Prediction of Compaction Characteristics of Coal Bottom Ash

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***Abstract*—Compaction is the process of artificially improving the mechanical properties of soil. However, determination of compaction characteristics in laboratory using Proctor compaction test is time consuming and expensive. Hence, there is a need of correlating compaction characteristics with other physical properties of bottom ash which can be obtained easily. This paper describes an innovative solution to predict the compaction properties of coal bottom ash for the preliminary assessment prior to geotechnical engineering related field applications. The data for required parameters of bottom ash for the model development were collected through a literature survey representing different parts of the world. After stepwise regression analysis, specific gravity and uniformity coefficient were found to be the most significant input parameters to predict the compaction characteristics of bottom ash. These parameters were then used to develop the models to predict maximum dry density and optimum moisture content of bottom ash using multiple regression analysis. The developed models were accurate with a prediction accuracy less than ±3% for both maximum dry density and optimum moisture content models. These empirical models were also presented graphically. According to those predictive curves, maximum dry density increases with increasing uniformity coefficient and specific gravity while optimum moisture content reduced.**

Keywords—bottom ash, compaction characteristics, gradational parameters, multiple regression analysis, specific gravity

I. Introduction and Background

Bottom ash (BA) is a granular, coarse and incombustible waste by-product generated in the coal combustion process in large quantities [1], [2]. In general, the particles of BA have dark, rough surface and angular shapes with porous textures [1]. The method used for the disposal of the BA is open dumping into lands which creates water and soil pollution. Hence, researchers attempted to use BA as a substitute for construction materials which will also be a solution for the scarcity of natural raw materials. According to literature, BA is being utilized in numerous applications in geotechnical engineering such as a fill material [2], [3], to prevent soil erosion [4], as a soil stabilizer [5] and as a soil amendment material [6].

Compaction is one of the most important parameters in the assessment of fill materials in any geotechnical applications. Compaction is needed for achieving the desired increase in strength, decrease in compressibility and also decrease in hydraulic conductivity of the fill material. Prior to the field compaction, the determination of compaction characteristics namely, maximum dry density (MDD) and optimum moisture content (OMC) is essential for effective planning of compaction procedure and methodology in the field.

In laboratory, these characteristics can be determined by Proctor compaction test. The MDD and OMC can be affected by the physical properties of soil, such as percentage of sand and silt content, liquid limit, plastic limit, particle size distribution, shape of the soil particles, specific gravity, and type of clay minerals [7].

The previous studies [2], [8] revealed that there is a large variation of MDD and also OMC for BA samples. The physical properties of BA depend on the type of burner, operation procedure of the power plant and quality and type of coal burned [3] and hence, it is considered as a highly heterogeneous material. It is often necessary for engineers to quickly assess the suitability of BA for any specific purposes in preliminary assessment stage. To solve this problem, prediction of MDD and OMC with the other influential physical properties of BA for compaction which can be easily measured in the laboratory from simple, speedy and inexpensive test procedures, will be advantageous.

Many models have been established in the past to predict the compaction characteristics of soil, based on several geotechnical properties such as coefficient of curvature (Cc), uniformity coefficient (Cu), plastic limit (PL), liquid limit (LL), plasticity index (PI), specific gravity (Gs) and compaction energy (CE).

Dokovic et al. [9] developed a multiple linear regression model for estimating compaction parameters based on the Atterberg limits. Jyothirmayi et al. [10] developed a probabilistic model to find the correlation between the optimum moisture content and the plastic limit. Al-Badran and Schanz [11] presented a theoretical model based on soil's volume change behaviour in relation to the compaction curve. Toms and Philip [12] performed a multiple regression analysis and concluded that specific gravity and index properties of soil have great influence in compaction characteristics.

BA has similar physical properties as a sandy soil [2], [6], [13]. When reviewing the models developed for predicting compaction characteristics of sandy soils, Mujtaba et al. [14] developed a prediction model by performing multiple regression analyses on 110 different sandy soils in terms of uniformity coefficient (Cu) and compaction energy (CE) as in (1) & (2). However, their models can be used for sandy soil

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with only non-plastic fines where fine content is less than 45% and gravel content is less than 5%.

$$MDD = 4.49\ log(Cu) + 1.51\ log(CE) + 10.2 \quad (1)$$

$$log(OMC) = 1.67 – 0.193\ log(Cu) – 0.153\ log(CE) \quad (2)$$

Arvelo [15] expressed a proportional relationship of MDD in terms of Cu for sandy soils as shown in (3).

$$MDD = 87.715 \text{ x } Cu^{0.166} \quad (3)$$

When considering the models developed to predict the compaction characteristics of fly ash, Hosada et al. [16] correlated MDD and OMC using the relationship presented in (4).

$$MDD = 59.94 \text{ x } OMC^{20.487} \quad (4)$$

In addition, Kaniraj and Havanagi [17] employed regression techniques and predicted the compaction parameters of fly ash as in (5) & (6) using specific gravity (Gs) of fly ash.

$$MDD = 8.1525Gs^2 – 30.237Gs + 40.13 \quad (5)$$

$$OMC = 49.466 – 12.834Gs \quad (6)$$

Bera et al. [18] developed an empirical model to predict maximum dry density of pond ash as in (7).

$$MDD = 17.4451Gs – 0.1386OMC – 22.3595 \quad (7)$$

There is a single study in literature done by Kumar [19] for predicting compaction parameters of BA with different energy levels as given in (8). However, this equation uses OMC to predict the MDD and hence, is not feasible for predicting the compaction characteristics without conducting the laboratory Proctor test.

$$MDD = 0.0004CE – 0.085OMC – 9.457Gs + 33.055 \quad (8)$$

Hence, performing a study to develop empirical predictive models to estimate compaction characteristics of BA as a function of easily determinable inputs will be very beneficial for facilitating the engineering decisions in the prefeasibility stages.

II. Methodology

Geotechnical properties of BA were collected for twenty-seven different BA samples through a comprehensive literature survey to create a dataset for the analysis from different power plants all over the world and are presented in Table 1.

Compaction characteristics of these BA samples were found by standard Proctor compaction test according to ASTM D698. Among these twenty-seven studies, eighteen samples were used for calibration of the model and validation of the predicted model was done by the remaining nine samples.

Next, a regression analysis was done using the data set for calibration to develop a correlation of MDD and OMC of BA (refer Fig. 1). The best correlation for MDD and OMC with the highest coefficient of determination (R^2) of 0.916 was given by the power function as presented in (9) where an increase in OMC results in a decrease in MDD of BA. A higher decrease in MDD can be observed up to around 20% of OMC and then the reduction in MDD becomes lesser gradually. This behaviour is similar to the observation by Hosada et al. [16] (refer (4)), who also found a power curve fit between MDD and OMC for fly ash. The validation of the predicted correlation for MDD and OMC is shown in Fig. 2 which depicts an error range of ±5%.

$$MDD = 3098.4 \text{ x } OMC^{-0.293} \quad (9)$$

A. Formulation of the models

According to Table 1, results of Atterberg limits of BA and compaction energy used for the Proctor compaction test, were not available and hence, could not incorporate into the present study. However, the prediction models of MDD and OMC in literature for sandy soil and fly ash have successfully established using gradational parameters [14], [15] and specific gravity [17]–[19]. Therefore, to develop the predictive model for MDD and OMC of BA in the present study, gradational parameters and specific gravity (Gs) were used which are available for all twenty-seven studies.

Analysis was performed where OMC and MDD are the dependent variables while percentage of sand, percentage of fines, uniformity coefficient (Cu), coefficient of curvature (Cc) and specific gravity (Gs) are the independent variables. The variations of the compaction parameters with gradational parameters and specific gravity are shown in Figs. 3 and 4. According to Figs. 3 and 4, compaction parameters have a considerably good correlation with Gs and Cu in comparison to other variables. In addition, increasing the fine and sand content of the BA decreases the MDD and increases the OMC. However, Cc of BA particles show an insignificant effect on the compaction parameters.

The multi linear regression (MLR) was used to predict the compaction parameters of BA. In order to develop the multi linear correlation, data set was divided as dependent variables (MDD and OMC) and independent variables (Gs and Cu). Here, only Cu and Gs were taken as the independent variables after conducting the stepwise regression analysis where it showed lesser impact from other variables on MDD and OMC. Therefore, MLR equations for MDD and OMC can be written as in (10).

$$\text{Compaction characteristics (MDD, OMC)} = f(Gs, Cu) \quad (10)$$

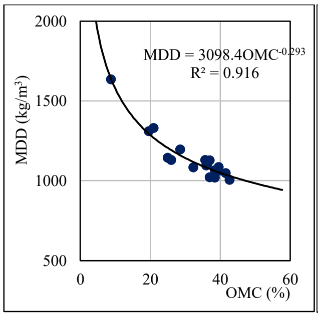

Fig. 1. Best fitting correlation of MDD with OMC for BA

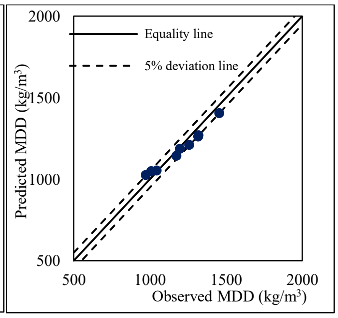

Fig. 2. Predicted correlation for MDD and OMC using (9)

TABLE I. DATA SET USED FOR MODEL CALIBRATION AND VALIDATION

	Symbol	MDD (kg/m^3)	OMC (%)	Gs	% of fine	% of sand	% of gravel	Cu	Cc	Permeability (m/s)	LL (%)	C (kPa)	Φ (°)	Source of BA and Reference
Data used for model calibration	BA1	1120	24.0	2.28	0.0	63.0	37.0	10.90	1.21	_	_	11	32	Tanjung Bin power plant, Malaysia [20]
	BA2	1060	39.5	1.80	0.3	92.7	7.0	3.11	1.60	_	_	0	31	Norochcholai power plant, Sri Lanka [2]
	BA3	1630	9.0	2.78	5.0	55.0	40.0	27.27	1.94	_	_	_	_	An Khanh thermal power plant, Viet Nam [21]
	BA4	1201	28.6	1.91	0.9	88.2	10.9	12.60	2.67	3.75×10^{-4}	43	0	34	Norochcholai power plant, Sri Lanka [2]
	BA5	1047	41.6	1.89	3.5	94.5	2.0	6.21	1.44	_	75	_	_	Norochcholai power plant, Sri Lanka [8]
	BA6	1095	36.0	2.08	4.6	93.8	1.6	6.06	1.18	1.2×10^{-5}	_	15	34	NSPCL, Rourkela, India [19]
	BA7	1066	38.5	2.10	26.0	71.0	3.0	5.33	1.33	1.4×10^{-5}	_	18	33	Vedanta, Jharsuguda, India [19]
	BA8	1130	36.5	2.09	16.5	83.5	0.0	12.67	11.3	_	68	0	27	Sejinkat power plant, Sarawak, Malaysia [22]
	BA9	1003	41.7	1.94	10.7	84.7	4.6	2.86	1.60	2.5×10^{-5}	_	21	33	Aditya Alumina, Lapanga Sambalpur, India [19]
	BA10	1137	38.0	2.17	50.0	25.0	25.0	10.00	0.70	_	_	_	_	Virginia [23]
	BA11	1080	32.0	2.10	27.5	72.5	0.0	10.58	1.45	_	_	2	34	Anpara power plant, India [24]
	BA12	1015	38.0	2.03	3.0	97.0	0.0	3.40	0.97	6.83×10^{-3}	23	_	_	Jamshedpur, India [25]
	BA13	1329	21.0	2.44	3.0	67.0	30.0	19.67	1.50	_	_	_	_	Tanjung Bin power plant, Malaysia [26]
	BA14	1090	40.0	2.07	26.1	73.9	0.0	6.10	1.49	_	_	_	_	Suratgarh Thermal Power Station, India [27]
	BA15	1000	35.0	1.97	5.0	95.0	0.0	4.00	0.87	_	_	1	37	EC Gdańsk, Poland [28]
	BA16	1100	37.0	2.10	25.7	74.3	0.0	10.80	1.46	_	_	_	_	Kota Super Thermal Power Station, India [27]
	BA17	1140	24.0	2.36	11.0	89.0	0.0	13.40	1.09	1.47×10^{-6}	_	10	36	Tanjung Bin power plant, Malaysia [29]
	BA18	1310	20.7	2.35	4.0	71.0	25.0	16.56	1.01	1.72×10^{-4}	_	0	46	Tanjung Bin power plant, Malaysia [30]
Data set used for model validation	BA19	975	43.0	1.88	4.0	94.5	1.5	2.19	1.49	9.9×10^{-5}	20	0	35	Norochcholai power plant, Sri Lanka (Present study)
	BA20	1100	24.5	2.23	1.0	79.0	20.0	14.68	1.15	2.41×10^{-3}	_	12	31	Tanjung Bin power plant, Malaysia [13]
	BA21	1177	32.0	2.19	1.4	81.3	17.3	11.77	1.15	_	_	_	_	Norochcholai power plant, Sri Lanka [2]
	BA22	1322	21.0	2.44	5.6	94.4	0.0	19.90	1.20	_	_	_	43	Jhajjar Thermal Power Plant, India [31]
	BA23	1010	40.4	1.77	7.8	83.0	9.2	4.00	1.00	2.01×10^{-4}	_	46	34	Kakatiya thermal power, India [32]
	BA24	1046	39.9	1.91	5.0	91.4	4.6	5.39	1.60	_	74	_	_	Norochcholai power plant, Sri Lanka [8]
	BA25	1260	25.5	2.32	15.5	84.5	0.0	17.20	11.3	_	45	1	27	Sejinkat Thermal Power Plant, Sarawak, Malaysia [22]
	BA26	1458	19.2	2.54	13.0	81.0	6.0	24.40	1.51	_	_	_	_	Jana Manjung Power Plant, Malaysia [33]
	BA27	1318	22.5	2.42	1.0	86.0	13.0	19.00	1.11	1.59×10^{-3}	_	7	38	Tanjung Bin power plant, Malaysia [34]

The MLR analysis was then conducted using the Microsoft EXCEL Analysis to explore the best fit predictive models for MDD and OMC.

III. MLR ANALYSIS RESULTS AND DISCUSSIONS

A. Prediction of MDD and OMC of BA

Eq. (11) shows the best fit model obtained for the prediction of MDD in BA.

$$\log (MDD) = 0.23 \log (Gs) + 0.006\, Cu + 2.917 \qquad (11)$$

Eq. (12) shows the best fit model obtained for the prediction of OMC in BA.

$$\log(OMC) = 2.696Gs - 0.712\, Gs^2 - 0.124\log(Cu) - 0.866 \qquad (12)$$

B. Analysis of MLR results

The regression analysis summary is shown in Table 2. The accuracy of the results by MLR analysis is verified with statistical tools such as coefficient of correlation (R) and the standard estimated error (SE). A good model must have high value of R and low value of SE. The R values are greater than 97% for both (11) and (12) which indicates a strong relation in both scenarios. SE values are small for the model predicted values with the experimental values (refer Table 2), which further indicates the good prediction capability of the proposed models. Considering the model for MDD, it can be noted that, independent variables Gs and Cu explain 94.3% of total variation in MDD ($R^2 = 0.943$) and 96% ($R^2 = 0.96$) total variation for OMC.

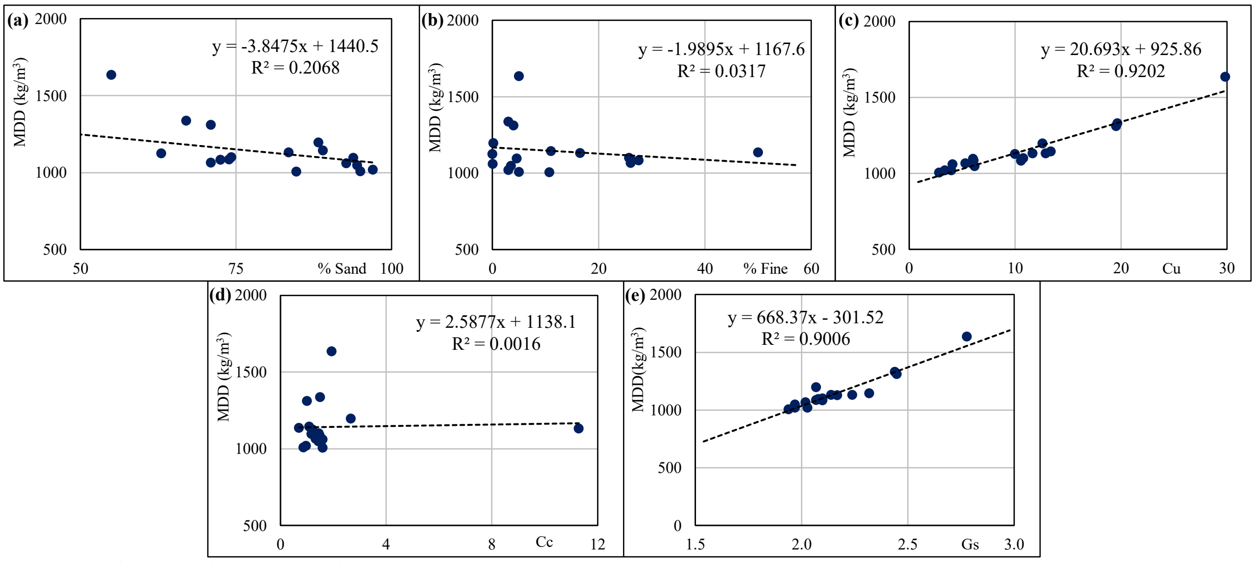

Fig. 3. Variation of MDD with (a) % Sand, (b) % Fine, (c) Cu, (d) Cc and (e) Gs

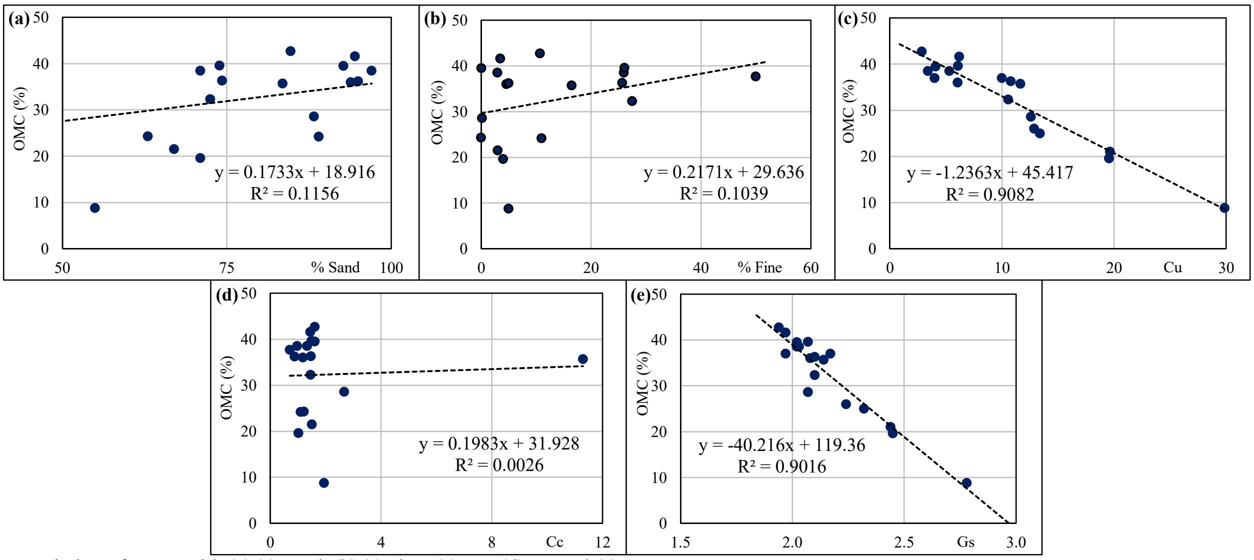

Fig. 4. Variation of OMC with (a) % Sand, (b) % Fine, (c) Cu, (d) Cc and (e) Gs

TABLE II. OUTPUT OF REGRESSION ANALYSIS FOR (11) AND (12)

Parameters	**MDD**		**OMC**		
Units	kg/m^3		%		
Multiple R	0.971		0.980		
R Square	0.943		0.961		
Adjusted R Square	0.935		0.952		
Standard Error	0.013		0.037		
Observations	18		18		
Constants	2.917		- 0.866		
Model *F*-value	124.08		113.47		
F-significance	4.67E-10		4.63E-10		
Variable Xi	log (Gs)	Cu	Gs	Gs^2	log (Cu)
Coefficients of Xi	0.230	0.006	2.696	- 0.712	- 0.124
P-value	0.042	0.003	0.014	0.003	0.018
t-value	0.822	3.621	2.803	-3.633	-1.665

Adjusted R^2 should be accounted as an indicator of adequacy of the model when more than one variable is used. When R^2_{adj} closes to one, the model is significant and it is satisfied by both models for MDD and OMC. For MLR models, significance F should be less than 0.05 [12] and the model F value should be higher than significance F value. The proposed models of both MDD and OMC satisfies these conditions (refer to Table 2). When evaluating the contribution of the input parameters, the p value for the independent variables in both models are less than 5% (refer to Table 2) which indicates the significance of input variables. Thus, these results clearly suggest that the developed model is accurate and promising.

C. Validation of the models

The effectiveness of the developed model was validated using the independent data sets of nine BA samples (refer Table 1) which were not used in developing the model. A good agreement with a prediction accuracy of ±2% and ±3% could be observed between the predicted values and the laboratory results consequently for MDD model and the OMC model (refer to Figs. 5 and 6).

D. *Model implications, Limitations and Recommendations*

Generally, it is difficult to accurately predict the values of compaction parameters of BA due to the influence of many variables and heterogeneity of BA. However, the developed correlations in the present study would be useful in quicker estimation of compaction parameters without performing the laboratory compaction tests during prefeasibility assessment of the project. Figs. 7 and 8 show the predictive curves generated from (11) and (12) for MDD and OMC of BA. According to Fig. 7, MDD of BA is affected by the heterogeneity of the BA where higher values of uniformity coefficient cause for an increase in MDD. The angular shaped BA particles fills the air voids effectively when it showcases well graded properties (when Cu is higher) and hence result in a higher MDD [19].

However, an inverse performance is showed by OMC of BA with uniformity coefficient. According to Fig. 8, OMC is higher when the sample is more homogeneous with a lower Cu value. Mujtaba et al. [14] also observed a similar behaviour of MDD and OMC with uniformity coefficient for sandy soil. This observation further confirms that BA has similar properties and behaviour as for sandy soils.

In addition, the MDD of BA increases with increasing specific gravity. Furthermore, 35 to 40% of higher OMC can be observed when the specific gravity of BA ranges between 1.6 to 2.2. Kaniraj and Havanagi [17] observed a similar behaviour for MDD in fly ash where dry density values increased when specific gravity of fly ash is increased. The predictive curves shown in Figs. 7 and 8 can be used for easy reference of the compaction parameters of BA when the Gs and Cu values under standard effort of Proctor compaction are available. Nevertheless, Proctor compaction test should be performed prior to the field application of BA to confirm the obtained results.

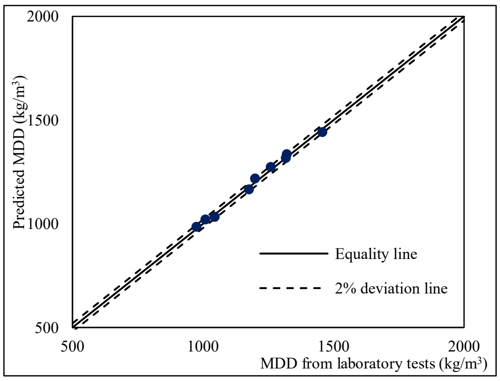

Fig. 5. Validation of proposed model for MDD of BA

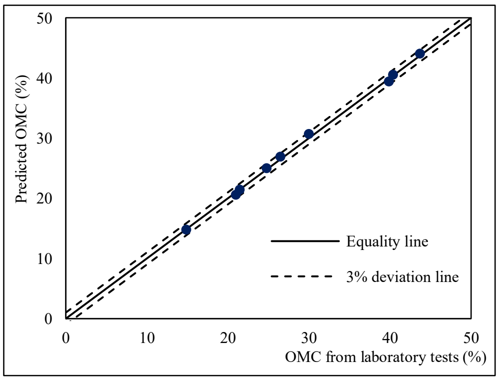

Fig. 6. Validation of proposed model for OMC of BA

In addition, following recommendations can be suggested to further improve these models for MDD and OMC to effectively predict compaction characteristics of BA.

- For the current study, only 27 samples with sufficient geotechnical properties were available in literature for evaluation. It is recommended to perform MLR analysis with a greater number of samples from different power plants to cover a wide range of MDD and OMC as BA is a heterogenetic material.
- These two predictive models for MDD and OMC of BA have been derived for Gs ranging from 1.80 to 2.78 and for Cu values ranging from 2.86 to 27.27. Therefore, any prediction beyond this range may be checked with laboratory results.
- Further, this study can be extended to correlate index properties of BA.
- In addition, there are some other factors such as coal type and chemical composition of BA which are, beyond the scope of this present study that could play a significant role in predicting the variables.
- Due to the lack of availability of compaction characteristics with different compaction energies for BA, the data used for the present study comprises of compaction values with standard Proctor effort only. Therefore, it is proposed to conduct experimental studies using different BA samples to include the influence of compaction energy to further improve the predictive models.

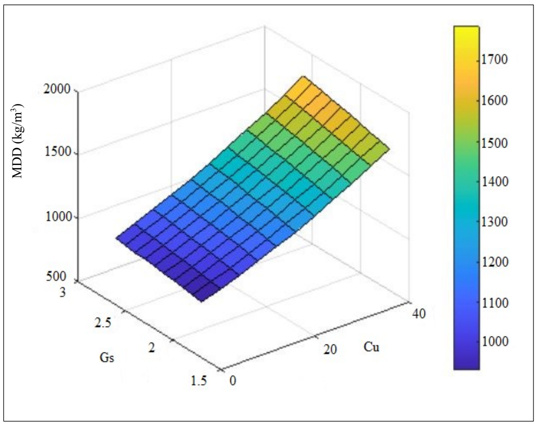

Fig. 7. Predictive curves for estimation of MDD for BA

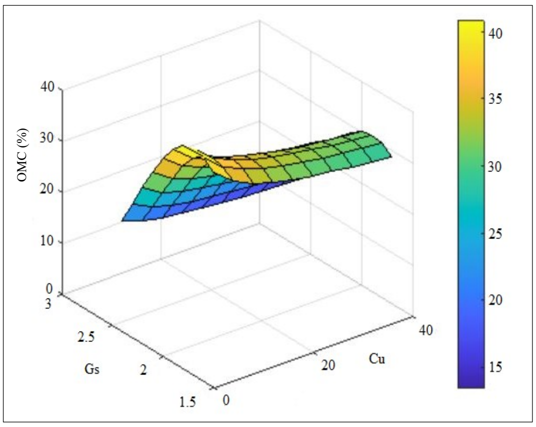

Fig. 8. Predictive curves for estimation of OMC for BA

IV. CONCLUSIONS

MLR analyses were conducted to develop predictive models from a statistical point of view to estimate MDD and OMC. Based on the analytical results,

- The MDD and OMC has a power curve fit with a prediction accuracy within ±5%.
- Compaction properties have better correlation ($R^2 > 0.90$ with the specific gravity and uniformity coefficient of BA compared to other physical properties.
- The MDD can be predicted by *log* (MDD) = 0.23 *log* (Gs) + 0.006 Cu + 2.917 and the validation of MDD values displayed ±2% error indicating the higher prediction accuracy of the model.
- The OMC can be predicted by *log* (OMC) =2.696Gs– 0.712 Gs^2 – 0.124 log (Cu) – 0.866 and the prediction accuracy of the model is ±3%.
- The heterogeneity and specific gravity of BA increase the MDD and decrease the OMC of BA under standard effort of Proctor compaction.

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