Experimental Investigation on Liquid Limit and Plasticity Index of Clay - Sand Mixtures

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***Abstract*—The classical concepts of soil mechanics were developed exclusively on the investigations of sedimentary deposits. These concepts if inadvertently applied to residual soils may result in misleading conclusions. The residual soils are often found to comprise of soils of different composition encompassing gravels sand silts and clays. Many engineering applications stipulate certain physical properties to be satisfied for use in infrastructure construction. For instance, the soils to be used in base courses shall have to satisfy consistency limits of definite specifications. Therefore, it of interest to investigate what is the relative influence of coarse fraction in fine fraction and vice versa. Accordingly, a detailed study has been taken up by considering three different clays and two different sands for the purpose of investigating the changes in consistency limits viz, liquid limit and plastic limit with different combinations of clay-sand mixtures. The soils considered for the study are obtained from surroundings of Tirupati town. The soils are tropical in nature and their residual formation is due to in-situ weathering of the rock, subsequently being subjected to cyclic wetting and drying. This is typical of natural soil formation in tropical regions. The investigation considers the laboratory testing on representative soil samples. The sand is collected from Swarnamukhi riverbed. The sand selected are of two types one is fine sand with uniform grain size and the other is coarse sand having representation of all sand sized particles. The experimental investigation and analysis of test results reveals that a framework can be proposed to predict the consistency limits. The proposed method is helpful for practicing engineers to estimate the type and amount of sand required to be added to the clay to achieve a targeted value of liquid limit**

Keywords— Residual soils, cohesive and non-cohesive components, liquid limit and plastic limit values, clay-soil mixtures

I. INTRODUCTION

Soils in general are regarded as multi component, poly phase, and particulate system with compositional and / or structural discontinuities. Both physical and engineering properties of natural soils primarily depend on mineralogy and exchangeable cations associated with clay fraction. For multi –component soil mixtures, soil samples must be obtained to be mixed, and they must be tested in the laboratory under conditions representing as nearly as field conditions. The problem would be greatly simplified if the engineering characteristics of the individual cohesive or non-cohesive soil could be used to predict or estimate the behavioral characteristics as a function of the percentage of components.

The difficulty inherent in using the engineering characteristics of the individual soil components to predict the behaviour of a mixture is that the mixture components interact among each other to influence the behaviour of soil mixture, hence such response may be considered soil-mixture interaction. This mixture or interaction response can seldom be predicted form the properties of its components as a simple proportion of the relative amounts of the components, that is, the response may not be linear function of the composition. Thus, a generalized principle of super position may not be valid, and the presence of particular clay component that may be present in small quantities may exert greater influence on the engineering behavior.

Both the engineering and physical properties are related to these individual constituents. Numerous established investigations have been carried out and correlations have been made for natural soils relating their physical and engineering properties. These investigations are essentially restricted to either purely cohesive soils or non-cohesive soils with various proportions. The mechanisms established in these investigations cannot be extended to the natural soils which contain both cohesive and non-cohesive soils with various proportions. Besides this, there are many situations where soil engineers have to use soil mixtures for modifying the existing properties of soils to suit the standard of new material as per the design considerations. Improving Soil properties become essential during geotechnical applications pertaining to wide spectrum of infrastructure projects. In residual soils, the soil particles ranging over different sizes exist making it too complex to understand the interaction behavior quite intricate. Adding complexity to the problem I variation in density of packing in the soil deposits. Many geotechnical applications require to satisfy the codal specifications, whereas the natural soils may not be truly meeting such stringent specifications. For example, the materials used in pavement construction shall have consistency limits of different values than those stringent values specified on specifications. In order to satisfy the requirements, it is often resorted to add geo-materials of contrasting properties to improve the characteristics.

In the light of the above observations, a detailed experimental programme has been planned to bring out property correlations in order to assess the natural soil behaviour by conducting experiments on soil mixtures.

II. BACKGROUND INFORMATION

Both compositional factors and environmental factors affect the engineering properties of behavior of soils [2]. compositional factors include type of minerals, amount of each mineral, particle shapes and size distribution, type of adsorbed cation and pore-water composition. Environmental

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factors include water content density, confining pressure, temperature, soil fabric and availability of water [2], and cementation. Many researchers conducted studies on the Atterberg limits of soils as a function of their clay size contents and made observations that are incoherent and found to be not in always in agreement. These studies mainly focused on the liquid limit of clay minerals mixed with silica sand ([3], [4], [5] and [8]. [5] in a study on the Atterberg limits of the clay minerals kaolinite, Illite and montmorillonite and their respective mixtures with sand, observed that there exists a linear relationship between liquid limit values and their respective clay contents, if the clay percentage is not too low. [4] and [5] have presented their findings on the basic properties of soil mixtures. They assumed that the inter particle forces in the non-clay fraction are negligible and that the individual particles in this fraction have negligible amounts of absorbed water associated with them. Thus, the entire content of a clay may be considered to be associated with the clay fraction of soil. If a soil contains a higher proportion of clay fraction and a small proportion of non-clay fraction the resulting when the soil mixed with water may be visualized as a series of individual non-clay particles floating in a sea of soft clay. Following the logic developed by [4] and [5], [9] have shown that the presence of coarser particles only dilutes the Physico-chemical potential of the soil proportionality and does not alter the nature of stress transfer. The compression behavior was examined of sand-marine clay mixtures, with carefully planned experimental work with theoretical application. The test data indicate that the normal compression path of a sand-clay mixture depends on sand content of clay-sand mixture and initial moisture content [6]. [7] investigated the virgin compression behavior of clay -sand matrix. The behavior was captured by two distinct variables viz., reference void ratio and remolded yield stress. These are correlated with the molding moisture content of the matrix. A structure variable termed equivalent void ration was introduced based on volume fraction of sand. [1] quantified the influence of the gravel on the plasticity of the mixture by determining liquid and plastic limits obtained by direct testing of the mixture. Polidori, 2007 conducted a detailed study on liquid limit (Casagrande's method) and plastic limit (rolling and thread method) of six inorganic soils in conjunction with mixtures with silica sand. The study revealed that the liquid limit and plastic limit values of the mixtures tested are related to the respective clay size contents by a linear relationship, except those with a low clay percentage.

The literature review prompts the need to develop a unified and coherent approach to analyse and understand the behaviour of clay-sand mixtures for use by practicing engineers.

III. METHODS AND MATERIALS

A. *Methods*

The various tests conducted on natural soils and soil mixtures include grain size distribution, liquid limit, plastic limit. All the tests have been performed in conformity with Bureau of Indian Standards (BIS), Table 1.

TABLE I. TESTS CONDUCTED

Serial Number	Description		IS Specification
1	Grain Size Distribution		IS: 2720 (Part. IV) 1985
	a	Dry Sieve Analysis	
	b	Wet Sieve Analysis	
2	Atterberg Limits		IS: 2720 (Part. V) 1985
	a	Liquid Limit	
	b	Plastic Limit	

B. *Materials*

Natural Soils

The soils considered for the study are obtained from surroundings of Tirupati town. The area falls in the Archaean age, and is mostly occupied by pegmatite, basalts, migmatites, quartzite and shale. The soils are tropical in nature and their residual formation is due to in-situ weathering of the rock, subsequently being subjected to cyclic wetting and drying. This is typical of natural soil formation in tropical regions. The investigation considers the laboratory testing on representative soil samples. The properties of these soils are presented in Table 2.

Sand

The sand is collected from Swarnamukhi riverbed. The Swarnamukhi River rises in Chandragiri Hills, passes through broad valley of Tirupati town, and reaches Srikalahasti. From Srikalahasti, it flows in a northeasterly direction into Nellore district and ultimately joins sea near Sidhavaram. The sand selected are of two types one is fine sand with uniform grain size and the other is coarse sand having representation of all sand sized particles. The grain size characteristics together with classification are given in Table 2. The grain size distribution curves for the soils and sand considered in the present investigation are shown in Table 3 and Figure 1.

TABLE II. BASIC PROPERTIES OF SOILS TESTED

Description	Clay 1	Clay 2	Clay 3	Sand 1	Sand 2
% Gravel	-	-	-	-	-
% Sand	48.00	15.00	6.00	98.40	98.00
% Silt+Clay	52.00	80.00	94.00	1.60	2.00
Liquid Limit %	76.00	55.00	45.00	-	-
Plastic Limit %	24.00	22.00	21.00	-	-
Plasticity Index,%	52.00	33.00	24.00	-	-
Coefficent of Curvature,C_c	-	-	-	0.71	1.40
Coeffiicient of Uniformity,C_u	-	-	-	2.67	2.56
Indian Standard Classification-1498	CH	CH	CI	SP	SP

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TABLE III. GRAIN SIZE DISTRIBUTION OF SOILS TESTED

IS sieve Size,mm	Clay 1	Clay 2	Clay 3	Sand 1	Sand 2
4.75	100.00	100.00	100.00	98.00	100.00
2.40	90.00	98.00	100.00	91.10	100.00
1.20	80.00	96.00	99.00	61.60	100.00
0.60	75.00	92.00	99.00	27.90	100.00
0.43	70.00	90.00	98.00	8.10	100.00
0.30	64.00	88.00	98.00	2.80	78.00
0.15	58.00	84.00	98.00	1.90	30.00
0.0745	52.00	80.00	94.00	1.60	2.00
0.0598	48.00	77.00	90.00	0.00	0.00
0.0425	43.00	72.00	84.00	0.00	0.00
0.0303	40.79	68.00	80.00	0.00	0.00
0.0215	39.62	64.77	71.62	0.00	0.00
0.0159	37.28	60.93	67.39	0.00	0.00
0.0114	34.93	57.10	63.15	0.00	0.00
0.0082	32.00	52.31	57.85	0.00	0.00
0.0052	27.00	45.00	50.00	0.00	0.00
0.0042	24.38	40.00	46.00	0.00	0.00
0.0031	22.00	36.00	40.00	0.00	0.00
0.0018	17.78	29.07	32.15	0.00	0.00
0.0013	15.59	25.48	28.18	0.00	0.00

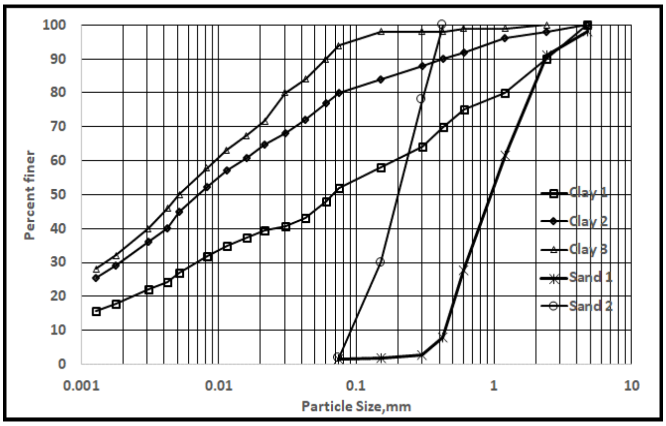

Fig. 1. Grain size distribution of soils and sand considered in the investigation.

Soil Mixtures Tested

The well documented studies on soils normally refer to either for purely cohesive soils or for cohesion less soil. The respective mechanisms cannot be directly extended to natural soils comprising of different constituent materials with varying proportions. There is also increase in need to understand the combined effects of individual constituents in view of large-scale land reclamation works that are taking place in different countries where space is a major constraint. The situations requiring ground modifications make use of soil mixtures for the purpose of modifying the existing properties of soils so as to suit to the standard of new material as per design considerations.

Most natural soils normally encountered, and soil mixtures used for various applications contain particles varying in size from < 2μ even up to 40mm. The present study considers the maximum size to be 4.75mm. The natural soils obtained are mixed with the fine sand and total sand size in different proportions to bring out the properties of different mixtures.

Procedure adopted for mixing

Mixing for specimen preparation can be done in two ways. First one consists of mixing the sand with the appropriate amount of water content before adding the clay in stages and thoroughly mixing by hand using a spoon of each addition of clay soil. Second one consists of mixing of dry sand and clay soil before adding the appropriate amount of water content from jar and mixing frequently by hand using spoon. In the present study second method was adopted for mixing the individual constituents of clay and sand fractions for preparing the sample for testing.

Details of Mix proportions considered for various investigations

Table 4 presents the different mix proportions used for conducting soil test to know the basic properties of clay-sand mixtures. As indicated in Table 4 the first series of tests comprise of using Clay 1 and Clay 3 in different combinations of Sand 1 and Sand 2. The Clay 1 and Clay 2 represent two boundary limits of liquid limit values considered in the investigation and Clay 2 represents intermediate value in terms of liquid limit values as seen Table 2. Accordingly, it was thought that the behavior of any clay-sand combination ranging in between can be predicted if a framework is examined using the proposed combinations.

TABLE IV. DIFFERENT MIX PROPORTIONS USED FOR DETERMINING INDEX PROPERTIES

Description	Series -1 For Formulation of Framework				Series -2 Data Used for Prediction	
Objective	For Formulation of Framework				For Prediction	
Soils Used	Clay 1: Sand 1	Clay 1: Sand 2	Clay 3: Sand 1	Clay 3: Sand 2	Clay 2: Sand 1	Clay 2: Sand 2
Broader Division	C1S1	C1S2	C3S1	C3S2	C2S1	C2S2
Proportions Used	C1 100:S1 0	C1 100:S2 0	C3 100:S1 0	C3 100:S2 0	C2 100:S1 0	C2 100:S2 0
	C1 85:S1 15	C1 85:S2 15	C3 85:S1 15	C3 85:S2 15	C2 85:S1 15	C2 85:S2 15
	C1 70:S1 30	C1 70:S2 30	C3 70:S1 30	C3 70:S2 30	C2 70:S1 30	C2 70:S2 30
	C1 60:S1 40	C1 60:S2 40	C3 60:S1 40	C3 60:S2 40	C2 60:S1 40	C2 60:S2 40
	C1 50:S1 50	C1 50:S2 50	C3 50:S1 50	C3 50:S2 50	C2 50:S1 50	C2 50:S2 50
	C1 35:S1 65	C1 35:S2 65	C3 35:S1 65	C3 35:S2 65	C2 35:S1 65	C2 35:S2 65

The grain size characteristics presented in the Figures 2-7. The grain size characteristics represent a wide range.

It may be observed from Table 5 that the original soil is clay with high compressibility (CH). Upon addition of sand at 15% the classification of soil changes to Clayey Sand (SC) in case of Clay 1 and Sand 1. The liquid limit is reduced from 76% to 27% with addition of 65% of sand which means 65% of reduction in liquid limit value. Similarly, the plasticity index is reduced from 52% to 13%, which turns out that there is a reduction of 75%. If the fine sand (S2) is used, the reduction in liquid limit is even more significant owing to the fact that fine sand would have fine fraction passing 425 μ leading to reduction in liquid limit. Accordingly, a steep reduction in liquid limit can be noticed from Figure 8 in respect of Sand 2 (S2). The observation is further reinforced with reference to Figure 9 which depicts liquid limit variation with respect fine fraction passing 425μ. It may be observed that for Sand 1 (S1), the fine fraction passing 425μ will reduce causing reduction in liquid limit whereas the reduction in

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liquid limit is associated with increase in fines in the case of fine sand (S2). This observation is of immense practical importance in engineering application where in the liquid limit of soil available locally has to be reduced to meet the speciation as applied to the given situation.

TABLE V. PROPERTIES OF CLAY-SAND MIXTURES (C1S1 AND C1S2)

Description	Mix Basic Poperties											
	C1S1						C1S2					
Mix Proportion	C1 100:S1 0	C1 35:S1 65	C1 50:S1 50	C1 60:S1 40	C1 70:S1 30	C1 85:S1 15	C1 100:S2 0	C1 35:S2 65	C1 50:S2 50	C1 60:S2 40	C1 70:S2 30	C1 85:S2 15
% Gravel	0.00	1.30	1.00	0.80	0.60	0.30	0.00	0.00	0.00	0.00	0.00	0.00
% Sand	48.00	79.46	72.20	67.36	62.52	55.26	48.00	80.50	73.00	68.00	63.00	55.50
% Silt+Clay	52.00	19.24	26.80	31.84	36.88	44.44	52.00	19.50	27.00	32.00	37.00	44.50
Liquid Limit %	76.00	27.00	41.00	48.00	55.00	65.00	76.00	24.00	34.00	41.00	50.00	62.00
Plastic Limit %	24.00	14.00	15.00	17.00	18.00	23.00	24.00	12.00	14.00	15.00	17.00	22.00
Plasticity Index,%	52.00	13.00	26.00	31.00	37.00	42.00	52.00	12.00	20.00	26.00	33.00	40.00
Indian Standard Classification-1498	CH	SC	SC	SC	SC	SC	CH	SC	SC	SC	SC	SC

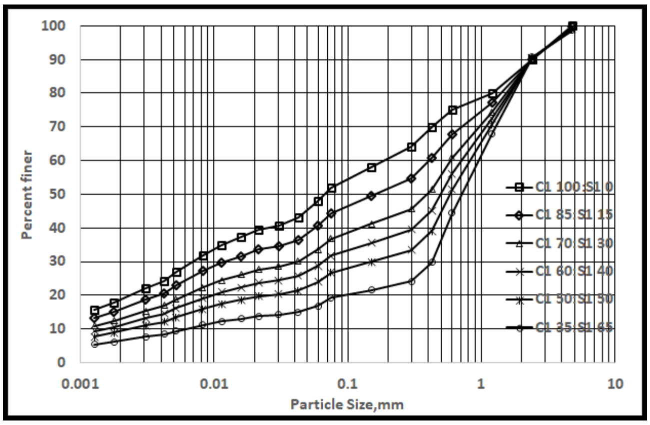

Fig. 2. Particle size distribution curves for the Soils used (C1S1).

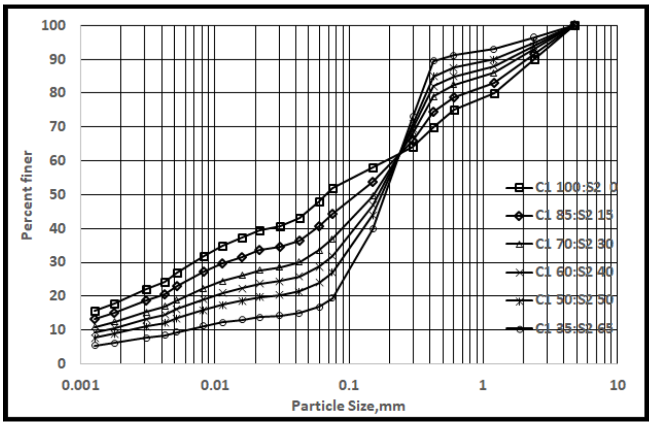

Fig. 3. Particle size distribution curves for the Soils used (C1S2).

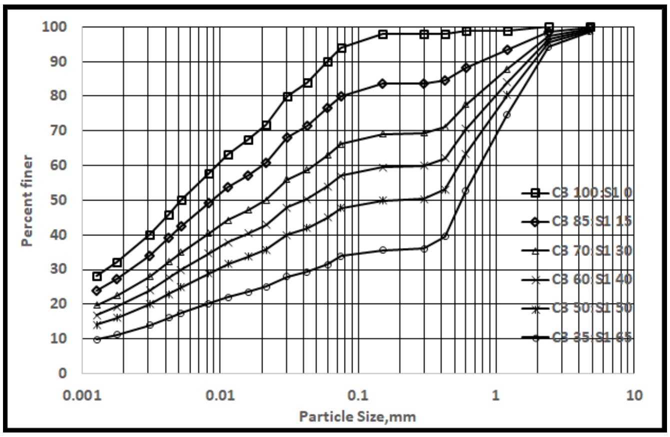

Fig. 4. Particle size distribution curves for the Soils used (C3S1).

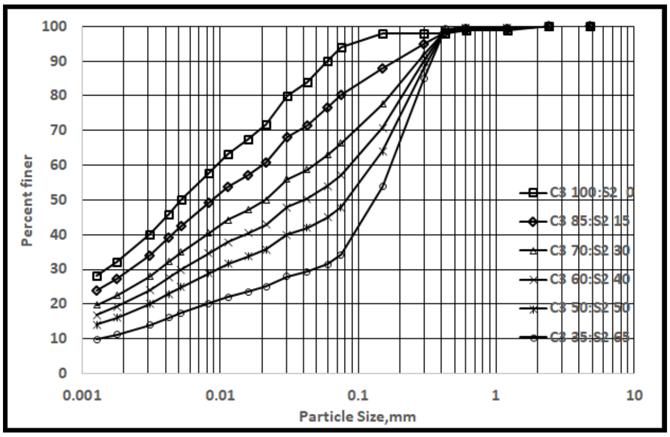

Fig. 5. Particle size distribution curves for the Soils used (C3S2).

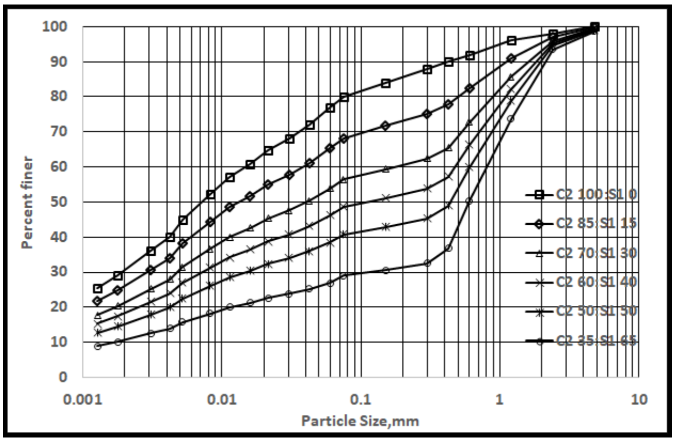

Fig. 6. Particle size distribution curves for the Soils used (C2S1).

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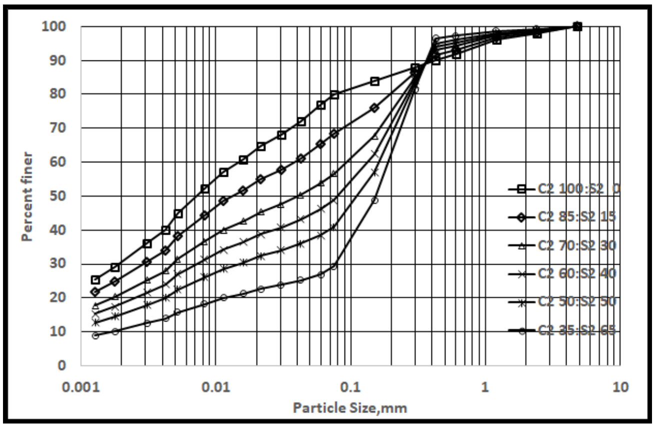

Fig. 7. Particle size distribution curves for the Soils used (C2S2).

The Figures 8 and 9, representing the data in Tables 5-7, depict the effect of coarse fraction and fraction passing 425µ on liquid limit values. It may be noticed that the increase in coarse fraction decreases the liquid limit value. This may be due to the fact that the coarse fraction has component of soil less than 425µ. This component in combination with the corresponding component of clay dilutes the activity causing reduction in the liquid limit value. Figures 10-11 represent the relationship between liquid limit values of mixtures with corresponding values of plasticity index in relation to classical A-line. In Figure 12-13, Normalized liquid limit values of clay-sand mixtures with liquid limit of clay in relation to fine and Coarse fraction and Figure 14 represents the Predicted values of liquid limit vis-a vis experimental values of liquid limit.

The Classical A-line equation used for sedimented soils will be modified to the clay sand mixtures as represented by

$$I_P = 0.81\,(LL-12) \qquad MPI = 0.80\,(LL-12) \qquad R^2=0.98 \tag{1}$$

$$\frac{(W_{LL})_{MAXIMUM}}{(W_{LL})_{CLAY}} = 0.010\ FF \qquad R^2=0.96 \tag{2}$$

$$\frac{(W_{LL})_{MAXIMUM}}{(W_{LL})_{CLAY}} = 1-0.009\ (CF) \qquad R^2=0.962 \tag{3}$$

TABLE VI. PROPERTIES OF CLAY-SAND MIXTURES (C3S1 AND C3S2)

Description	Mix Basic Properties											
	C3S1						C3S2					
Mix Proportion	C3 100:S1 0	C3 35:S1 65	C3 50:S1 50	C3 60:S1 40	C3 70:S1 30	C3 85:S1 15	C3 100:S2 0	C3 35:S2 65	C3 50:S2 50	C3 60:S2 40	C3 70:S2 30	C3 85:S2 15
% Gravel	0	1.3	1	0.8	0.6	0.3	0	0	0	0	0	0
% Sand	6	64.76	51.2	42.16	33.12	19.56	6	65.8	52	42.8	33.6	19.8
% Silt+Clay	94	33.94	47.8	57.04	66.28	80.14	94	34.2	48	57.2	66.4	80.2
Liquid Limit %	45	18	25	32	35	41	45	18	24	29	31	39
Plastic Limit %	21	14	16	17	19	20	21	13	14	15	17	18
Plasticity Index,%	24	4	9	15	16	21	24	5	10	14	14	21
Indian Standard Classification-1498	CI	SC	SC	CL	CI	CI	CI	SC	SC	CL	CL	CI

TABLE VII. PROPERTIES OF CLAY-SAND MIXTURES (C2S1 AND C2S2)

Description	Mix Basic Properties											
	C2S1						C2S2					
Mix Proportion	C2 100:S1 0	C2 35:S1 65	C2 50:S1 50	C2 60:S1 40	C2 70:S1 30	C2 85:S1 15	C2 100:S2 0	C2 35:S2 65	C2 50:S2 50	C2 60:S2 40	C2 70:S2 30	C2 85:S2 15
% Gravel	0.00	1.30	1.00	0.80	0.60	0.30	0.00	0.00	0.00	0.00	0.00	0.00
% Sand	20.00	69.66	58.20	50.56	42.92	31.46	20.00	70.70	59.00	51.20	43.40	31.70
% Silt+Clay	80.00	29.04	40.80	48.64	56.48	68.24	80.00	29.30	41.00	48.80	56.60	68.30
Liquid Limit %	55.00	22.00	33.00	37.00	42.00	48.00	55.00	23.00	33.00	36.00	41.00	50.00
Plastic Limit %	22.00	14.00	16.00	17.00	18.00	20.00	22.00	13.00	15.00	16.00	17.00	20.00
Plasticity Index,%	33.00	8.00	17.00	20.00	24.00	28.00	33.00	10.00	18.00	20.00	24.00	30.00
Indian Standard Classification-1498	CH	SC	SC	SC	CI	CI	CH	SC	SC	SC	CI	CI

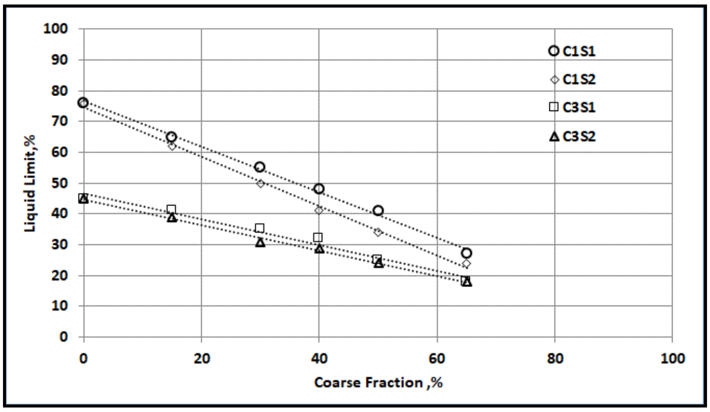

Fig. 8. Variation of liquid limit with percent coarse fraction

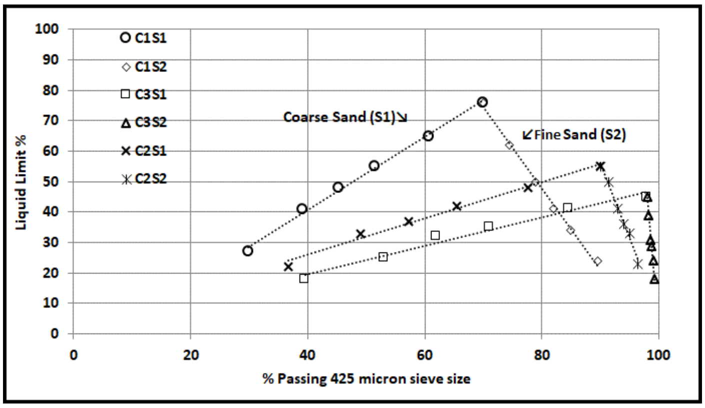

Fig. 9. Variation of liquid limit with percent passing 425µ

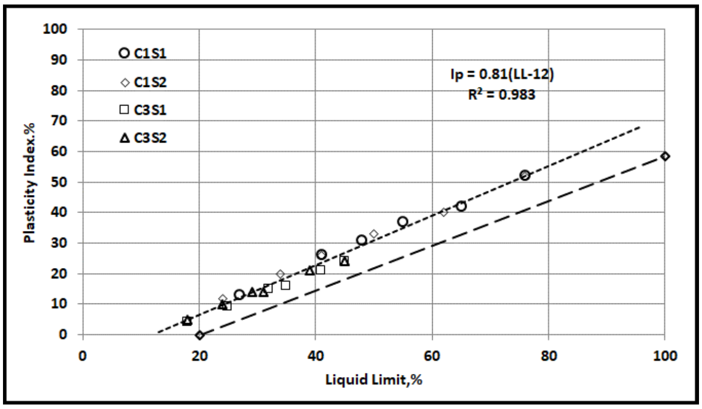

Fig. 10. Relationship between liquid limit with plasticity index (Clay-soil mixtures) in relation to A-Line

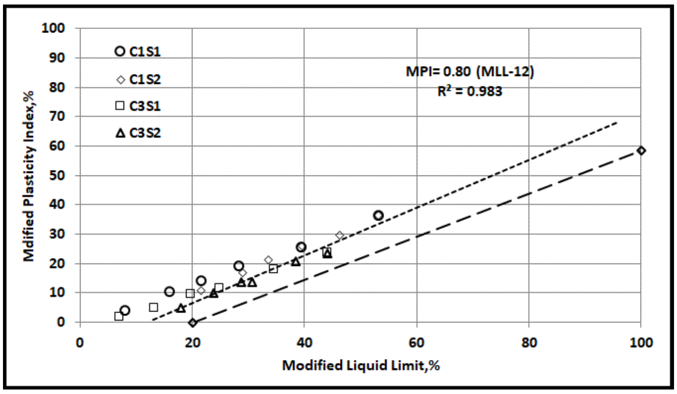

Fig. 11. Relationship between modified liquid limit with modified plasticity index (Clay-soil mixtures) in relation to A-Line

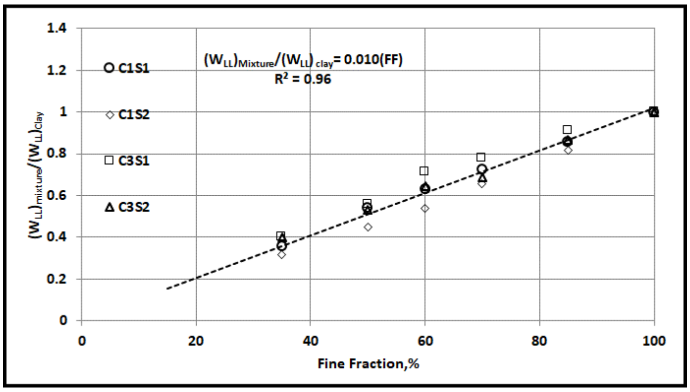

Fig. 12. Normalized liquid limit values of clay-sand mixtures with liquid limit of clay in relation to fine fraction

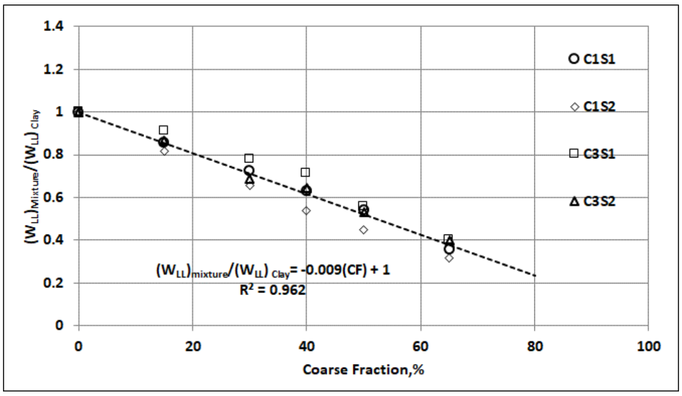

Fig. 13. Normalized liquid limit values of clay-sand mixtures with liquid limit of clay in relation to coarse fraction

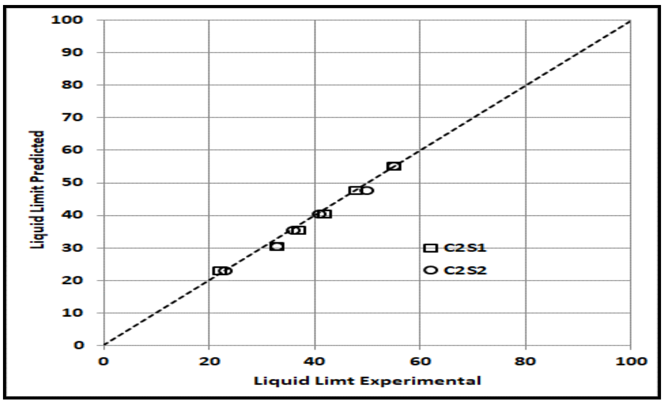

Fig. 14. Predicted values of liquid limit vis-a vis experimental values of liquid limit

IV. CONCLUDING REMARKS

Based on experimental investigation conducted on Clay-Sand mixtures the following concluding remarks may be made on basic properties

- A limited experimental program has been planned to understand the behavior of clay- sand mixtures to explore the possibility of suggesting methods for analysis and assessment of behavior natural soils found in this region for use by practicing engineers in order to bring out quantitatively the effect of fine fraction on liquid and plastic limits of soils.
- The soils selected represent wide spectrum of clays normally encountered in practice in terms of their liquid limit values ranging from 45-75%. The sand is selected from Swarnamukhi river basin is from a particular location to ensure uniform characteristics.
- It is observed that the original soil of clay with high compressibility (CH), the classification of soil changes to Clayey Sand (SC) in case of Clay 1 and Sand 1 upon addition of sand at 15%. The liquid limit is reduced from 76% to 27% with addition of sand which means 65% of reduction in liquid limit value. Similarly, the plasticity index is reduced from 52% to 13%, which turns out that there is a reduction of 75%. If the fine sand (S2) is used, the reduction in liquid limit is even more significant, owing to the fact that fine sand would have fine fraction passing 425 µ leading to reduction in liquid limit. It may be observed that for Sand 1, the fine fraction passing 425µ will reduce causing reduction in liquid limit whereas the reduction in liquid limit is associated with increase in fines in the case of fine sand. This observation is of immense practical importance in engineering application where in the liquid limit of soil available locally has to be reduced to meet the speciation as applied to the given situation.
- Addition of Fine Sand is suggested to reduce the liquid limit value instead of coarse sand.
- The quantity of sand to be used to arrive at specific value of liquid limit can be estimated based on the equations developed in order to get a preliminary estimate for use in a specified engineering application as per standard specifications.

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