Influence of Fly Ash Content on Compaction Characteristics of Fly Ash Clay Mixture

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ABSTRACT

In the present paper, a series of compaction tests have been performed to investigate the effect of fly ash content on compaction characteristics of fly ash clay mixture. Three types of fly ash and three types of clay have been used in this investigation. From the test results, it is observed that with the increase in fly ash content (0 to 25%) in the fly ash clay mixture, the value of maximum dry density decreases irrespective of type of soil, type of fly ash and type of compaction method. Fly ash content also influences significantly the optimum moisture content of fly ash clay mixture. Based on the present experimental data, a number of linear regression models have been developed to estimate the values of optimum moisture content and maximum dry density of fly ash clay mixture.

KEYWORDS: Fly ash, Clay, Compaction, Regression, MDD, OMC.

INTRODUCTION

Nowadays, it is a general trend to develop alternative improved materials by using waste materials such as fly ash with soil to replace the soft and weak soils in the field. Clayey soils are soft and sometimes unsuitable for construction of road sub-grade or embankment. Fly ash, a solid waste, may be used to improve clayey soil for construction of road sub-grade. A few studies are available on engineering properties of mixtures of soil with fly ash alone. Mir and Sridharan (2013) studied physical properties and compaction behavior of black cotton soil clay mixture. Bera and Ghosh (2011) presented a regression model for the prediction of optimum moisture content and maximum dry unit weight of fine grained soil. Classification of time-dependent unconfined compression strength of fly ash treated clay was studied by Goktepe et al. (2008). Prabakar et al. (2004) studied the influence of fly ash on the strength behavior of typical soils. They opined that fly ash addition into soil can also be effectively used as base material for roads, backfilling and improvement of soil bearing capacity of any structure. Detailed study on compaction characteristics of pond ash has been performed by Bera et al. (2007). Bera (2014) studied the compaction characteristics of fine grained soil rice husk mixture. However, detailed study on compaction characteristics of fly ash clay mixture is scarce. In the present investigation, an attempt has been made to study the compaction characteristics of fly ash clay mixture. A number of mathematical models have been developed to predict the optimum moisture content of fly ash clay mixture (OMC_{mix}) and maximum dry density of fly ash clay mixture (MDD_{mix}).

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MATERIALS

In this investigation, three types of fly ash collected from Kolaghat thermal power station (KTPS), Badge Badge thermal power station (BBTPS) and Bandel thermal power station (BTPS) in west Bengal, India. The above three types of fly ash may be designated as KTPS, BBTPS and BTPS, respectively. Two types of artificial clay (Montmorillonite and Kaolinite) were collected from the local market in Kolkata in the month of January 2013 for performing the tests and may be designated as Clay M and Clay K, respectively. Also, one natural clay was collected from Midnapore, west Bengal, India in the month of January 2013 and may be designated as Clay N.

Fly Ash

Fig.1 shows the typical grain size distribution curve for KTPS fly ash. Table 1a presents the physical properties of three types of fly ash. From Table (1a), it is found that the particle sizes for all three types of fly ash are mostly silt size. In accordance with ASTM 2487 (1992), the above three fly ash types may be classified as ML.

Table 1a. Physical properties of fly ash

Physical property	Values of physical properties		
	KTPS	BTPS	BBTPS
Sand size (%)	22	20	17
Silt size (%)	78	80	80
Clay size (%)	0	0	3
D_{10} (mm)	0.013	0.014	0.011
D_{30} (mm)	0.022	0.035	0.028
D_{50} (mm)	0.072	0.036	0.052
D_{60} (mm)	0.074	0.048	0.069
C_u	5.29	3.7	6.27
C_C	1.18	0.78	1.03
Specific gravity (G)	2.33	2.12	2.13
LL and PL	Non-plastic	Non-plastic	Non-plastic

Soil

Table (1b) presents the physical properties of the three different clays. In accordance with ASTM 2487 (1992), the above three types of soil (Clay M, Clay K and Clay N) may be designated as CH, CL and CL, respectively.

Table 1b. Physical properties of clay

Physical property	Values of physical properties		
	Clay M	Clay K	Clay N
Sand size (%)	3.0	1.0	2.6
Silt size (%)	27.0	45.0	72.4
Clay size (%)	70.0	54.0	25.0
D_{10} (mm)	0.00059	0.00046	0.00098
D_{30} (mm)	0.00070	0.00085	0.00346
D_{50} (mm)	0.00079	0.00180	0.00800
D_{60} (mm)	0.00090	0.00360	0.0148
C_u	1.53	7.82	15.10
C_C	0.92	0.44	0.83
Specific gravity (G)	2.734	2.668	2.647
LL	179.00	49.00	40.50
PL	52.80	26.50	25.30

EXPERIMENTAL PROGRAM AND EXPERIMENTAL METHOD

To investigate the compaction characteristics of fly ash clay mixture, an experimental program has been carried out as shown in the series presented in Table 2. In series A, compaction tests have been performed with varying compaction energies in a wide range (2700 kJ/m^3, 594 kJ/m^3 and 300 kJ/m^3) and varying fly ash content (0%, 5%, 10%, 15%, 20% and 25%) to study the effect of compaction energy and fly ash content on fly ash clay mixture. A number of researchers (Daniel and Benson, 1990; Boltz et al., 1998; Bera et al., 2007; Bera and Ghosh, 2011; Bera, 2014) considered all three types of laboratory compaction tests; i.e., modified proctor test, standard proctor test and reduced proctor test in their studies. In series B, standard proctor compaction test has been performed on three types of clay with fly ash content (0-25%) for two types of fly ash (BTPS and BBTPS). Both standard proctor compaction and modified proctor compaction have been performed in accordance with ASTM Standard D 698 (1992) and D 1557 (1992), respectively. Reduced proctor compaction test has been performed by applying the blows on the consecutive three layers (13, 12 and 13), so that a compaction energy of 300 kJ /m^3 per layer is achieved. Reduced proctor effort may be applied in the field where a minimum level of compactive energy is required, such as for a typical soil liner or cover. Compaction test of fly ash clay mixture depends very much on compaction delay. Just after fly ash clay mixing with water, reaction for hydration started and with time hydration products began to bond particles of the mixture in loose state. As a result, disruption in achieving the required density took place. Ferguson (1993) reported that the maximum dry density fly ash soil mixture reduces with the increase in delay in compaction. To achieve maximum benefit, in the present investigation, each compaction test has been started just after clay and fly ash mixing.

Table 2. Testing program

Series	Types of Compaction Tests	Compaction Energy, E (kJ/m^3)	Types of Soil	Types of Fly Ash	Fly Ash Content (%)
A	Modified Proctor Compaction Standard Proctor Compaction Reduced Proctor Compaction	2700 594 300	Clay M, Clay K, Clay N	KTPS	0-25
B	Standard Proctor Compaction	594	Clay M, Clay K, Clay N	BTPS, BBTPS	0-25

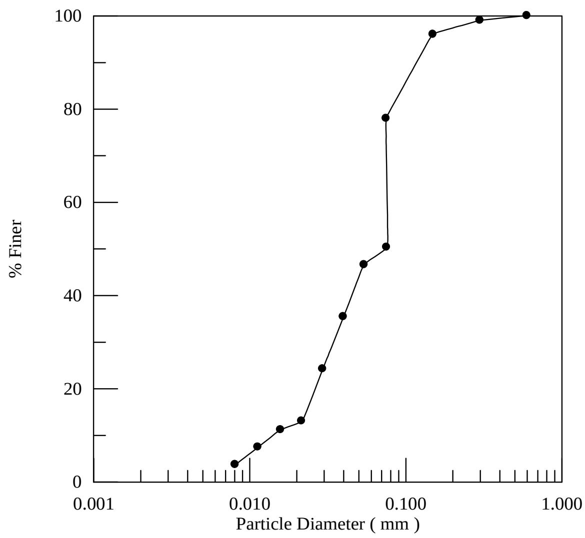

Figure (1): Typical grain size distribution curve for KTPS fly ash

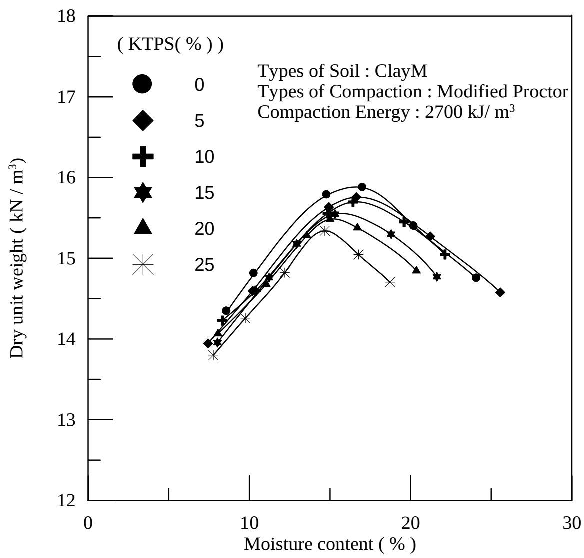

Figure (2): Typical dry unit weight *versus* moisture content curve with clay M-KTPS fly ash mixture (varying percentages of fly ash)

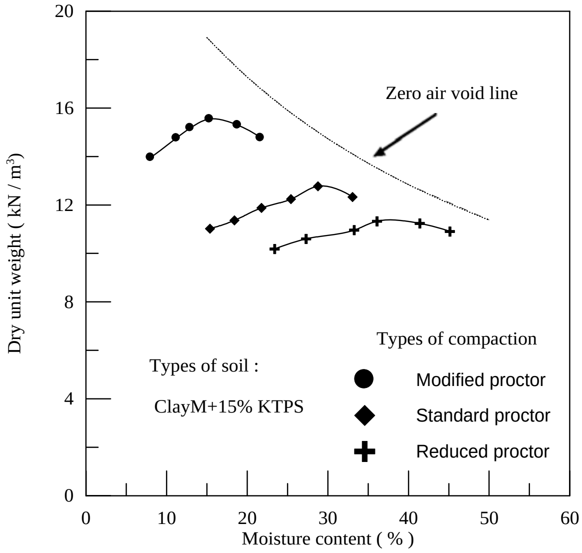

Figure (3): Typical dry unit weight *versus* moisture content curve with clay M and 15% KTPS fly ash mixture (varying compaction energy)

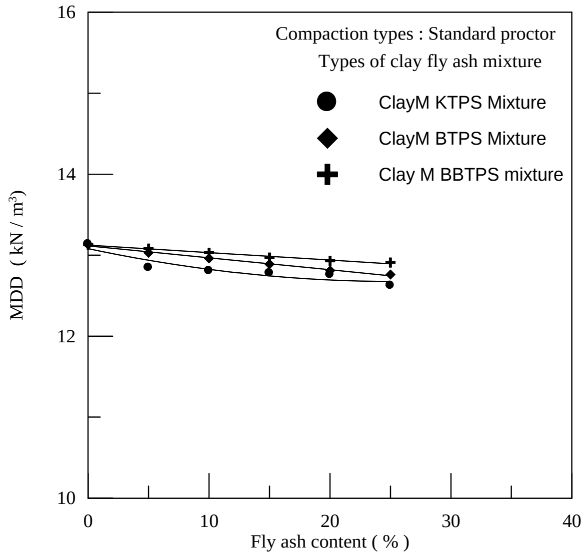

Figure (4): Maximum dry density *versus* fly ash content curve for clay M fly ash mixture (varying types of fly ash)

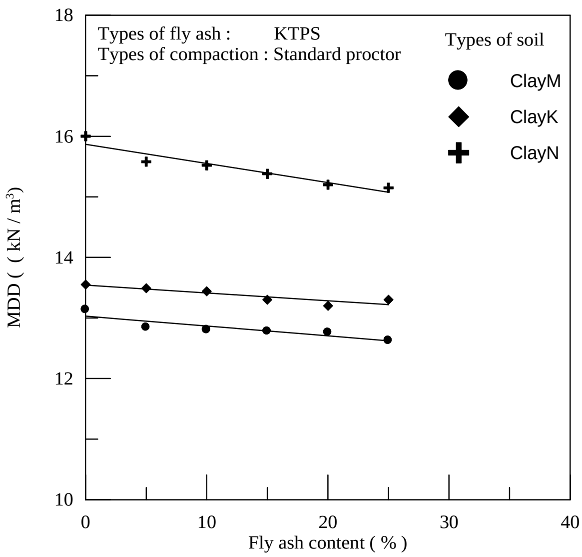

Figure (5): Maximum dry density *versus* fly ash content curve for clay and KTPS fly ash mixture (varying types of clay)

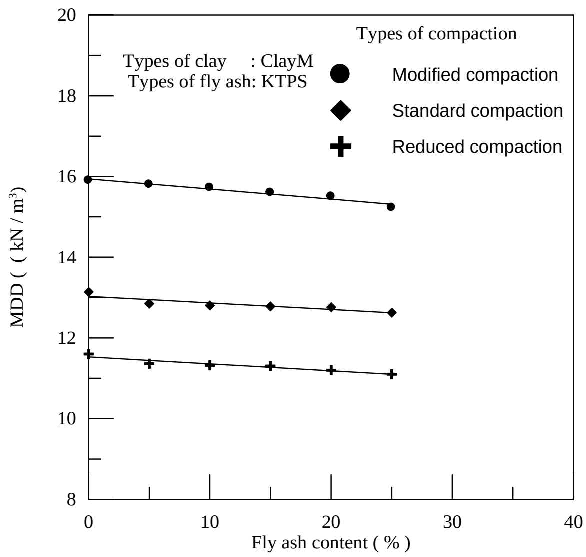

Figure (6): Maximum dry density *versus* fly ash content curve for clay M fly ash mixture (varying types of compaction)

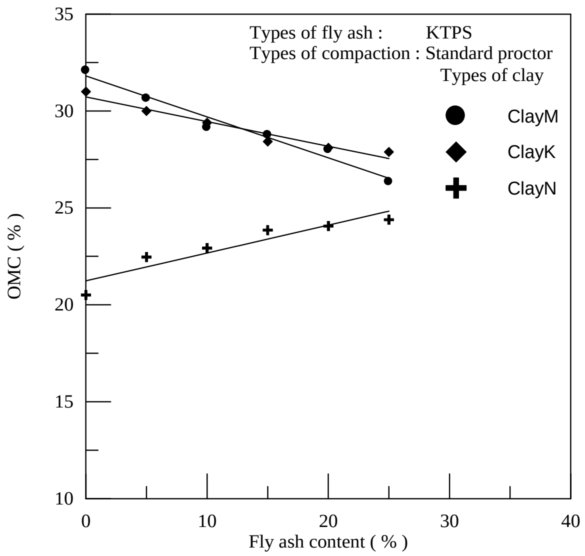

Figure (7): Optimum moisture content *versus* fly ash content curve for fly clay ash mixture (varying types of clay)

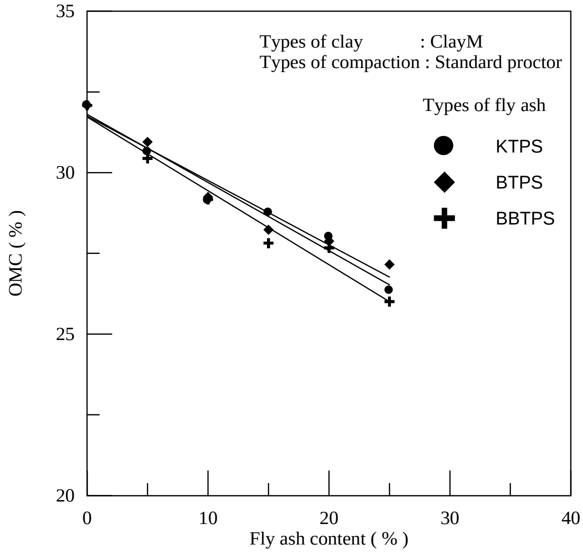

Figure (8): Optimum moisture content *versus* fly ash content curve for fly ash clay mixture (varying types of fly ash)

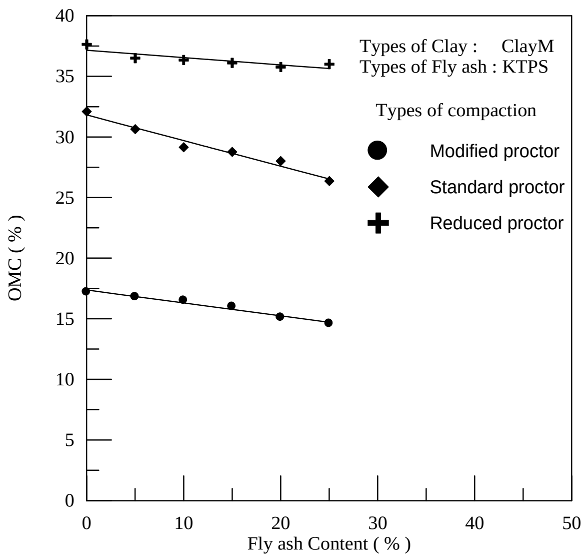

Figure (9): Optimum moisture content *versus* fly ash content curve for clay M fly ash mixture (varying types of compaction)

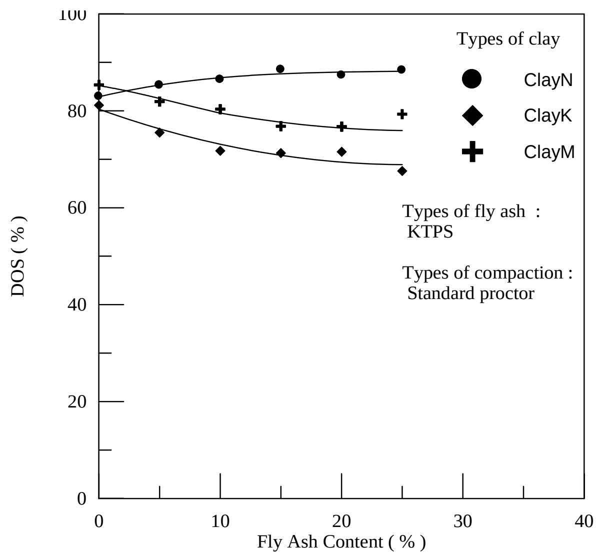

Figure (10): Degree of saturation *versus* fly ash content curve for clay and KTPS fly ash mixture (varying types of clay)

RESULTS AND DISCUSSION

Compaction test data obtained from the experiments are plotted and presented in graphical form. Fig. 2 shows the typical dry unit weight *versus* moisture content curve with varying percentage of fly ash content for clay M-KTPS mixture. Typical dry unit weight *versus* moisture content curve with varying compaction energy for clay M and 15% KTPS mixture is shown in Fig.3. Fig.4 shows the maximum dry density *versus* fly ash content curve with varying types of fly ash for clay M fly ash mixture. Fig.5 shows the plots of maximum dry density *versus* fly ash content curve with varying types of clay for clay and KTPS fly ash mixture. Fig.6 shows the plots of maximum dry density *versus* fly ash content curve with varying types of compaction for clay M fly ash mixture. Fig. 7 shows the plots of optimum moisture content *versus* fly ash content curve with varying types of clay for fly ash clay mixture. The plots of optimum moisture content *versus* fly ash content curve with varying types of fly ash for fly ash clay mixture are shown in Fig.8. Fig.9 shows the optimum moisture content *versus* fly ash content curve with varying types of compaction for clay M fly ash mixture. Figs. 10 and 11 show the degree of saturation *versus* fly ash content curve for clay KTPS mixture with varying types of clay and types of fly ash, respectively.

Based on the experiment results, discussion is made as follows:

Effect of Fly Ash Content on Maximum Dry Density of Fly Ash Clay Mixture

Fig. 2 shows the typical dry unit weight *versus* moisture content curve of clay M-KTPS mixture. From the curve, it is found that with the increase in fly ash content, the dry density of clay M-KTPS mixture decreases. This may be due to the reason that the fly ash light weight material compares to clay. Mir and Sridharan (2013) explained that the decrease of maximum dry unit weight of black cotton soil and fly ash mixture with the increase in fly ash content is mainly due to lower specific gravity and poor gradation of fly ash. Figs. 4-6 show the maximum dry density *versus* fly ash content curve with varying types of fly ash, types of clay and types of compaction, respectively. From Figs. 4-6, it is found that with the increase in fly ash content maximum dry density decreases. For every case (varying types of fly ash, types of clay and types of compaction), the reason is the same as stated above, which is that the fly ash light weight material compares to clay. As a result, with the increase in fly ash content in the fly ash clay mixture, the maximum dry density of the mixture decreases.

Effect of Fly Ash Content on Optimum Moisture Content of Fly Ash Clay Mixture

Optimum moisture content is one of the key parameters for any type of compaction. Plots of optimum moisture content *versus* fly ash content with varying types of soil are presented in Fig.7. From the figure, it is found that with the increase in fly ash content optimum moisture content increases in case of clay N-KTPS fly ash mixture. In case of clay M and Clay K fly ash mixture, the value of optimum moisture content decreases with the increase in fly ash content. This may be due to the reason that in case of Clay N, the value of OMC of Clay N is much lower than the value of OMC of KTPS fly ash. As a result, with the increase in fly ash content of Clay N and KTPS fly ash mixture, the value of OMC increases. In case of Clay M and Clay K, the value of OMC of KTPS fly ash is higher than that of Clay M and Clay K. As a result of increase in fly ash content the value of OMC decreases. Figs. 8 and 9 show the OMC *versus* fly ash content curves for Clay M-KTPS fly ash mixture with varying types of fly ash and types of compaction. From the curves, it is found that with the increase in fly ash content the value of OMC of Clay M-KTPS fly ash mixture decreases irrespective of type of fly ash and type of compaction. This may be due to the reason that the value of OMC of Clay M is much higher than OMC values of the three fly ash types (KTPS, BTPS and BBTPS).

Effect of Fly Ash Content on Degree of Saturation at OMC and MDD Fly Ash Clay Mixture

Degree of saturation at OMC and MDD is one of the important parameters for compaction of any type of soil. Benson and Boutwell (1992) reported that for clay, the optimum moisture content normally occurs at a degree of saturation of nearly 85%. Figs.10 and 11 show the plots of degree of saturation *versus* fly ash content curve for fly ash clay mixture with varying types of soil and varying types of fly ash, respectively. From the curve in (Fig.10), it is found that with the increase in fly ash content, the degree of saturation at OMC increases slightly (82.9%-88.4%) in case of clay N-KTPS fly ash mixture. In case of clay M and clay K, the degree of saturation at OMC decreases with the increase in fly ash content (Fig.10). Similar trends were found in case of degree of saturation *versus* fly ash content curve with varying types of fly ash for clay M fly ash mixture. From Figs. 10 and 11, it is also revealed that the degree of saturation is not affected by the type of fly ash, but is affected by the type of soil. This may be due to the reason that the degree of saturation at OMC has been calculated in terms of OMC, MDD and specific gravity of a particular clay fly ash mixture. In case of varying types of fly ash in fly ash clay mixtures for a particular compaction energy and for a particular fly ash content (%), the variation of MDD value (Fig. 4) and the variation of OMC value (Fig. 8) are negligible. As a result, the degree of saturation of fly ash clay mixture is not affected by the type of fly ash. In case of varying types of clay in fly ash clay mixtures for a particular compaction energy and for a particular fly ash content (%), the variation of MDD value (Fig. 5) and variation of OMC value (Fig. 7) are significantly large. As a result, the degree of saturation of fly ash clay mixture is affected by the varying type of soil.

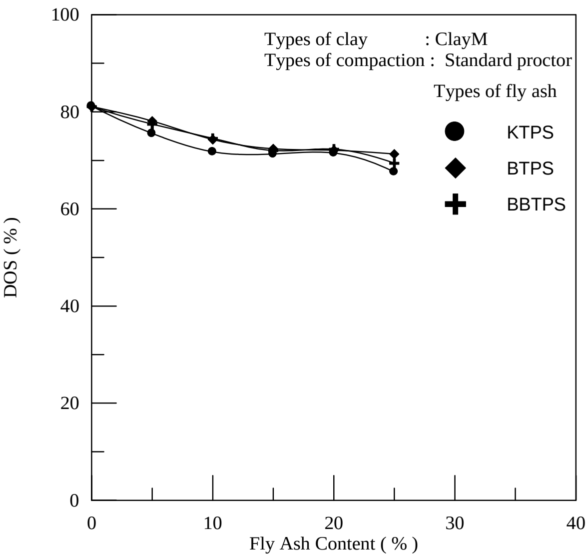

Figure (11): Degree of saturation *versus* fly ash content curve for fly ash clay mixture (varying types of fly ash)

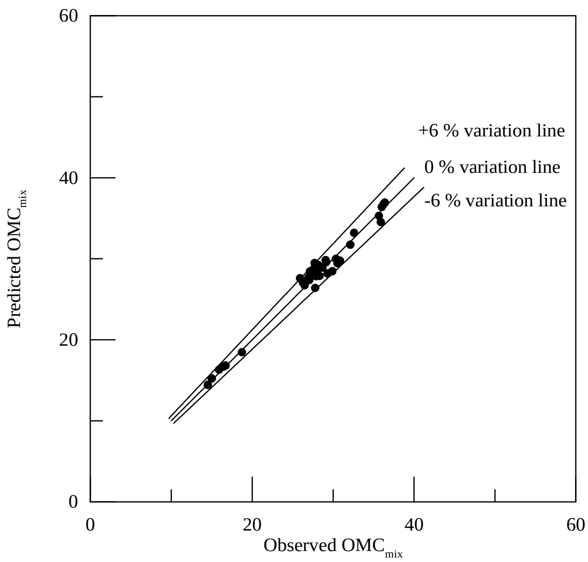

Figure (12): Predicted OMC_{mix} *versus* observed OMC_{mix} curve for equation 1

MATHEMATICAL MODEL FOR OMC_{mix} AND MDD_{mix} OF FLY ASH CLAY MIXTURE

From the experimental results previously presented, it is found that OMC and MDD of fly ash clay mixture depends on a number of parameters such as OMC and MDD of clay, OMC and MDD of fly ash and specific gravity of the fly ash clay mixture. To get a rough idea regarding OMC_{mix} and MDD_{mix} in the laboratory as well as in the field by considering all the parameters, a number of empirical models have been developed herein.

Empirical Model for OMC_{mix}

From the experimental results (Fig. 7), it is found that with the increase in fly ash content, the value of optimum moisture content of fly ash clay mixture decreases or increases depending on the relative values of OMC of fly ash (OMC_{FA}) and OMC of clay (OMC_{clay}). In the present investigation, two separate linear empirical models have been developed for OMC_{mix} as follows:

In case $OMC_{clay} > OMC_{FA}$

Based on the 39 experimental data points, a linear model has been developed to predict OMC_{mix} in terms of OMC_{clay}, OMC_{FA} and fly ash content (FA). To develop the model, multiple regression analysis has been performed. Details of the regression analysis have already been presented elsewhere (Bera et al., 2005).

$$\widehat{OMC}_{mix} = 12.14 \times G_{mix} + 0.72 \times OMC_{clay} + 0.45 \times OMC_{FA} - 38.61 \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where,

$\widehat{OMC}_{mix}$ = predicted value of optimum moisture content of fly ash clay mixture (%).
OMC_{clay} = optimum moisture content of clay (%).
$OMC_{fly\ ash}$ = optimum moisture content of fly ash (%).
G_{mix} = specific gravity of fly ash clay mixture (%).

Values of coefficient of determination (R^2) and estimated error (E_s) of Eqn. 1 are 0.98 and 0.84%, respectively, which indicates that the model is efficient enough. To investigate the significance of the model, values of $F_{statistic}$ of all the parameters as a whole and also $t_{statistic}$ for each parameter have been calculated and presented in Table (3a). From the table, it is observed that all the parameters as a whole as well as independently have significant contribution to the model (Eqn.1). The plots of observed OMC_{mix} *versus* predicted OMC_{mix} are shown in Fig. 12. From the plots, it is found that all the data points are within 6% error. Table (3b) shows the comparison of $\widehat{OMC}_{mix}$ (predicted, using additional data not used in developing the model) and corresponding observed OMC_{mix} and error (P_E) in percentage.

In case of $OMC_{clay} < OMC_{FA}$

Based on the experimental data points available in the present investigation, a linear model has been developed to predict OMC_{mix} in terms of OMC_{clay}, OMC_{FA} and fly ash content (FA) as follows:

$$\widehat{OMC}_{mix} = 104.5 - 41.49 \times G_{mix} + 1.736 \times OMC_{soil} - 0.287 \times OMC_{FA} \ldots\ldots\ldots\ldots \quad (2)$$

where,

$\widehat{OMC}_{mix}$ = predicted value of optimum moisture content of fly ash clay mixture (%).
OMC_{clay} = optimum moisture content of clay (%).
$OMC_{fly\ ash}$ = optimum moisture content of fly ash (%).
G_{mix} = specific gravity of fly ash clay mixture (%).

Table 3a. Values of *F*-statistic and *t*-statistic for different parameters of eqn. 1

Parameter	Value of coefficient	Standard error	*t*-statistic	$t_{critical} = t_{(0.975,35)}$	*F*-statistic	$F_{critical} = F_{(3,35,0.95)}$
Intercept	*-38.61*	5.104795	-7.56433	2.0315	581.6	2.88
G_{mix}	*12.14*	1.881132	6.45356			
OMC_{clay}	*0.72*	0.043747	16.47425			
OMC_{clay}	*0.45*	0.073011	6.31558			

Table 3b. Comparison of $\widehat{OMC}_{mix}$ (predicted, using additional data not used in developing the model) and corresponding observed OMC_{mix}

G_{mix}	OMC_{soil} (%)	OMC_{FA} (%)	OMC_{mix} (%) (observed)	$\widehat{OMC}_{mix}$ (%)	Percentage error, P_E (%)
2.669	32.086	26.597	29.138	29.175	0.13
2.555	31.000	26.597	28.10	27.00907	-4.04
2.666	31.000	27.79	28.89	28.90671	0.06
2.550	32.086	27.29	27.88	28.04627	0.59

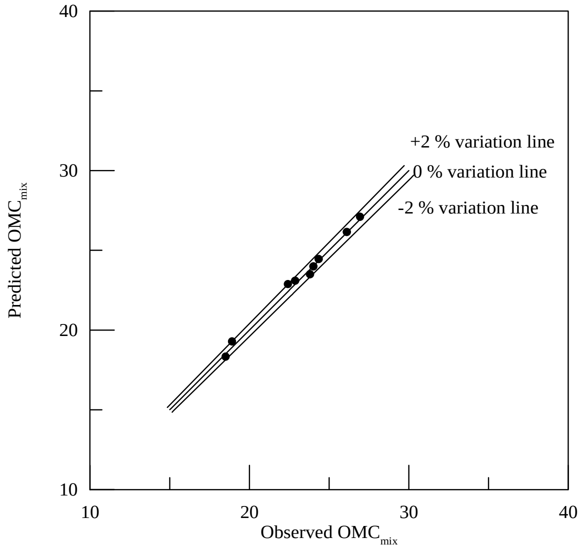

Figure (13): Predicted OMC_{mix} *versus* observed OMC_{mix} curve for equation 2

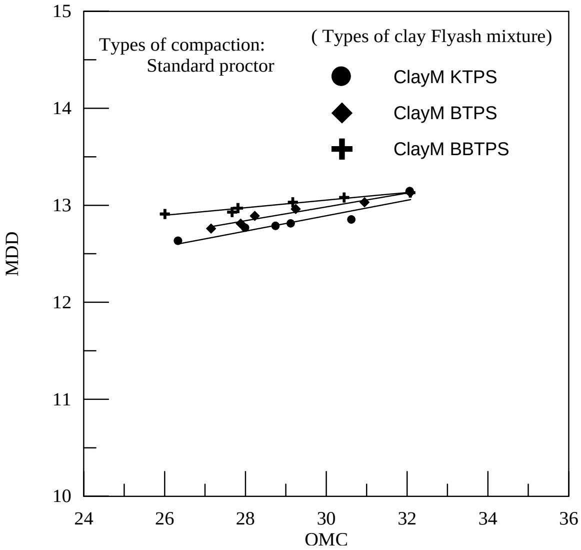

Figure (14): Maximum dry density *versus* optimum moisture content curve for fly ash clay mixture with varying types of fly ash

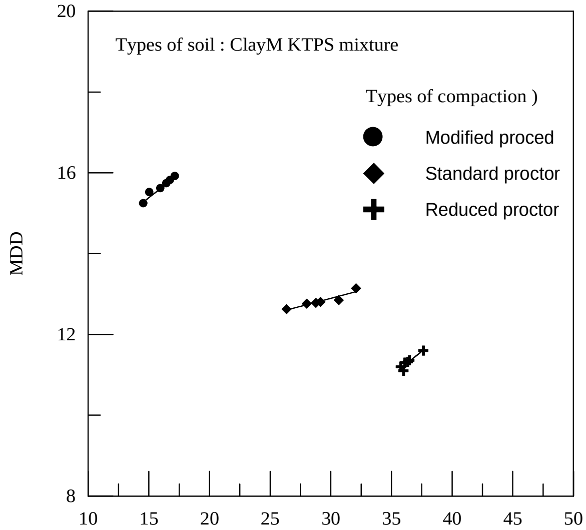

Figure (15): Maximum dry density *versus* optimum moisture content curve for fly ash clay mixture with varying types of compaction

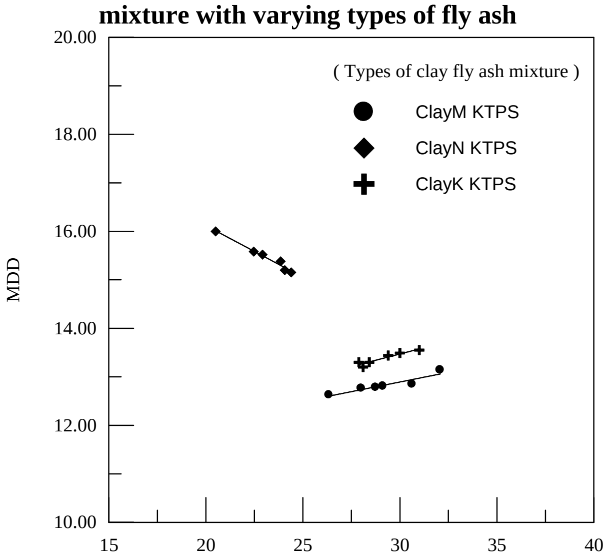

Figure (16): Maximum dry density *versus* optimum moisture content curve for fly ash clay mixture with varying types of clay

Table 4. Values of *F*-statistic and *t*-statistic for different parameters of eqn. 2

Parameter	Value of coefficient	Standard error	*t*-statistic	$t_{critical} = t_{(0.975,5)}$	*F*-statistic	$F_{critical} = F_{(3,5,0.95)}$
Intercept	*104.496*	20.61397	5.069173	2.571	228.2	5.41
G_{mix}	*-41.4894*	*7.960266*	-5.21206			
OMC_{clay}	*1.735677*	*0.161638*	10.73805			
OMC_{clay}	*-0.28693*	*0.087746*	-3.27004			

The values of R^2 and E_s of (Eqn. 2) are 0.99 and 0.309%, respectively. The significance of the model has been checked by calculating the values of $F_{statistic}$ and $t_{statistic}$ (Table 4) of (Eqn. 2). Fig. 13 shows the plots of observed OMC_{mix} *versus* predicted OMC_{mix}. From the plots, it is found that all the data points are within 2% error.

Empirical Model for MDD_{mix}

Figs. 14-16 show the MDD *versus* OMC curve for fly ash clay mixture with varying types of fly ash, types of compaction and types of clay, respectively. From Figs.14 and 15, it is found that with the increase in OMC, the value of MDD increases. From Figs. 14 and 15, it is also observed that there is a linear relationship between MDD and OMC. From Fig. 16, it is found that with the increase in OMC, the value of MDD decreases in case of clay N fly ash mixture, whereas the value of MDD increases with the increase in OMC in case of clay M fly ash mixture and clay K fly ash mixture. In the present investigation, linear empirical models have been developed for MDD_{mix} as follows:

In case $MDD_{clay} > MDD_{FA}$

$$\widehat{MDD}_{mix} = 10.1842 + 3.32 \times G_{mix} - 0.2043 \times OMC_{mix} \quad (3)$$

In case of $OMC_{clay} < OMC_{FA}$

$$\widehat{MDD}_{mix} = 38.75 - 5.85 \times G_{mix} - 0.347 \times OMC_{mix} \quad (4)$$

where,

$\widehat{MDD}_{mix}$ = predicted value of maximum dry density of fly ash clay mixture (%).

OMC_{mix} = optimum moisture content of clay (%).

G_{mix} = specific gravity of fly ash clay mixture (%).

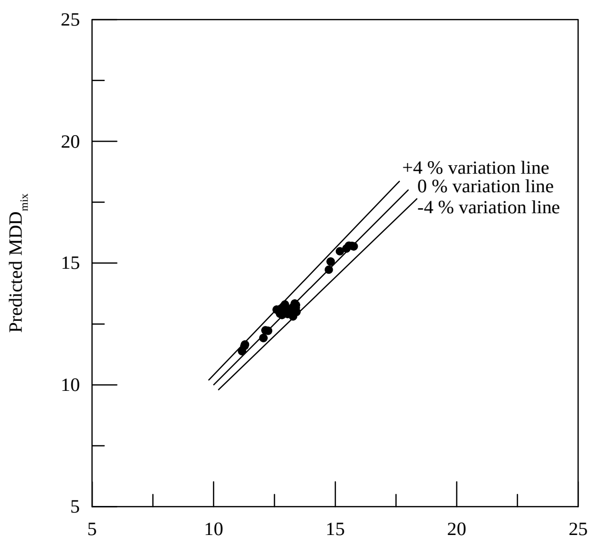

Figure (17): Predicted MDD_{mix} *versus* observed MDD_{mix} curve for equation 3

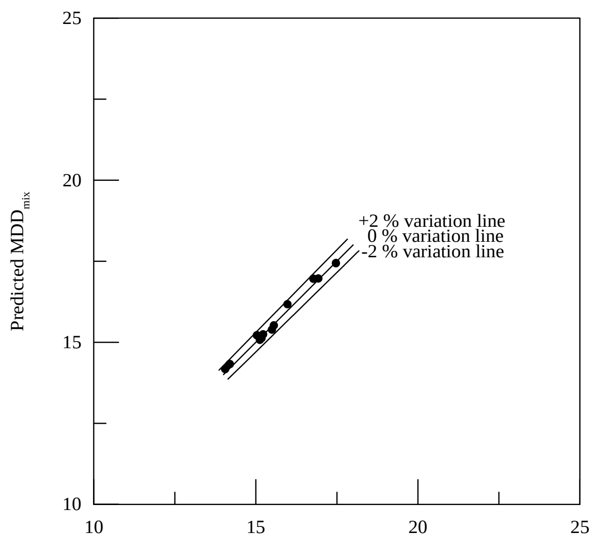

Figure (18): Predicted MDD_{mix} *versus* observed MDD_{mix} curve for equation 4

Table 5a. Values of *F*-statistics and *t*-statistics for different parameters of eqn. 3

Parameter	Value of coefficient	Standard error	*t*-statistic	$t_{critical} = t_{(0.975,37)}$	*F*-statistic	$F_{critical} = F_{(2,37,0.95)}$
Intercept	*10.184*	1.3457	7.568	2.027	456.7	3.257
G_{mix}	*3.320*	0.5270	6.298			
OMC_{mix}	*-0.2043*	0.0067	-30.220			

Table 5b. Comparison of $\widehat{MDD}_{mix}$ (predicted, using additional data not used in developing the model) and corresponding observed MDD_{mix}

G_{mix}	OMC_{mix} (%)	MDD_{mix} (%) (observed)	$\widehat{MDD}_{mix}$ (%)	Percentage error, P_E (%)
2.683	30.95	13.03	12.77	2.06
2.666	30.00	13.49	12.90	4.56
2.619	27.24	13.30	13.31	0.09
2.683	36.49	13.36	11.63	2.36
2.486	35.99	11.10	11.08	0.17

Table 6. Values of *F*-statistic and *t*-statistic for different parameters of eqn. 4

Parameter	Value of coefficient	Standard error	*t*-statistic	$t_{critical} = t_{(0.975,9)}$	*F*-statistic	$F_{critical} = F_{(2,11,0.975)}$
Intercept	*38.75*	5.952	6.51	2.262	428.6	3.98
G_{mix}	*-5.85*	2.224	-2.63			
OMC_{mix}	*-0.35*	0.0124	-28			

Values of coefficient of determination (R^2) of Eqns. 3 and 4 are 0.96 and 0.99, respectively. Values of standard error for Eqns. 3 and 4 are 0.228 kN/m^3 and 0.118 kN/m^3, respectively. Significance of Eqns. 3 and 4 are tested by calculating $F_{statistic}$ and $t_{statistic}$. Table 5a and 6 present the values of $F_{statistic}$ and $t_{statistic}$ for Eqn. 3 and Eqn. 4, respectively. Table 5b shows the comparison of observed MDD_{mix} and predicted MDD_{mix} based on Eqn. 3.

Limitations

The above mathematical models (Eqns.1-4) are very helpful for construction engineers in the field for preliminary estimation of OMC_{mix} and MDD_{mix} within the range of specific gravity (G) 2.49 to 2.68, OMC_{clay} in the range of 37.63% to 17.20% and $MC_{fly\ ash}$ in the range of 34.14 % to 22.49%. Beyond this range of the above parameters, users must check the equations with the help of laboratory test data.

CONCLUSIONS

Based on the results and discussion, the following conclusions can be drawn:

- With the increase in fly ash content in the fly ash clay mixture, the value of maximum dry density decreases irrespective of type of clay, type of fly ash and type of compaction.
- Optimum moisture content of fly ash clay mixture increases with the increase in fly ash content in case of clay N, whereas in case of clay M and clay K the value of OMC of fly ash clay mixture decreases with the increase in fly ash content.
- Degree of saturation at OMC and MDD increases slightly with the increase in fly ash content in case of Clay N fly ash mixture. In case of Clay M and Clay K fly ash mixture, with the increase in fly ash content, the value of degree of saturation at OMC and MDD decreases.

- A number of linear regression models have been proposed to estimate OMC_{mix} and MDD_{mix} of fly ash clay mixture.
- The above regression models are valid in the range of specific gravity (G), 2.49 to 2.68, OMC_{clay} in the range of 37.63% to 17.20% and $OMC_{fly\ ash}$ in the range of 34.14 % to 22.49%.

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