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Optimizing Green Strength of Foundry Sand Using Natural Starch as Additive

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Abstract

For any naturally bonded sand to be used for metal casting, it must possess a minimum of certain physio-chemical and mechanical properties such as green strength. It is possible to optimize some of these properties, for example, green strength by using additives in different forms and quantities. In this study, several properties of Bida foundry sand were investigated and the values of the green compressive strength (GCS) and green shear strength (GSS) were optimized using Taguchi's L9 orthogonal array with % additive and % water content as input factors. Thereafter the responses obtained from the designed experimental runs were evaluated using analysis of variance (ANOVA). Many of the physio-chemical properties obtained indicated that the sand studied is suitable for non-ferrous castings. With the addition of a natural starch (Cassava, Manihot esculenta Crantz) an increase in green strengths were obtained with a maximum of up to 30% when the additive was in gelatinized form. Quantity of additive was found to be the most significant factor with optimal values of GCS and GSS being 30.36 kN/m^2 and 19.8kN/m^2. To control the effect of process variability, the range of input factors to achieve optimal values was found to be 3 – 6% additive and 5.5 – 7% water content. The results obtained indicate that the green strength of the moulding sand increased with the addition of a natural starch in powdery and gelatinized forms. This can increase the application applications of sand in making foundry moulds for non-ferrous castings.

1. Introduction

Sand casting is a metal forming process whereby objects of desired shapes, sizes, and chemical composition are fabricated by pouring molten metal into a prefabricated mould made from sand and allowing it to solidify. The process of sand casting encompasses some operations carried out according to a defined order: pattern making, preparation of sand with mixtures, sand moulding, melting of metal, pouring into prepared moulds, cooling, shake-out, cleaning, finishing operations, and final inspection [1]. Moulds prepared from sand are comparatively cheap, and appropriately refractory including for steel foundries, thus over 60% (by weight) of metal castings are manufactured by the sand casting process [2]. Sands used for moulding that are neither set (dry) nor uncured are referred to as green sands and are mostly made of 85–95% silica sand, 4–10% of the bentonite clay as a binder then 2–10% of additives [3]. As highlighted in some studies [4-5], the compositions of moulding sands are not fixed and vary depending on the type of sand and the location of the deposit. Therefore, it is necessary to conduct standard tests on some specific properties such as grain finesse, bulk density, compression and shear strengths, permeability, and others [7]. Green (wet) strength is one of the important properties to be maintained within a specified range [6-8]. Suitable strength in various forms is essential, for when the moulding sand is mixed with a proper binder it should improve interconnection among its grains to form and remain as a continuous mould. It should also stick to the mould-box or other unit(s) when rammed, and withstand movement and relocating of moulds before pouring of molten metal [2]. Furthermore, the moulding sand must correspondingly improve acceptable strength with a binder to endure the compressive and force exerted by the molten metal during and after pouring in the mould cavity [2, 9]. In most cases, the metallic alloys transferred to moulds mostly have high density leading to erosion, expansion and collapse of the mould causing some defects on castings such as leakage, bursting, bulging, and swelling [1, 7].

Some sand deposits do not possess the required strength, this deficiency is reduced by using additional materials (additives) such as the green sand mould like green compression strength, dry compression strength, green shear strength, dry shear strength, and permeability [2, 6-7]. Thus, a study [10] was conducted to determine some properties of olive sand used for casting after adding coconut shell ash, tamarind powder, and fly ash. In this work, it was discovered that the compression strength attained its maximum level in the moulding mixture having coconut shell ash when compared to those with tamarind powder and fly ash. During another investigation [11], it was discovered that sand moulding mixture with sawdust showered more green strength with 25% of coal dust, sawdust, and iron filling on the moulding sand. Whereas, the mixture with coal dust displayed enhanced permeability and porosity, in a way decreasing the flaws in casted products. Many other studies have also been carried out with the outcomes confirming that when some materials are added to sand moulding mixtures, the strength increases, thus giving better castings [12-13].

In several studies conducted on the effect of additives on the strengths of moulding sands, it was ascertained that cassava (*Manihot esculenta Crantz*) is comparatively more effective [10, 14]. This may be attributed to the high starch content in cassava which is easy to be processed. In 2018, about 278 million tonnes were produced with Nigeria contributing the largest share (21%) and Thailand exporting the largest cassava-made starch [15]. Therefore, a starch made from cassava and in various forms can be accepted as the most suitable additive to be used for improving the green strengths of naturally-bonded moulding sands.

However, ranges of the ratio of additives to enhance strengths added to sand moulding mixtures in many cases used the One Factor at a Time (OFAT) method as indicated in several works [4, 16]. This may negatively affect the experimental results due to shortcomings associated with using OFAT [17]. To determine the best possible values of moulding sand strengths, many research works were carried out using various optimization methods. Taguchi's method was used to establish the best factors for strengths in the green sand moulding process [9, 16-18]. Response surface methodology (RSM) was used by others to examine the effect of some input factors related to the strength and other properties of sand moulding mixtures with results obtained giving optimal values of the output [8, 19]. Apart from applying Taguchi's method and RSM, other methods were used to optimize the strengths of sand moulding mixture such as mathematical modelling using computer simulation, Artificial Neural Networks, Genetic Algorithm, and multiple regressions [20, 21].

Furthermore, it was observed that the optimal values obtained for several factors studied are not all-purpose and vary according to the sand deposit studied. Consequently, there is a need to optimize the required parameters for each sand deposit to be used for moulding in metal casting. In this study, the influence of cassava additive on green compression and shear strengths of naturally-bonded sand in Bida, Nigeria were investigated using Taguchi Method. In this approach, the amount of water and additive contents should be determined in other to obtain maximum strengths for the moulding sand under study.

2. Materials and Methods

2.1 Materials

2.1.1 Foundry Sand

The naturally bonded foundry sand was obtained in the outskirt of Bida (9° 4' 59.98" N and 6° 1' 0.012" E) located in Niger State, Nigeria. The sand was sieved to remove leaves, plant roots, and other extraneous materials.

2.1.2 Cassava Starch

Cassava tubers obtained from a local market in Bida were peeled and washed appropriately. Thereafter the washed tubers were milled into pulp form. Then water was added to ease the extraction of starch required. This led to the formation of a suspension and then left for two (2) hours and water that settled on top of the container was drained. The moist starch residue was then dried; ground and passed through 150 mesh obtaining an odourless, tasteless, and whitish powder. When needed, gelatinized cassava was obtained by adding boiled water gradually to the produced powder until slurry of desired thickness is formed. All the processes followed are similar to those used in similar studies [21, 22].

2.2 Physical Properties Tests

Some physical properties of the Bida naturally bonded foundry sand was conducted using standard procedures specified by the American Foundry Society (AFS) and others [6, 7, 23 & 24]. Physical tests conducted are colour test, grain shape test, grain fineness number, active clay content test, loss on ignition, and refractoriness test [7, 23]. Other physical tests carried out are the water requirement test, bulk density test, and permeability test [4, 6, 13, and 23].

2.3 Green Strengths without Cassava Additive

The moulding sand having moisture is designated as green sand. The strength of the sand in a green or wet state is named green strength and in compressive or shear form. The Green Compressive Strength (GCS) of the Bida sand with determining water requirement without cassava additive. The Green Shear Strength (GSS) without additive was also determined using the same procedure but the loading surface was changed to the shear plate in the Universal Strength Machine (*Ridsdale-Dietert, Model No 33-USSM*).

2.4 Optimizing the Green Strengths of Bida Sand

Optimization of green strengths was carried out using Taguchi's method with the help of *Minitab19©* software. Input factors are % additive and % water contents with 3 levels that were selected based on results from earlier studies [18, 24- 25]. The input factors and their respective levels are shown in Table 1.

Table 1: Input factors with different levels

Factors	Level 1	Level 2	Level 3
% Additive	3	6	9
% Water Content	4	7	10

The design matrix was developed using the Taguchi method indicated in Table 2 and then used to conduct tests for all the runs to determine the green compression strength (GCS) and green shear stress (GSS) with the addition of cassava in powdered (P) and gelatinized (G) forms.

Table 2: Design matrix using L9 orthogonal array

	Input(factors)	
Runs	% Water	% Additive
1	4	3
2	4	6
3	4	9
4	7	3
5	7	6
6	7	9
7	10	3
8	10	6
9	10	9

Thereafter, statistical analysis was carried out to assess the responses of the green strengths of Bida sands with cassava additive in gelatinized form as functions of % additive and % water contents.

3. Results and Discussion

3.1. Physio-Chemical and Structural Properties of Bida Moulding Sand

Some of the physio-chemical and structural properties of the sand studied are summarized in Table 3. The pink colour and 11.55% content of raw clay indicate that the Bida sand studied is naturally bonded based on AFS standards and other findings [8, 23, and 26].

Table 3: Physio-Chemical and Structural Properties of Bida Moulding Sand

Sand Colour	Pink (*5 YR 7/3*on *Munsel* Scale)
Sand Grains Shape	Sub-Angular
Raw Clay content	11.55%
Refractoriness	1235^{o}C
Loss of Ignition (LOI)	2.65%
Bulk Density	1630 Kg/m^3
Permeability No (AFS)	67
Grain Fineness Number (GFN)	116

The clay acts as a binder and together with specific moisture to impart required tensile and shear strengths on the moulding sand. Most of the grains of the Bida sand studied have a sub-angular shape, thus it may likely possess enhanced green strength due to the mechanical interconnection of the grains [6].

With 1630 kg/m^3 as bulk density and grain fineness number (GFN) of 116, the sand investigated should be classified as fine due to having 0.18 mm as grain diameter; this gives the acceptable capacity to withstand applied forces during ramming. This is confirmed by 2.65% obtained as the loss of ignition, which is within the acceptable limit of 10% [7]. Refractoriness gives moulding sands additional ability to withstand breakage at high temperatures and is classified depending on the type of liquid metal to be poured into prepared moulds [12, 23]. With 1235°C obtained as refractoriness, Bida sand is suitable for moulding operations.

3.2. Optimization of the Green Compressive and Shear Strengths

3.2.1. Main Effects on Responses

Without additives, the green compressive and shear strengths were 73.5kN/m^2 and 11.8kN/m^2 respectively. And the results obtained from the designed L9 experiments are listed in Table 4 showing for all runs cassava in the gelatinized form increased the green strengths more in comparison to when in powdered form.

Table 4: Green Strength of Bida Naturally bonded sand obtained from experiments conducted

Input(factors)			Responses			
Runs	% Water	% Additive	GCS(P)	GCS(G)	GSS(P)	GSS(G)
1	4	3	88.00	93.10	13.00	15.68
2	4	6	93.00	93.10	13.00	15.68
3	4	9	96.00	96.04	15.00	17.15
4	7	3	95.00	99.96	16.00	18.62
5	7	6	88.00	103.36	15.00	19.80
6	7	9	81.00	102.00	16.00	19.60
7	10	3	78.00	98.00	14.00	19.00
8	10	6	69.00	89.00	12.00	18.70
9	10	9	63.00	77.00	11.00	18.00

The increase in green strengths was up to 30% due to extra binding capacity added to the moulding sand mixture by the additives as also achieved in some previous works [14, 22, and 27]. The main effects of the input factor % additive and % water on GCS and GSS are illustrated in Figures 1 and 2.

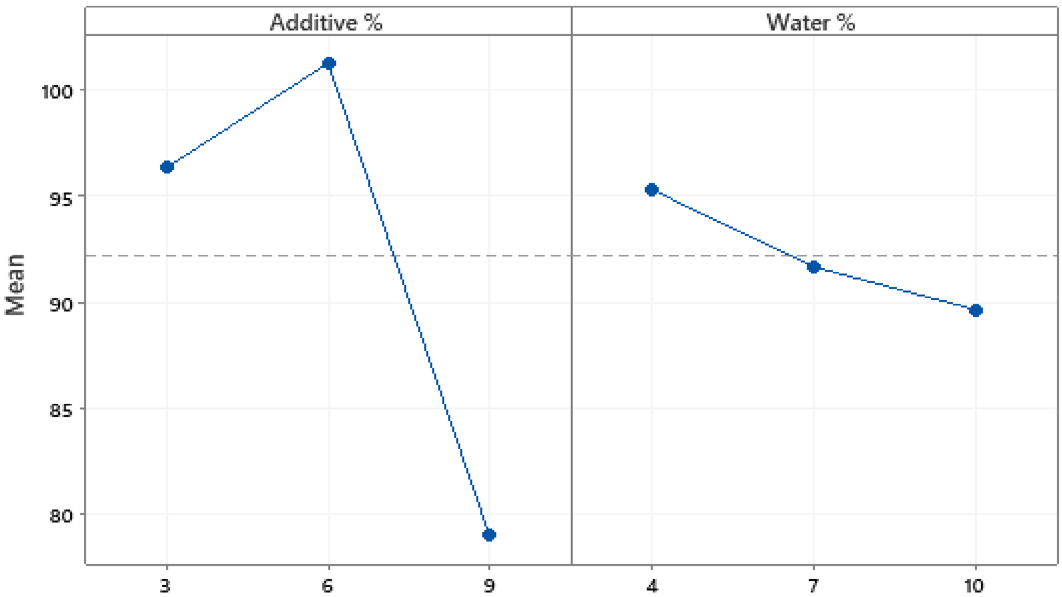


Figure 1: Main Effects Plots of Green Compressive Strength (GCS)

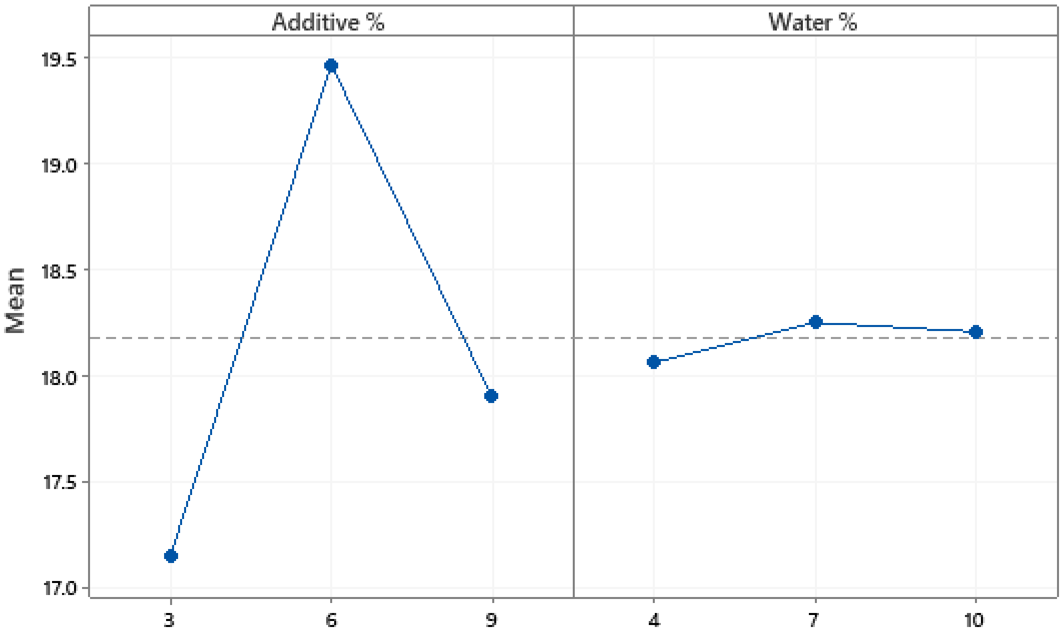


Figure 2: Main Effects Plots of Green Shear Strength (GSS)

From the plots in Figure 1, the GCS increased gradually to an ultimate value of 104 kN/m^2 at 6% additive, while the effect of water was maximal at 4% and thereafter reduces for both factors. Comparatively, the effect of additive on GSS is similar to that on GSC and the water content has a slight increase of up to 7%. As shown in Figure 2, % additive is the most influential factor on green strengths with optimal values being 6% additive and 4% water content for GCS while GSS are 6% additive and 7% water content. The results obtained agree with earlier studies [13, 21].

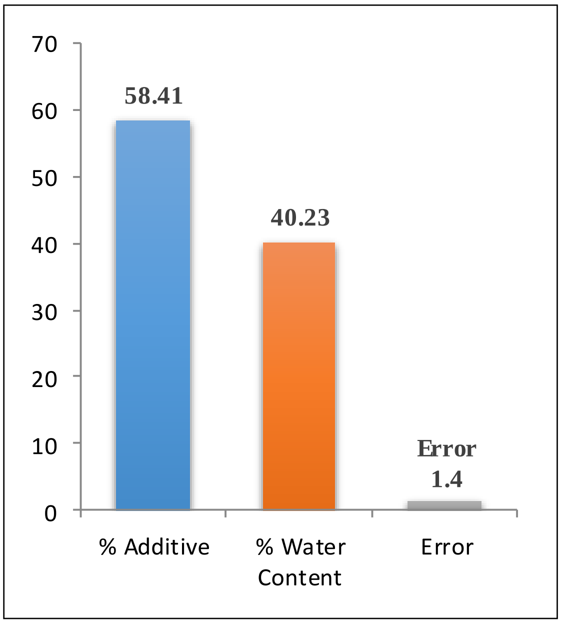
3.2.2 Significance of Input Factors

The significance of each input on the output was further analyzed as a general linear model via Analysis of Variance (ANOVA) with results obtained shown in Table 5. As obtained in main effects plots, a similar result was obtained from ANOVA indicating that % additive is the most influential factor with P-values being 0.004 and 0.003 for GCS and GSS respectively which is within the acceptable region (P<0.005) at a 95% confidence level.

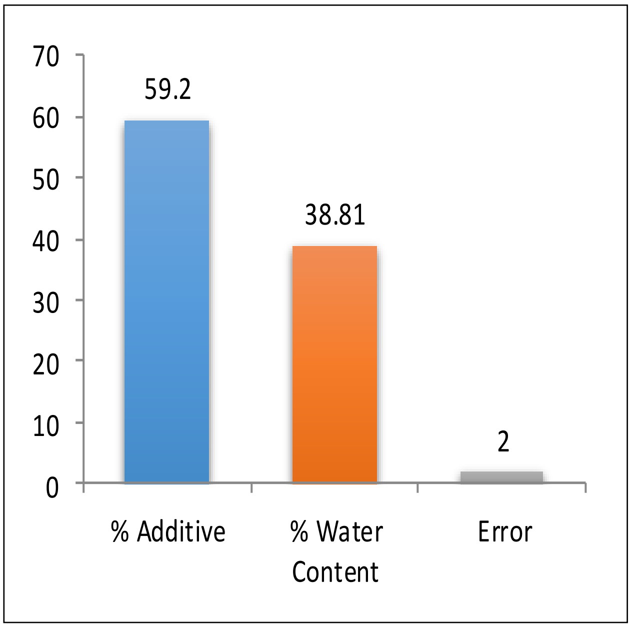
Table 5: ANOVA for various mean response variables at 95% confidence level

Output Variables	Input	DF	Sum of Squares	Mean of Squares	F-value	P-value	Contribution (%)
GCS	%Additive	2	452.4	150.8	5.1	0.004	58.41
	% Water	1	311.65	103.88	0.54	0.08	40.23
	Error	3	10.53	3.51			1.4
	Total	6	774.58				
GSS	% Additive	2	455.6	151.87	6.3	0.003	59.20
	% Water	1	298.7	99.57	0.87	0.066	38.81
	Error	3	15.33	5.11			2.0
	Total	6	769.63				

It was also observed that respective input factors showed more influence on changing the output factors (responses). Figure 3 symbolizes the comparative influence of each respective input factor on the outputs (responses).



(a)



(b)

Figure 3: Charts showing the relative contribution of Gelatine Cassava Additive on the Green Compressive Strength (a) and Green Shear strengths (b) of Bida Moulding Sand

As obtained in the main effect plots and ANOVA, the % additive is the utmost significant factor influencing an increase in the green strengths with similar proportions for both GCS and GSS.

3.2.3 Mathematical Model between Input Factors and Output

From the regression analysis conducted using *Minitab19*, the mathematical relationship between the inputs during experimental runs and the output obtained as response is shown in Equations 1 and 2:

$$GCS = 106.2 + 1.03A - 0.95W \quad (1)$$

$$GSS = 17.25 + 0.16A + 0.14W \quad (2)$$

Where,

GCS= Green Compressive Strength with galvanized cassava additive

GSS= Green Shear Strength with galvanized cassava additive

A = % of Cassava additive

W = % of Water content

The maximum response for GSC as presented in Table 4 is 103.36 kN/m^2 with 6% additive and 7% water content. Using the values of inputs at that point, the GSC from Equation (1) is 101.19 kN/m^2 giving a difference of 2.1% between the experimental and predicted values. Using a similar procedure for Equation (2), the experimental and predicted values of the GSS is 3.2%.

Results for the goodness test of the obtained model fit are summarized in Table 6 where S represents the standard deviation indicating variations in a set of values. Also, R^2 is the determination coefficient signifying ratio of the variance in responses that is predictable from the input factors and may also be expressed for the mean as adjusted R^2 (adj R^2).

Table 6: Summary of the Model Fit for GCS and GSS

Response Variables	S	R^2 (%)	Adjusted R^2 (%)
GCS	3.85	91.56	89.15
GSS	0.27	94.45	92.94

The value of R^2 computed for GCS is 91.56% indicating that only about 8.46% of the variation is not affected or acceptable using the model obtained in equation 1. An adjusted R^2 of 89.15% obtained for GSC specifies that the model obtained from statistical analysis is highly significant. A similar trend was also observed for GSS with low S value and high values for both R^2 and adjusted R^2. All the values obtained confirm that Equations (1) and (2) can be used to effectively predict the responses (GCS and GSS). A similar pattern of results was obtained in other studies [3, 28].

3.2.4 Optimized Ranges for Responses

Methods used for obtaining optimal values are the main effects, ANOVA, and regression analysis as highlighted in relevant sections earlier. Only single values were obtained for each response, but this may not be easily attained during the real production process. To obtain ranges of inputs that will give an optimal response, a contour graph was plotted as indicated in Figure 3.The optimal values (in (kN/m^2) are in zones indicated in contour plots Figure 4 and Table 7.

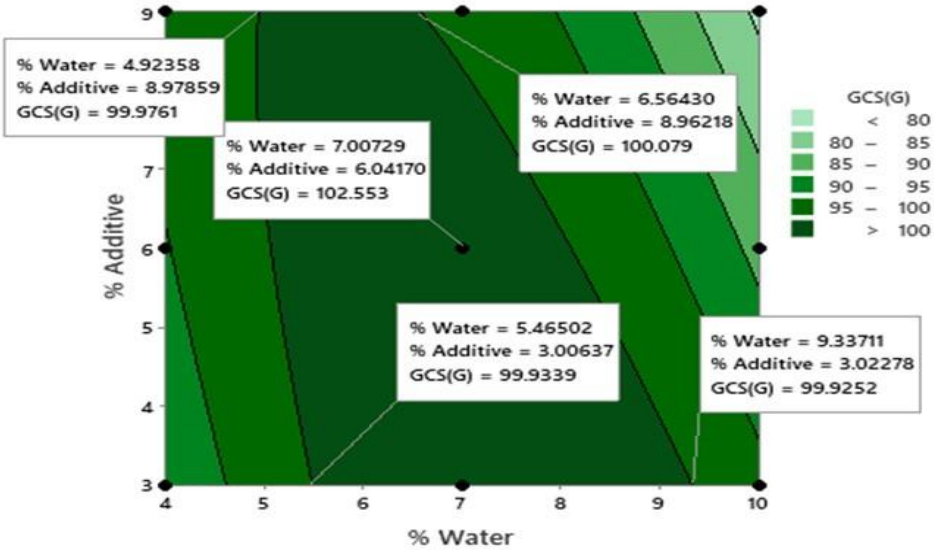


Figure 4: Contour plots of a Response (GCS) vs. % Additive and % Water Content

Table 7: Lower and higher levels of Input for Optimal

Response Variables (kN/m^2)	Lowest Optimal	Highest Optimal
GCS	99.98	102.5
% Additive	3.06	6.04
% Water	5.5	7.03

From the contour plot (Figure 3) and values determined, the optimal values obtained are 3 – 6% additive and 5.5 – 7% water content. The overall optimum value obtained on the contour plot is 102.5 kN/m^2, which is almost the same as the result (103.36 kN/m^2) during experimental runs.

3.2.5 Confirmation Test

The confirmation test was conducted by checking skewness in the normal probability plot in residuals as shown in Figure 4. As indicated, all the spots in the normal probability plots for both GCS and GSS are very near the tie line and no extreme points occurred which depicts no extreme skewness. Thus, the optimal values obtained from experimental runs and statistical analysis for the green strengths of Bida naturally bonded moulding sand is within recommended ranges making it suitable for non-ferrous castings [6-7, 23-24].

4. Conclusion

This study was conducted to determine some physio-chemical and structural properties of Bida naturally bonded foundry sands in addition to optimizing its green strength using the Taguchi method. From the results obtained the Bida moulding sand can be classified as naturally bonded and suitable for non-ferrous castings and without additives, the green compressive and shear strengths were 73.5kN/m^2 and 11.8kN/m^2 respectively. Using the Taguchi method of optimization with the quantity of additives and % water content as input factors, green strengths were increased by 59% by cassava additive. The optimal values obtained for GCS and GSS are 103.36kN/m^2 and 19.8kN/m^2 respectively with 6% additive and 7% water content. Reliable optimal values for the green strength may be achievable through process variability. As a way out, further analysis was used to estimate the range of efficiency to be 3 – 6% additive and 5.5 – 7% water for GCS and GSS respectively.

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