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Influence of clay content on the shear strength and physico-mechanical properties of sand-clay mixtures – a laboratory study

Stability analysis of any dump slope containing clayish and sandy material requires a detailed characterization of the material's indices and its physico-mechnical properties but, due to random proportion of clay and sand, and their heterogeneous distribution in the dump material, it becomes an arduous and cumbersome task for geotechnical engineers. A laboratory scale study has been carried out to understand the behaviour of composite mixtures containing a cohesive material (kaolin clay) and a non-cohesive material (sand) with proportion varying at an interval of 5% each by weight at specific moisture content. Laboratory tests for different indices and geotechnical properties like Atterberg's limits, shear strength parameters (cohesion and friction angle), compaction properties (maximum dry density and optimum moisture content) and swelling potential were carried out to categorize the mixed material based on percentage of clay/sand contents.The findings of the study have been presented in this paper.

Keywords: Atterberg's limit, shear strength, compaction properties, swelling potential.

1. Introduction

Soils containing sand and clay mixture are very difficult to classify since they possess properties of both sand and clay. The presence of the clay fraction in soil is crucial in determining its physico-mechanical properties such as strength and compressibility. Extensive research has been done for finding the effects of clay/silt contents on the index properties, shrink-swell potential and the shear strength of soils (Holtz and Lowitz 1957; Holtz 1985; Shakoor and Cook 1990; Shelley and Daniel 1993). Direct shear tests on sand mixed with varied proportions of silt and clay have been conducted by many researchers (Kurata and Fujishita 1960; Panagiotoponlos et al. 1997; Lius and Roger 2000; Naser Al Shayea 2001; Mehmet and Ozden 2007; Shanyoug et al. 2009; Mohammad et al. 2011; Rozalina and Yanful 2012) for studying the effects of silts and clay on frictional properties of such mixtures. Naser Al Shayea (2001) claims that clay minerals have a commanding influence on the behaviour of the total soil mass even if they are present in small fractions. According to Wasti and Alyanak (1968) when clay content was just enough to fill the voids of the granular portion at its maximum porosity, the structure of the mixture changes and the linear relationship between the Atterberg's limits (plastic and liquid limits) and the clay content is no more valid and soil changes its behaviour from sand to clay. Novais and Ferreira (1971) have shown the influence of clay content on shear strength in the sand-clay mixture and defined three separate zones of behaviour within the mixture.

Similar analysis done by Yanrong Li et al. (2013) shows that friction angle increases with increase in gravel content in clay gravel mixture. Vallejo and Mawby (2000) revealed that the shear strength of clay-aggregate composites depends upon relative concentrations of the aggregates and the clay by weight such that if the content of the granular material in the composite is greater than 75%, the shear strength is influenced by the aggregate alone. Similarly, with less than 40% granular material, clay has a controlling influence on shear strength of the composite mixture. Furthermore, shear strength of composite containing granular materials between 40% and 75% is partially controlled by the granular phase. Almost all the researchers have a convergent opinion based on their experimental findings that there is a significant effect of clay or fines content on the shear strength of mixed materials. This paper describes the details of laboratory experiments carried out for finding the physico-mechanical and index properties for characterization of the composite mixture containing sand and clay in different proportions. Index properties like Atterberg's limit, maximum dry density, optimum moisture content and the shear strength parameters (cohesion and friction angle) as well as the swelling index of the mixtures were studied to characterise the composite mixture containing sand and clay in different proportions. The outcome of the study has been analysed and presented.

2. Selection of material and testing procedure

With a view to select a clay material of high to moderate

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cohesion but low friction angle, tests were conducted on a number of clay minerals like fire clay, normal clay, and kaolin clay. Preliminary tests of samples to know the cohesion and friction angle were done by small direct shear box test following Indian standard testing procedure. The test results of three different types of clay are given in Table I. Based on these results, kaolin clay has been chosen for further test.

TABLE I: SHEAR STRENGTH PARAMETERS FOR DIFFERENT TYPES OF CLAY

Clay type	Cohesion (kPa)	Friction angle (degree)
Fire clay	29	26.8
Local clay	18	32.4
Kaolin	41	13.5

SAND

The sand collected for the purpose of tests belonged to Damodar river, located about 10 km from Dhanbad. The river sand consists mainly of coarse (2.0-4.75 mm) to medium grained (0.425-2.0 mm) sand particles with some gravel-size sediment (4.75 mm-80 mm) and small portion (<2%) of clay size fraction (<0.075 mm). The coarse grained and medium grained sand particles accounted for about 95% of the total mass, while silt and clay fractions constituted 1-5% only.

CHINA CLAY

Kaolin, also known as china clay, is formed by chemical weathering of aluminium silicate minerals like felspars. It is relatively pure clay having predominant proportion of kaolinite ($Al_2Si_2O_5(OH)_4$) but associatedwith other clay minerals like dickite, halloysite, nacrite and anauxite in small proportions.This clay was collected from the famous clay belt of Bankura district in the state of West Bengal, located within latitudes 22°46' and 22°34' and longitudes 86°30' and 87°29'. The clay is pale buff to off-white, soft and highly plastic in nature and deposited under a shallow overburden of about 1m from the surface.

The particle size distribution of the sand and clay as shown in Fig.1 was done following the Indian standard testing procedure IS: 2720 (Part 4) - 1985. The river sand used for testing was classified to be well graded with a co-efficient of uniformity, C_u = 6.43 and co-efficient of curvature or gradation, C_c = 1.27 whereas the particle gradation in clay has a C_u and C_c values as 3.3 and 0.96 respectively.

The consistency of clay sample was determined fromAtterberg's limit tests through standard testing procedure, IS: 2720 (Part 5) -1985. The liquid limit (LL) and Plastic Limit (PL) tests were conducted to know the physical behaviour of clay under different moisture content. The liquid limit for clay as obtained through fall cone penetration test was found to be 44% and the plastic limit was 26.7%. The plastic index was calculated to be 17.3. Based on the results obtained the clay was classified to be of CL type with intermediate plasticity as per Indian standard soil classification system. The properties of pure sand and pure clay are presented in Table II.

3. Analysis and discussion on various tests results

Uniformly mixed samples were prepared by mixing river sand and the cohesive clay (kaolin) for conducting various laboratory experiments. The results of various tests thus conducted to study the physico-mechanical properties like Atterberg's limit, compaction characteristics and the shear strength parameters (cohesion and friction angle) of the sand-clay mixtures are presented below with the analysis thereof.

3.1 ATTERBERG'S LIMITS TEST

The consistency behaviour of sand-clay mixture was studied by conducting Atterberg's limits tests on the composite mixtures with the percentage of sand/clay varying at 10% intervals. The results of the tests are presented in Table III.

The influence of clay/sand content in the mixture in terms of Atterberg'slimits, i.e.plastic limit, liquid limit and plasticity index was presented following a definite pattern (Fig.2, Fig.3 and Fig.4).

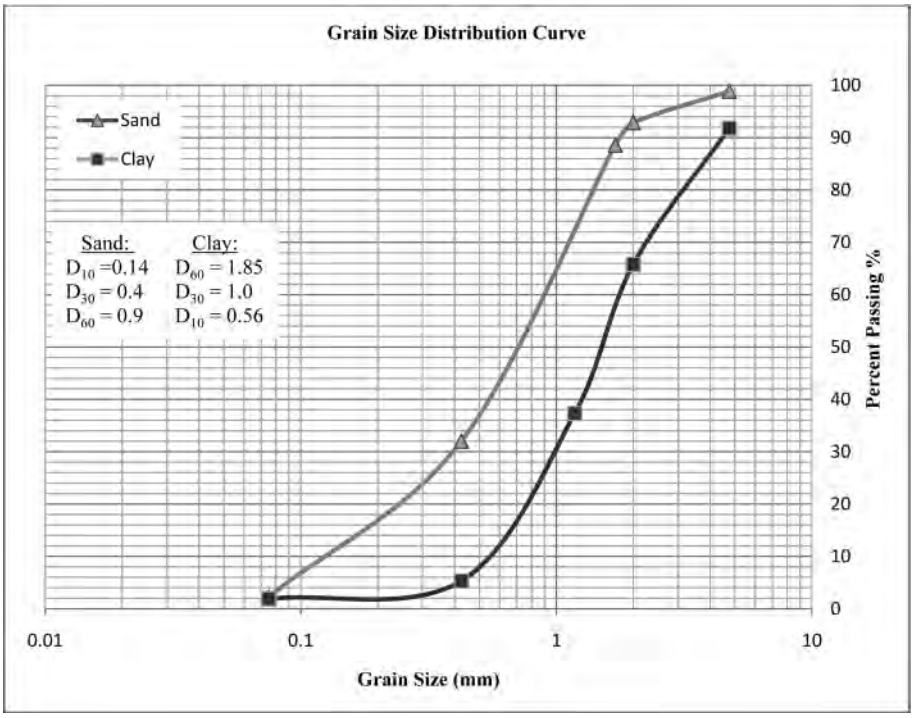

Fig.1 Grain size distribution curve of sand and clay by sieve analysis

TABLE II: PROPERTIES OF SAND AND CLAY

Properties	Sand	Clay
Size distribution	Well graded	Uniformly graded
Specific gravity	2.66	2.58
Atterberg's limit	NA	LL=44%, PL=26.7%
Cohesion	0.29kPa*	41kPa
Friction angle	39.5°	13.5°

*For wet sand

TABLE III: ATTERBERG'S LIMITS FOR DIFFERENT MIXTURES OF SAND-CLAY

Sand:clay	Plastic limit %	Liquid limit %	Plastic index
100:0	NA	NA	NA
90:10	NA	23	NA
80:20	NA	24.7	NA
70:30	NA	25.5	NA
60:40	16.45	26	9.55
50:50	21.2	32	10.8
40:60	21.8	34	12.2
30:70	22.73	35	12.27
20:80	23.05	41.57	18.52
10:90	25.8	42.5	16.7
0:100	26.7	44	17.3

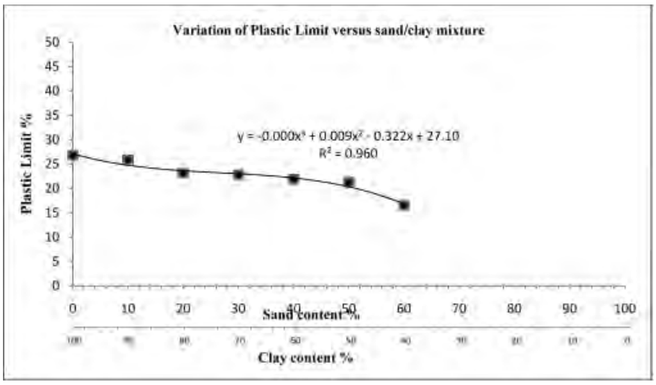

Fig.2a Variation of plastic limit with sand/clay content (3rd order equation)

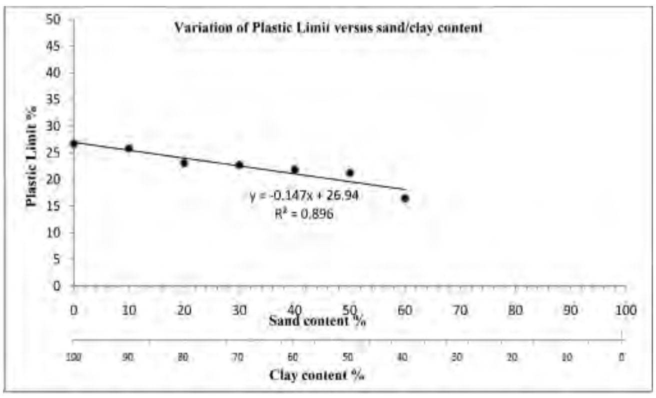

Fig.2b Variation of plastic limit with sand/clay content (linear equation)

The variation of Atterberg's limits with sand content shows somewhat similar characteristics in each case of plastic limit, liquid limit and plasticity index. The plastic limit of the composite mixture follows a non-linear trend with variation of sand/clay proportion and a little variation in its moisture content.With excessive content of non-cohesive material (sand in this case), the composite mixture fails to form cluster and hence mixtures containing more than 60% sand cannot be subjected to plastic limit test.This is because of the fact that with the increasing sand content the water absorbing capacity of the mixture goes on decreasing and comes to a minimum at zero clay content. The plastic limit of the mixture decreases non-linearly following a 3rd order polynomial with coefficient of determination, $R^2 = 0.96$ (Fig.2a). The plastic limit data also represents a straight line (Fig.2b) but with smaller coefficient of determination ($R^2 = 0.89$).

As the mixed material cannot be tested beyond sand content of 60% and more, liquid limit of the mixtures was ceased at this juncture. The liquid limit as in Fig.3a and Fig.3b shows a declining trend with the increase in sand content in the mixture, fitting to both, a straight line (Fig.3a) with

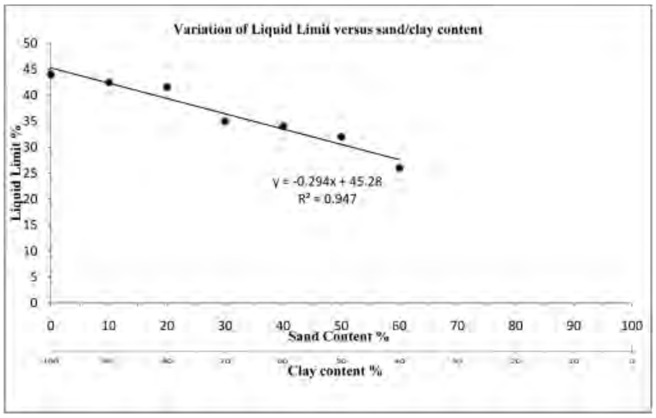

Fig.3a Variation of liquid limit versus sand/clay content (linear equation)

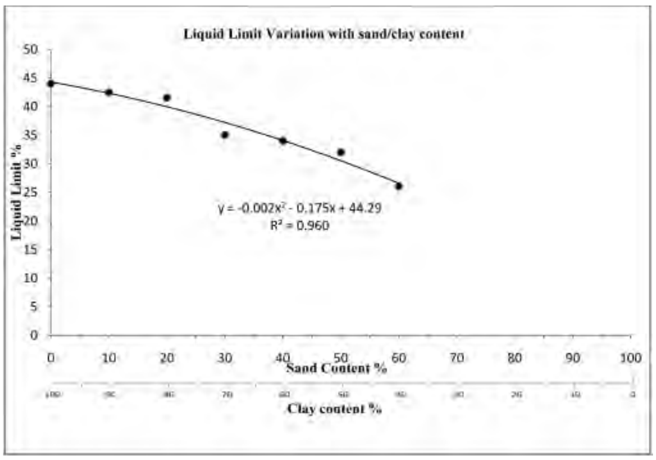

Fig.3b Variation of liquid limit versus sand/clay content (2nd order equation)

coefficient of determination, $R^2 = 0.9477$ as well as a 2nd order polynomial showing a declining trend with a coefficient of determination of $R^2 = 0.9606$ (Fig.3b).

The plasticity index, however, decreases linearly with increase in sand (Fig.4). However, the correlation between plasticity indexes and sand content in the mixture is rather poor of the order of 0.8169.

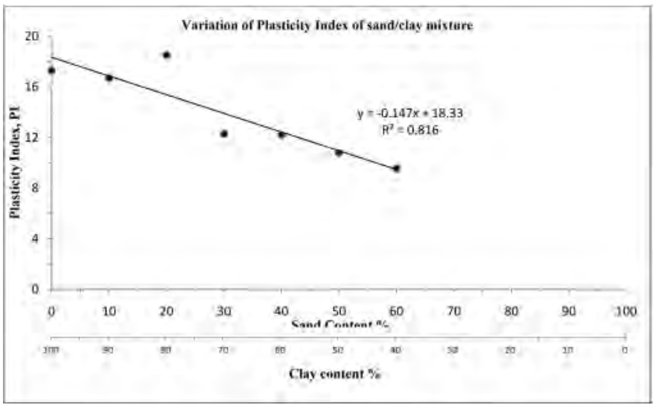

Fig.4 Variation of plasticity index versus sand/clay content

3.2 Shear strength parameters

Direct shear box (6 cm×6 cm) tests were carried out as per Indian Standard testing procedure (IS: 2720(Part 13) - 1986) for mixtures of river sand and cohesive clay (kaolin). Sand content was varied from zero to 100 percent at an interval of 5% and tests were conducted on composite mixtures containing sand/clay in varying proportions. A total of 252 samples (21 set × 4 NL load × 3 moisture content) were tested using small direct shear box at three different moisture content of 16%, 19% and 22% respectively. The shear tests were conducted at 4 different normal loads of 0.5 kg/cm^2, 1.0 kg/cm^2, 1.5 kg/cm^2 and 2.0 kg/cm^2 for each sample type after being compacted by normal load for a time period of 8 hours. Drained and undrained direct shear tests were conducted depending upon the percentage of fines or clay content in the mixtures. Drained tests were done on composite mixtures containing up to 50% of content and beyond that undrained tests were performed when clay became dominating content in the mixture. The values of cohesion and friction angle, as obtained for mixtures containing sand/clay in varied proportions were plotted (Figs.5 and 6) to find out the effect of sand/clay contents on the frictional behaviour of the mixtures.

It may be observed from Fig.5 that the cohesion of the mixed material decreases non-linearly with increase in sand content. The plot as shown in Fig.-5 is a perfect non-linear 3rd degree polynomial. The plot may apparently be divided into three distinct zones based on gradient of the curve, viz. a zone of cohesiveness (clay>70%, sand<30%), an intermediate zone (70%>clay>25%, 30 %< sand<75%) and a zone of non-cohesiveness (clay<25%, sand>75%). At sand content between 0% and 30% the slope of cohesion curve is gentle indicating a significant effect of clay on the mixture properties. At sand content between 30% and 75%, the curve has a steep slope and again, it becomes flatter in the range of sand content above 75% representing a region of sand dominance. More or less similar results were obtained by Dewangan (1998) and Alam (2001) too.

In Fig.6, the friction angle parameter depicts a trend opposite to that of cohesion plot (Fig.5). Here the friction angle increases with increasing sand content. Unlike cohesion curve, the trend of friction versus sand/clay content follows a linear trend with more or less distinctable zones indicating the influence of sand/clay percentage on friction angle. These zones may be regarded as zone of clay dominance, intermediate zone and zone of sand dominance respectively.

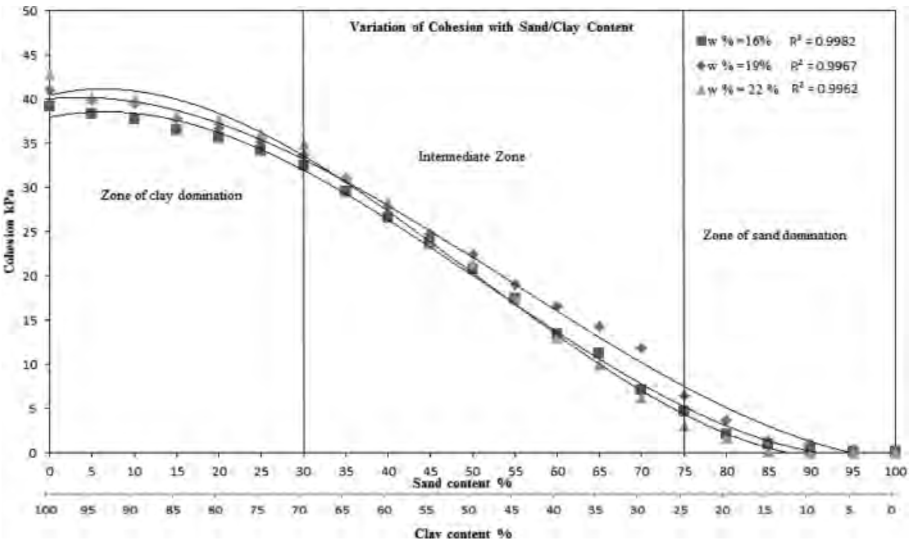

Fig.5 Variation of cohesion with sand/clay content

3.3 Compaction characteristics

Standard Proctor compaction tests (IS:2720 (Part VII) - 1980) were carried out with mixtures of different composition to know the variation of maximum dry density (MDD) at different percentages of cohesive and non-cohesive material. The plot of maximum dry density versus sand content (Fig.7) shows a non-linear curve fit of 3rd order with dry density values gradually decreasing with decreasing clay content. Because of its high ability to absorb water (as corroborative of high plasticity index) and low uncompacted density, the clay content is liable to give maximum dry density at a specified compactive effort as compared to sand which is less compressible.

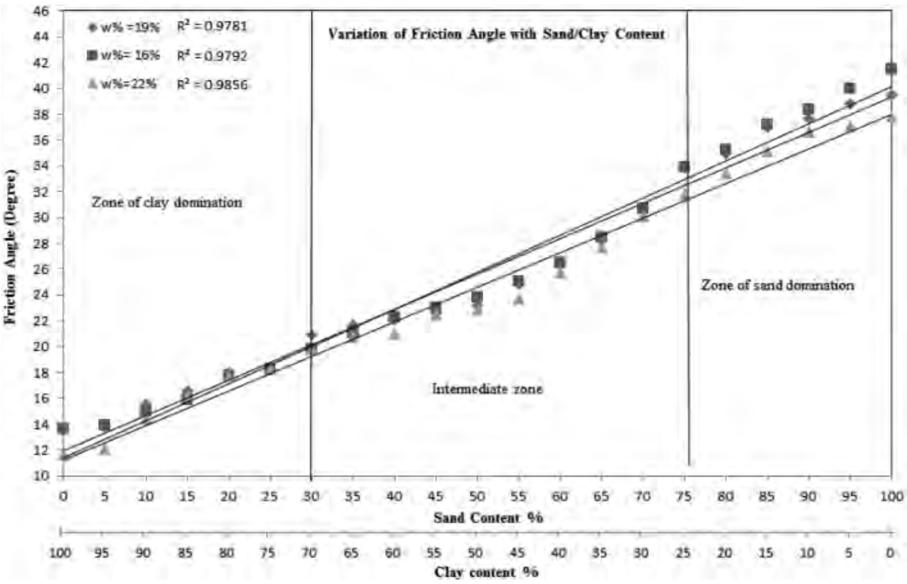

Fig.6 Variation of friction angle with sand/clay content

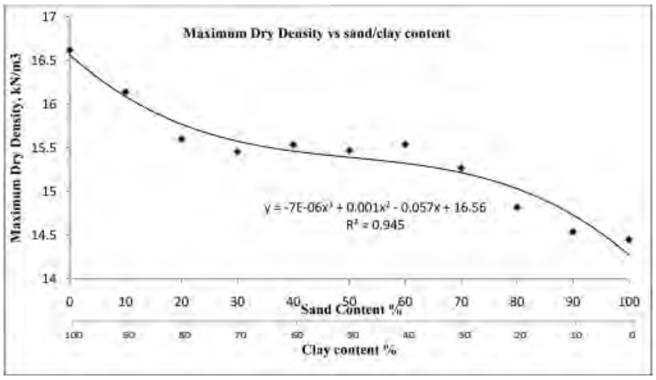

Fig.7 Variation of maximum dry density with sand/clay content (%)

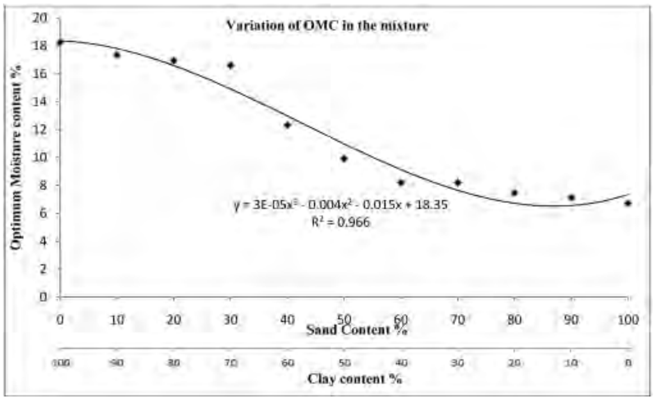

Fig.8 Variation of OMC with sand/clay content (%)

It has been observed that the optimum moisture content (OMC) corresponding to the maximum dry density decreases non-linearly with an increase in sand content following a 3rd order polynomial fit (Fig.8). This indicates that with the increasing presence of non-cohesive content (sand) the mixture achieves a maximum dry density at lower moisture content.

3.4 Swelling index test

The swelling phenomenon, a potential danger of unpredictable behaviour of such soils in terms of volume change, is considered as one of the most serious challenges that the foundation engineers face(Seed et al. 1962; Komornik and David 1969). Soil containing clay shows a wide variation in its volume when subjected to moisture content that significantly alters the strength of soil indicating a strong influence of clay on the stability of mixed material. Tests for swelling potential of the sand-clay mixtures were carried out following Indian Standard (IS: 2720 (Part XL)-1977) using Free Swell Index Testing method on the specified sample with increasing sand content at an interval of 10% each.

As the clay (kaolin) has high plasticity index, in a range where it can absorb moisture in transition from plastic to liquid limit, it shows wide fluctuations in its volume. In Fig.9, the plot shows the behaviour of swelling index potential versus the percentage of sand content.

The swelling index for pure clay was found to be 37%. So, it may be classified as material of moderate expansiveness, and the data fits perfectly in a 2nd order non-linear polynomial. From the plot it may be observed that there is an increase in the swelling potential of the mixture with the increase in clay content.

3.5 Variation of cohesion variation and internal angle of friction with density and OMC

The cohesion and internal angle of friction of the mixture also show definite relationship with Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) at a specific

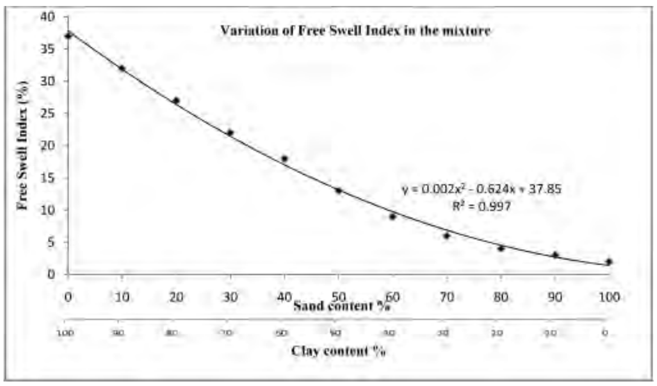

Fig.9 Variation of free swelling index (%) with sand/clay content

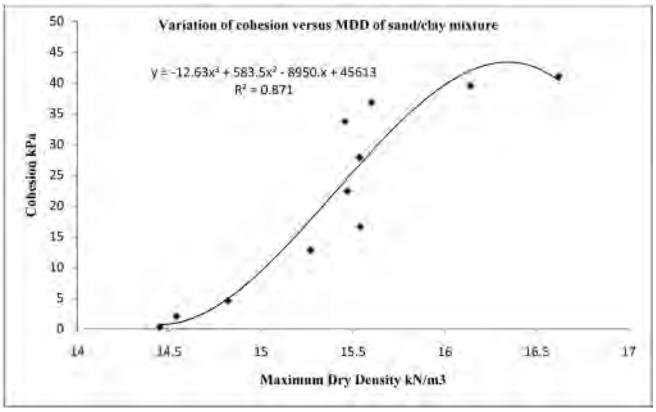

Fig.10 Variation of cohesionversus maximum dry density (MDD) of mixed material

compactive effort.With increase in the maximum dry density for given compactive effort the cohesion of the mixed material increases in a non-linear 3rd order polynomial fashion showing a rather poor correlation, R2 = 0.87 (Fig.10). Whereas, with increase in optimum moisture content, cohesion for the same mixture increases non-linearly following a 3rd order polynomial fit (Fig.11).

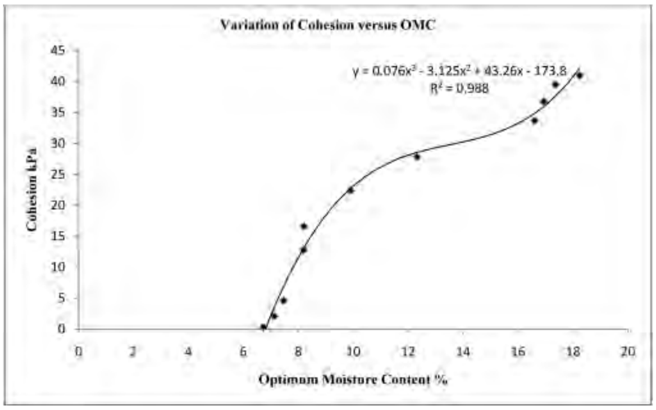

Fig.11 Cohesion variation of mixture with OMC of mixed material

The variation of internal angle of friction versus MDD and OMC of the sand-clay mixtures is plotted in Figs.12 and 13 respectively. It may be observed from the figure that both the maximum dry density (MDD) and optimum moisture content (OMC) follow anon-linear 2nd order polynomial.

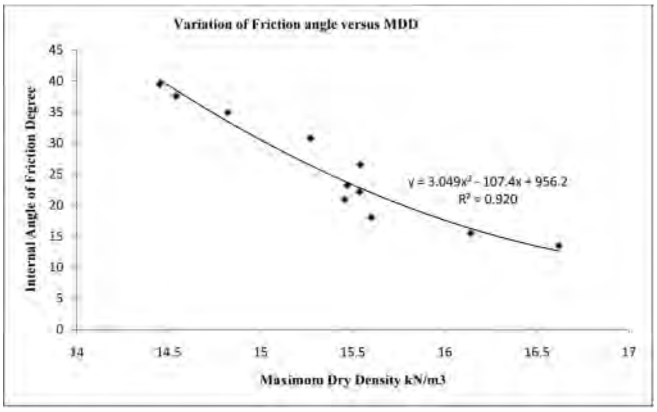

Fig.12 Internal angle of friction vs maximum dry density of mixed material

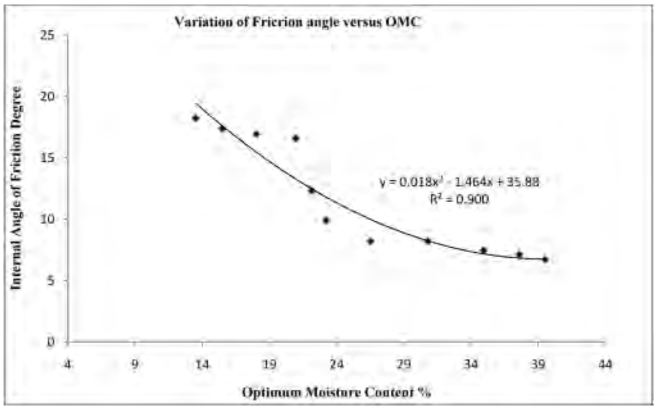

Fig.13 Internal angle of friction vs optimum moisture content (OMC)

4. Summary and conclusion

The experimental results obtained from the laboratory study shows a marked influence of clay/sand content on overall physico-mechanical properties of sand-clay mixtures. The following observations and conclusions may be devised out of the said experimental observations.

a. Both the liquid limit and the plastic limit decrease with increase in sand content (Figs.2 and 3). However, at sand content above 60%, the mixture fails to build aggregates. As the sand cannot absorb water, the plasticity index decreases with increase in sand content (Fig.4) in the mixture.

b. The shear strength parameters (cohesion and friction angle) of the mixed materials are significantly influenced by the clay content in the mixture. The variation of both the cohesion and friction angle with sand/clay content follow a non-linear trend. Cohesion varies with the sand/clay content in a definite pattern depicting three different ranges of behaviours which may be due to formation of clay dominated and a sand dominated region with an intermediate zone in between (Fig.5). The friction angle however increases with increases in sand content, a non-cohesive component in the mixture (Fig.6).

c. The maximum dry density (MDD) and subsequent optimum moisture content (OMC) at a specified compactive effort shows a decreasing trend with an increase in sand content (Figs.7 and 8). MDD and OMC are high when clay content is more in the mixture because of high compressibility and water retaining power of clay. A similar behaviour is also observed in case of swelling potential of the mixtures (Fig.9).

d. The cohesion of the mixtures was observed to increase with the increase in MDD as well as OMC (Figs.10 and 11), while the plot between friction angle versus MDD and OMC shows a declining trend (Figs.12 and 13).

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