 % and 85 % were used to conduct moisture adsorption tests. The effect of binder type, rate of binder and compaction pressure were investigated through measuring pellet's compressive strength and moisture adsorption. Statistical analysis was performed to determine factors that have more influences on compressive strength and moisture adsorption. As the rate of binder and the compaction pressure increased, the more the compressive strength increased. Moisture adsorption increased greatly by increasing relative humidity. Moisture adsorption depends also on the used binder type. All charcoal pellets had compressive strength above 1.0 MPa and their moisture adsorption reach 3 % to 12 % depending on relative humidity conditions. In our experiment field, statistical analysis showed that binder type and the rate of binder had more significant effects on compressive strength. The moisture adsorption was more influenced by relative humidity and binder type.

Keywords: charcoal fines, binder, compaction pressure, compressive strength, moisture adsorption and statistical analysis

Introduction

The use of wood and charcoal as household cooking fuels poses serious environmental issues in many countries, particularly in developing countries. Deforestation is being more important. The increase of senegalese population places more energy supply, to the extent that the increase use of these traditional fuels exposes the country to deforestation, pollution and human health. According to the national survey, more than 6 million cubic meter of wood are consumed as cooking fuel each year in Senegal (PROGEDE-2, 2014). In addition, according to statistical data from the World Health Observatory,
7 904 deaths recorded in Senegal in 2016 have been attributed to household air pollution (World Health Organization, 2018) by use of biomass cooking fuel. To address these various energy challenges, coal briquettes can be one of the alternatives fuel. In recent years, vegetable coal briquettes have been known as fuel substitute for wood and lump charcoal in order to reduce the problems of deforestation and the emission of toxic pollutants (Li et al., 2019; Qi et al., 2017). Considered as green fuels, their use should no way poses more problems than that of traditional fuels. However, these are sometimes subject to external solicitations, during transport, loading and storage operations, thus causing breakage, moisture adsorption, crumbling.

To enlarge their dissemination, those alternative cooking fuels have to respect minimal standards namely ability to resist to mechanical strength during transport and loading and reduced moisture absorption for maintaining high combustion quality.

Previous studies showed that the addition of binder like starch, arabic gum, molasse,… had effects on physical and mechanical properties of coal briquettes (Manyuchi et al., 2018; Sen et al., 2016).

The purpose of this study is to determine compressive strength and moisture adsorption of charcoal pellets. This study makes it possible, among other things, to have an idea about the factors that most influence compressive strength and moisture adsorption.

To do this, moisture adsorption and mechanical compressive tests were carried out on charcoal pellets based on wheat starch and arabic gum for different levels of binder, compressive pressure and relative humidity.

Materials and Methods

In this study, charcoal fines was used to produce pellets by applying wheat starch and arabic gum. The moisture content and calorific value of charcoal were respectively 3 % and 30.02 MJ/kg.

Preparation of pellets

Charcoal was crushed and sieved to obtain a granulometry of 1 mm. Charcoal pellets were prepared by adding wheat starch and arabic gum as binders. Two levels of binder rate were used (6 % and 10 %). Binders of wheat starch and arabic gum were obtained by mixing wheat starch or arabic gum with water. A ratio of binder/water equal to 0.1 was used. The solution obtained was heated until a viscous solution was obtained (around 70 °C). Charcoal pellets were produced by compressing 2 g of sample through 13 mm die diameter. A compressive testing machine (ADAMEL Lhomargy DY 36 - DY36D MTS) was used and pressures of 20 MPa, 30 MPa and 50 MPa were applied by a piston with a diameter of 275 mm at a constant speed of 0.05 mm/s.

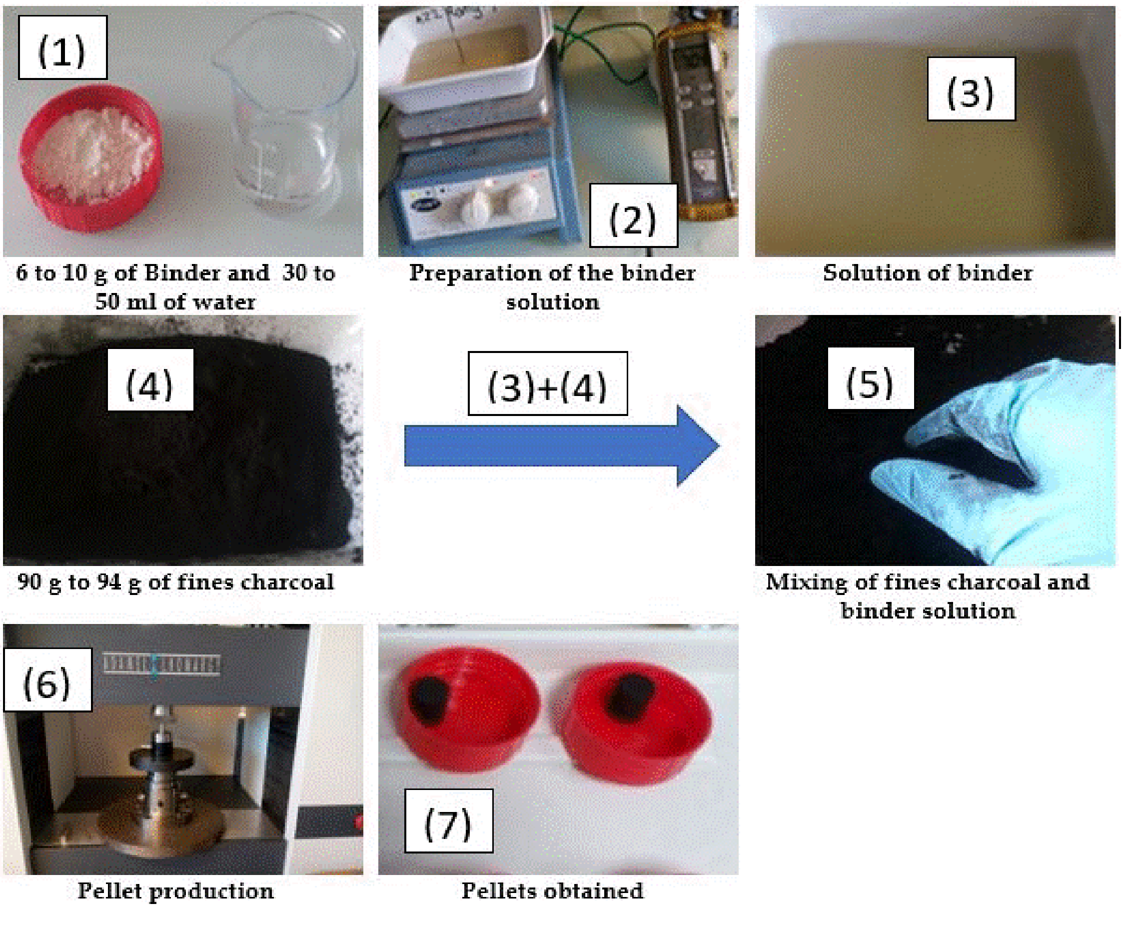

Fig.1: Scheme showing the different steps of pellets production

Compressive strength and moisture adsorption of charcoal pellets

Charcoal pellets are sometimes subjected to external solicitations, during transport, loading and storage operations, thus causing breakages, moisture adsorption, crumbling. The tests conducted in order to determine the compressive strength of charcoal pellets were also performed by using the compressive testing machine (ADAMEL Lhomargy DY 36 - DY36D MTS). The tests were based on applying a compressive load until the structure of the charcoal pellet failed (Borowski, 2011). The axial compressive strength is given by:

$$\sigma = \frac{F_{\max}}{S} \quad (1)$$

where F_{max} (N) is the maximum load and S (mm^2) the section of the charcoal pellets.
For moisture adsorption tests, a Memmert oven were used by applying the following

parameters: temperature and relative humidity. The applied temperature was 30 °C and values of relative humidity were 30 %, 65 % and 85 %.The sample is weighted every 24 hours until its mass become constant. When equilibrium is reached, the moisture adsorption is calculated by the following equation:

$$m_a = \frac{m_{eq}}{m_i} \quad (2)$$

Where m_{eq} is the mass of the sample at equilibrium and m_i the dry mass of the sample.

Statistical analysis

Statistical analysis was performed, using experimental designs, to determine the factors that have the greatest influence on the compressive strength and the moisture adsorption. ***STATISTICA*** software (version 13.3.704.20) was used for the analysis. STATISTICA offers a wide range of tools for statistical analysis, management and graphical representation of data. It includes in its database several options among which we can mention that of the plans of experiments. A plan of experiments allows to analyze a phenomenon in a methodical way. The method of the plans of experiments is a safe, practical and indispensable tool for conducting a study involving many parameters with the best possible efficiency: limited time, reduced costs, increased accuracy and improved reliability.

Results and discussion

Axial compressive strength

Compressive tests were performed on charcoal pellets with wheat starch and arabic gum, made with compaction pressures of 20 MPa, 30 MPa and 50 MPa. The compressive test results of these pellets, made with 10 % of wheat starch and 10 % of arabic gum, are respectively shown in figs 2 and 3. On the different figs, maximum points were observed on every compressive curve. These points correspond to the axial compressive strength, strength from which the sample loses its structure. As we observe on figs 2 and 3, the compaction pressure and the type of binder influence the compressive strength. So, it will be interesting to know if these influences are significant or not; that's why statistical analysis were conducted.

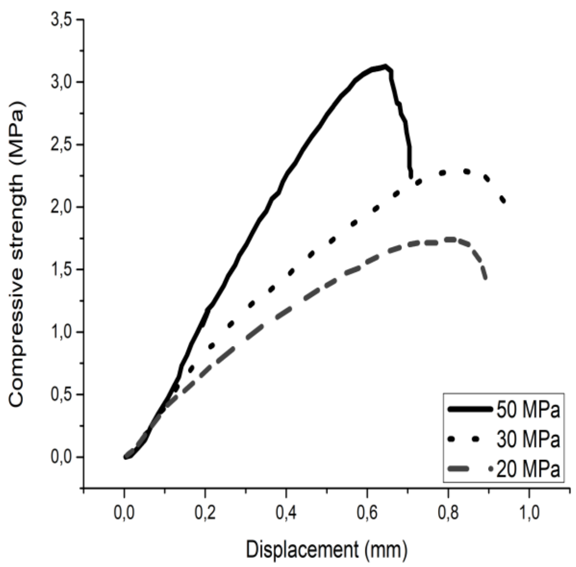

Fig.2 : Compressive strength of charcoal pellets with 10% of wheat starch

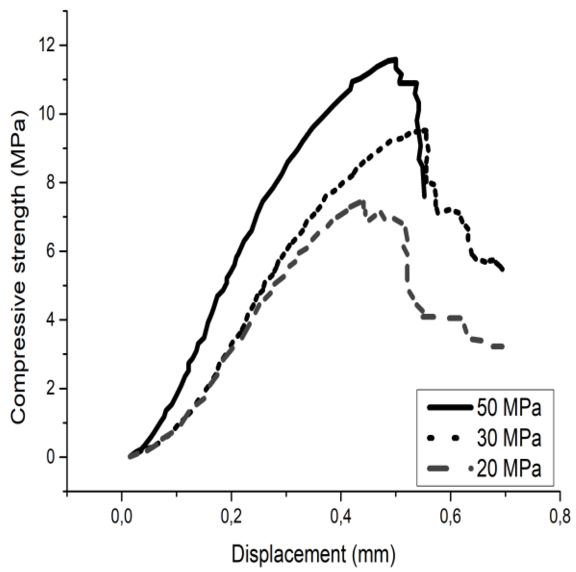

Fig.3 : Compressive strength of charcoal pellets with 10% of arabic gum

All compressive test results are shown in table 1. Table 1 indicates all parameters of briquettes production and the compressive strength of every charcoal pellets.

Table 1: Compressive strength of charcoal for different conditions of briquettes production

Independent variables			Dependent variable
Binder type	Binder rate (%)	Compaction pressure (MPa)	Compressive strength (MPa)
Arabic gum	6	20	2.70
Arabic gum	6	30	3.18
Arabic gum	6	50	4.04
Arabic gum	10	20	7.14
Arabic gum	10	30	9.55
Arabic gum	10	50	11.56
Wheat starch	6	20	1.23
Wheat starch	6	30	1.55
Wheat starch	6	50	1.78
Wheat starch	10	20	1.79
Wheat starch	10	30	2.33
Wheat starch	10	50	3.14

The results showed that the more the rate of binder and the compaction pressure increased, the more the compressive strength was important. Charcoal pellets with arabic gum had the better compressive strength compared to those produced with wheat starch. According to the study of (Borowski et al., 2017), the minimum compressive strength value, for briquette with better quality, should be above 1.0 MPa. (Ramaroson et al., 2015) found compressive strength of 1.25 MPa with coal briquette made of 6% cassava starch and compaction pressure equal to 39,8 MPa. Authors like (Białowiec et al., 2018; Demirbas, 1999; Deniz, 2013; Hu et al., 2016) found that the compressive strength increased with increasing the rate of binder and compaction pressure. (Deniz, 2013) found also that compressive strength decreased with compaction pressures from 60 MPa to 150 MPa and with addition of lime from 2.5 % to 10 %.

Moisture adsorption

Charcoal pellets, obtained in the same conditions than those used for compressive tests, were also used to perform moisture adsorption tests in different atmospheres at fixe temperature of 30 °C and relative humidity of 30 %, 65 % and 85 %. The results of these tests, for charcoal pellets with 10 % of wheat starch and charcoal pellets with 10 % of arabic gum, are indicated in figs 4 and 5.

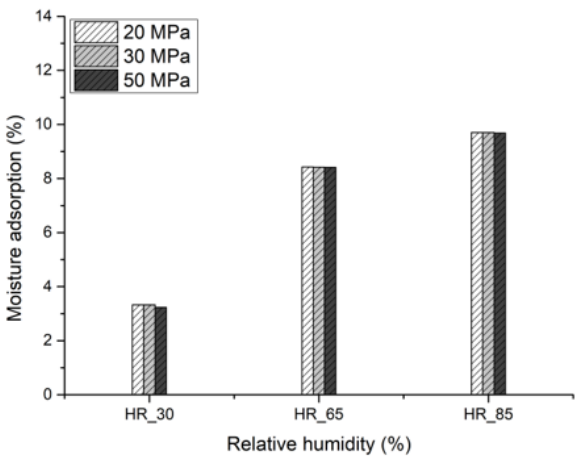

Fig.4: Moisture adsorption of charcoal pellets with 10% of wheat starch;

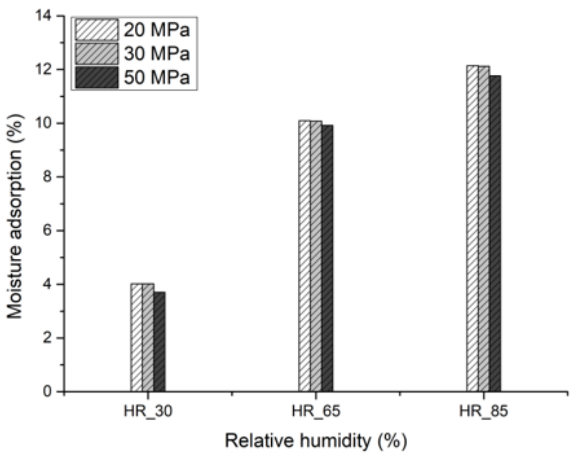

Fig.5: Moisture adsorption of charcoal pellets with 10% of arabic gum;

As observed on figs 4 and 5, moisture adsorption is mainly influence by relative humidity. It is evident. It was also observed that the type of binder influence the moisture adsorption of charcoal pellets. It seems that compaction pressure had no significant effect on moisture adsorption. Statistical analysis (Cf. part Statistical analysis) were performed to verify if influences are significant or not. Moisture adsorption of charcoal pellets with 6% of respectively arabic gum and wheat starch are shown below in table 2. Table 2 indicates the results of moisture adsorption tests and the independent variables (type of binder, rate of binder, compaction pressure and relative humidity).

Table 2: Moisture adsorption tests results.

Binder type	Binder rate (%)	Compaction pressure (MPa)	Relative humidity (%)	Moisture adsorption (%)
Wheat starch	6	20	30	3.63
Wheat starch	6	20	65	8.70
Wheat starch	6	20	85	10.00
Wheat starch	6	30	30	3.73
Wheat starch	6	30	65	8.89
Wheat starch	6	30	85	10.12
Wheat starch	6	50	30	3.67
Wheat starch	6	50	65	8.97
Wheat starch	6	50	85	10.12
Wheat starch	10	20	30	3.33
Wheat starch	10	20	65	8.43
Wheat starch	10	20	85	9.70
Wheat starch	10	30	30	3.33
Wheat starch	10	30	65	8.42
Wheat starch	10	30	85	9.70
Wheat starch	10	50	30	3.23
Wheat starch	10	50	65	8.42
Wheat starch	10	50	85	9.68
Arabic gum	6	20	30	3.05
Arabic gum	6	20	65	8.70
Arabic gum	6	20	85	10.25
Arabic gum	6	30	30	4.10
Arabic gum	6	30	65	9.90
Arabic gum	6	30	85	11.47
Arabic gum	6	50	30	4.02
Arabic gum	6	50	65	9.84
Arabic gum	6	50	85	11.40
Arabic gum	10	20	30	4.02
Arabic gum	10	20	65	10.09
Arabic gum	10	20	85	12.14
Arabic gum	10	30	30	4.02
Arabic gum	10	30	65	10.08
Arabic gum	10	30	85	12.12
Arabic gum	10	50	30	3.70
Arabic gum	10	50	65	9.94
Arabic gum	10	50	85	11.97

Moisture adsorption increased considerably by increasing the relative humidity from 30 % to 85 %. The maximum value (12.14 %) of moisture adsorption was observed for charcoal pellets with arabic gum. It was observed that the moisture adsorption of charcoal pellets with arabic gum increased with the increase of the rate of arabic gum. For charcoal pellets with wheat starch, we observed that moisture adsorption decreased with increasing of the rate of binder. These variation of moisture adsorption of charcoal pellets with wheat starch is in contrary of those found by (Hu et al., 2015).

Moisture adsorption reached 3 % to 12 % by increasing relative humidity from 30% to 85%, depending on the binder used. (Li et al., 2009) found, by working with a relative humidity of 75% at 30°C, that the dried low rank coal tends to equilibrate at the moisture content of approximately 13%.

Statistical analysis

The aim of this part was to verify, on the one hand, the influence of type of binder, the rate of binder and compaction pressure on compressive strength, and on the other hand, the influence of relative humidity and the factors listed above (type of binder, rate of binder and compaction pressure) on the moisture adsorption. So, data obtained from compressive and moisture adsorption tests were submitted to statistical analysis. The module "experimental design" of *STATISTICA* software was used for the analysis. The tests of ANOVA were made. The test of ANOVA is used to determine if the effect of a factor on the response is significant. A low value of probability (P_value) allow to say if a factor is significant. A factor will be considered as significant if its P_value is inferior to 0.05. During the tests, the type of binder, the rate of binder, the compaction pressure and the relative humidity were replaced by factors respectively coded as X_1, X_2, X_3 and X_4. Tables 3 and 4 respectively show the results of the significance test of factors X_1, X_2, X_3 and X_4 on compressive strength and the moisture adsorption.

Table 3: Significance test of factors X_1, X_2 and X_3 on compressive strength

Factors	Sum of square	Degree of freedom	Mean square	F_value	P_value
Type of binder, X_1	57,8602	1	57,86021	16,32145	**0,004933**
Rate of binder, X_2	36,8551	1	36,85508	10,39623	**0,014566**
Compaction pressure, X_3	7,3355	2	3,66776	1,03462	0,403967
Error	24,8153	7	3,54504		
Total	126,8661	11			

Table 4: Significance test of factors X_1, X_2, X_3 and X_4 on moisture adsorption

Factors	Sum of square	Degree of freedom	Mean square	F_value	P_value
Type of binder, X1	9,7552	1	9,7552	37,667	**0,000001**
Rate of binder, X2	0,0860	1	0,0860	0,332	0,568793
Compaction pressure, X3	0,6700	2	0,3350	1,293	0,289689
Relative Humidity, X4	332,2570	2	166,1285	641,456	**0,000000**
Error	7,5106	29	0,2590		
Total	350,2788	35			

For compressive strength, the results of the tests of ANOVA showed that the type of binder and the rate of binder had statistically significant influences. Their P_values were inferior to 0.05. The effect of the type of binder on compressive strength was more important. The results showed also that the effect of compaction pressure was not statistically significant. In addition to the effect of the relative humidity, the effect of the type of binder on moisture adsorption was also statistically significant.

The linear models without interaction between factors didn't allowed a good correlation between the values observed and the values predicted. By considering the interactions between factors, two models of prediction were proposed. These models are represented by the following equations.

For compressive strength:

$$Y_1 = -831.1 + 8{,}08429X_1 + 133.869X_2 + 6.36738X_3 - 0.00149583X_3X_3 - 1.3025X_1X_2 - 0.0616786X_1X_3 + 0.0154018X_2X_3$$

Where X_1=102 if the type of binder is arabic gum or X_1=103 if the type of binder is wheat starch.

For moisture adsorption:

$$Y_2 = 247.774 - 2.54813X_1 - 24,5434X_2 + 0,425167X_3 - 0.0175275X_3X_3 - 2.16588X_4$$
$$- 0.00149535X_4X_4 + 0.248333X_1X_2 + 0.00012096X_1X_2X_3 + 0.0241559X_1X_4$$
$$- 0.0416806X_2X_3 + 0.000506944X_2X_3X_3 + 0.00182124X_2X_4$$

Where X_1=102 if the type of binder is arabic gum or X_1=101 if the type of binder is wheat starch.

The two models proposed had respectively the coefficient of determination (R^2) and the coefficient of determination adjusted (R^2_{adj}) equal to 0.99282 and 0.98026 for compressive strength and 0.99673 and 0.99502 for moisture adsorption. These high coefficients of determination indicate a good correlation between the values observed and the values predicted in the limits of our experimental field. The correlations between the values observed and the values predicted are shown in figs 6 and 7.

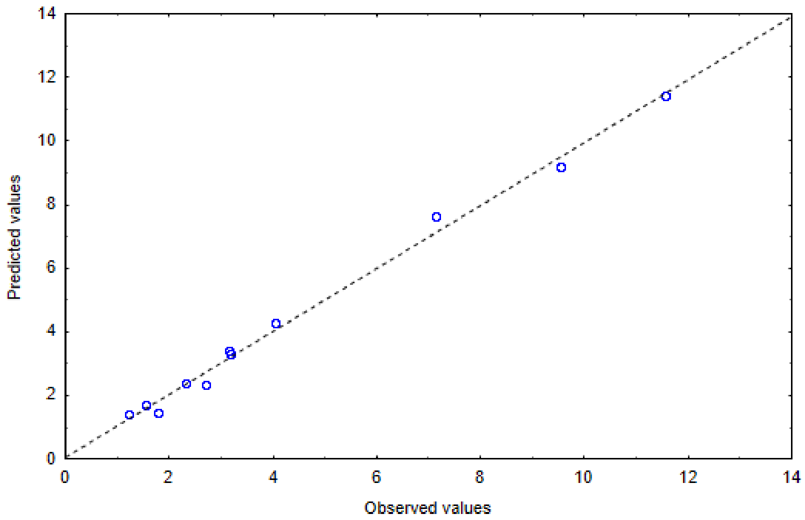

Fig.6: The correlations between the observed values and the predicted values of compressive strength

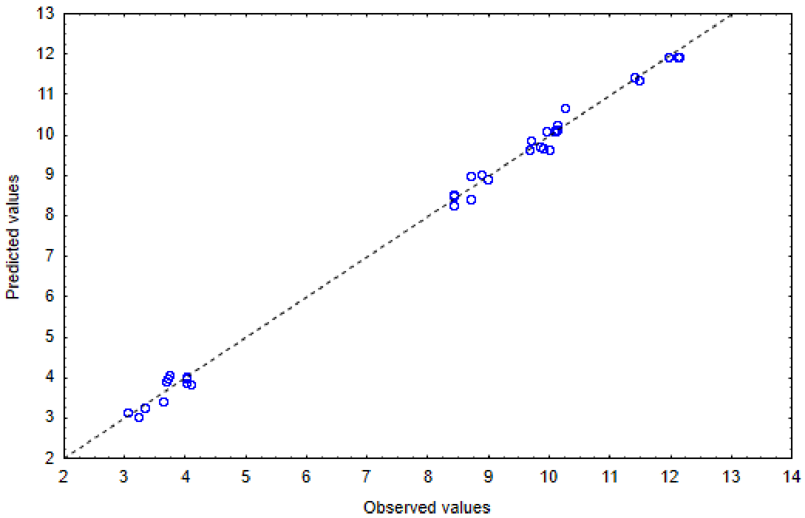

Fig.7: The correlations between the observed values and the predicted values of compressive strength

Figures 6 and 7 showed that the values of compressive strength and moisture adsorption were closed to the linear straight. That's mean a good correlation between the values.

Conclusion

Wheat starch and arabic gum can be use as binders source to produce adequate compressive strength charcoal pellets (above 1.0 MPa). The addition of wheat starch as well as arabic gum results in a charcoal pellet with compressive strength respectively of 1.23 MPa and 11.56 MPa when compaction pressure are between 20 MPa and 50 MPa and the rate of binder between 6 % and 10 %. When charcoal pellets are stored in atmosphere of 65 % of relative humidity, their moisture content can be reach 10 %. Statistical analysis showed that compressive strength can be more improve by increasing the rate of binder or choosing a good binder. To improve moisture adsorption, attention will be pay in the choice of the binder.

Acknowledgement

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