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Correlation of Index Properties with Free Swell Index for Expansive Soil

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ABSTRACT
Expansive soils are fine-grained geomaterials that undergo significant volumetric changes in response to variations in moisture content. These soils are typically characterized by a dark coloration, high plasticity, and a predominant presence of the clay mineral montmorillonite, which governs their swelling–shrinkage behavior. Upon wetting, these soils exhibit an increase in volume accompanied by the development of substantial swelling pressure, which can induce distress and structural damage, particularly in lightly loaded or shallow foundations.

Therefore, in geotechnical design involving expansive subgrades, it is essential to quantitatively estimate both the magnitude of swell and the corresponding swell pressure to ensure structural stability and serviceability. Key parameters used to characterize swelling behavior include free swell index, swelling index, shrinkage limit, swelling potential and swelling pressure. Additionally, clay activity defined as the ratio of plasticity index to the percentage of clay-sized particles is widely employed as an indicator of expansiveness. The ability to predict swelling characteristics from readily measurable index properties would significantly enhance the efficiency of site characterization and enable informed decisions regarding soil suitability and the extent of ground improvement required. Extensive research has been conducted to establish empirical and semi-empirical correlations between swelling parameters and index properties, as well as the physical state of soils.

The present study focuses on the development of predictive models for swelling behavior of expansive soil based on their correlation with index properties such as liquid limit, plastic limit, plasticity index and physical properties including determination of grain size distribution, especially evaluation of clay fraction. Considering data set-1 experimental findings obtained from expansive soils tested at the Central Soil and Materials Research Station (CSMRS), New Delhi, have been utilized for model development. The validity and robustness of the proposed models are subsequently evaluated through independent variables using other data set-2 obtained from the same region but different location.

I. INTRODUCTION

Expansive soils are highly plastic, fine-grained materials that exhibit pronounced volumetric instability due to fluctuations in moisture content. These soils undergo swelling upon water ingress during wet seasons and shrinkage during dry periods due to moisture loss through evaporation. Such cyclic swelling–shrinkage behavior induces repeated volume changes, which can lead to degradation of soil structure, loss of bearing capacity and consequent distress or instability in overlying civil engineering structures.

Accurate identification and characterization of expansive soils are therefore essential for selecting appropriate ground improvement and mitigation measures capable of accommodating or minimizing future volumetric deformations. In the context of foundation engineering, reliable estimation of anticipated swell and associated heave is critical for safe and serviceable design. Although the oedometer test performed on undisturbed specimens is widely regarded as the standard and most reliable method for determining swelling pressure and swell characteristics, these parameters can also be estimated through correlations with other readily measurable soil properties.

The swelling and shrinkage behavior of expansive soils is primarily governed by their mineralogical composition, particularly the presence and proportion of active clay minerals such as montmorillonite. In addition, fundamental soil properties significantly influence this behavior; among these, plasticity characteristics play a dominant role in defining the soil response to moisture variation. Extensive research has been conducted globally to understand the swelling behavior of expansive soils, leading to the development of numerous empirical relationships that correlate swelling parameters with physical and index properties such as Atterberg limits, clay fraction, initial moisture content and in-situ density. Swelling characteristics are typically quantified using parameters such as swell potential and free swell index. In the present study, emphasis is placed on the free swell index and its correlation with key index properties—including clay-sized fraction, liquid limit, plastic limit and plasticity index—is systematically investigated.

II. OBJECTIVES

The objectives of the present study can be summarized as:

a. Laboratory testing of the selected soils for their index properties (Liquid limit, Plastic Limit, Platicity Index and physical properties (Percentage of clay size). The Free Swell Index Test is done for studying the swelling characteristics of the selected soil samples.
b. Development of predictive models by studying the statistical correlation between the swelling characteristics with selected index and physical properties respectively.
c. Validation study of the developed models using variables of other data set-2 obtained from the same region but different location.

III. MATERIALS AND METHODS

Expansive soils are predominantly fine-grained materials characterized by a high proportion of active clay minerals. Hence, for the present study fifteen numbers of representative clayey soil samples were selected for the purpose of laboratory investigations from southern part of India in the state of Andhra Pradesh. All soil samples were subjected to detailed laboratory testing to determine their index and physical properties in accordance with relevant Indian Standard (IS) codes. Grain size distribution analysis (IS 2720 Part 4) was performed to quantify the percentage of clay-sized particles. Atterberg limits tests (IS 2720 Part 5) were conducted to determine the liquid limit, plastic limit and plasticity index. The swelling characteristics of the soils were assessed by conducting the Free Swell Index (FSI) test in accordance with IS 2720 Part 40. The differential free swell index test procedure was adopted for this purpose. Oven-dried soil samples passing the 425 µm sieve were used and 10 g of each sample was placed into two separate 100 ml graduated cylinders. One cylinder was filled with distilled water and the other with kerosene oil to serve as a non-polar reference fluid. The suspensions were left undisturbed for a minimum duration of 24 hours to allow complete swelling. Subsequently, the final equilibrium volumes of the soil in both media were recorded.

The Free Swell Index (FSI) is then computed using the standard relationship, as expressed in Equation given below.

$$FSI = \frac{(V_d - V_k)}{V_k} \times 100$$

Where V_d is the volume of soil in distilled water
and V_k is the volume of soil in kerosene oil.

IV. RESULTS AND DISCUSSIONS

4.1 Laboratory test results

The main swelling parameter selected for the present study is the free swell index. It's correlation with each other selected soil properties; relevant to its expansive property are studied. The consensus of the different laboratory test results are shown in Table 1 below.

Table 1 Consensus of the Laboratory Test results

Characteristics (%)	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14	S-15
Liquid Limit	64.90	63.20	53.60	56.80	56.50	61.20	75.60	75.85	56.80	63.75	66.35	57.95	56.00	69.75	57.33
Plastic Limit	26.41	25.06	21.60	23.65	22.10	23.10	29.30	29.93	21.12	26.31	27.10	23.20	21.90	26.79	22.50
Plasticity Index	38.49	38.14	32.00	33.15	34.40	38.10	46.30	45.92	35.68	37.44	39.25	34.75	34.10	42.96	34.83
Percent Clay Size	45.50	40.70	30.70	35.30	31.10	34.30	51.40	54.20	37.40	42.00	41.67	34.00	35.20	43.12	33.50
Free Swell Index	68.30	65.30	56.00	62.00	58.90	63.00	74.90	77.50	61.00	66.70	67.00	58.60	58.96	69.45	59.32

4.2 Development of predictive models

The predictive models obtained for correlation of free swell index with liquid limit, plastic limit, plasticity index and percentage clay size are shown in Figures 1(a) to 1(d) respectively.

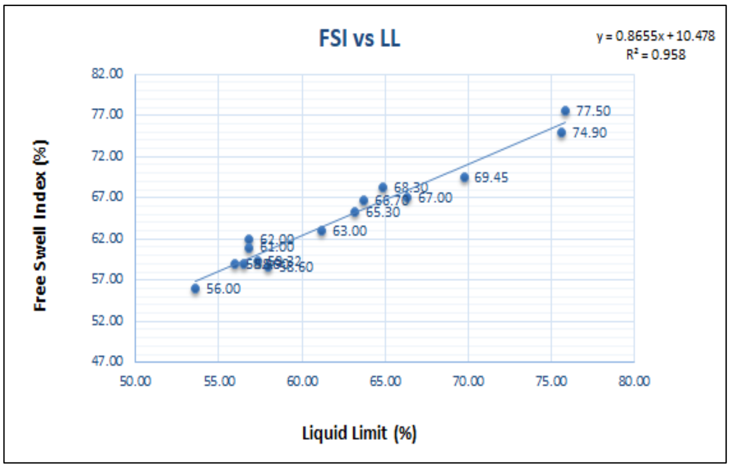

Fig. 1 (a)

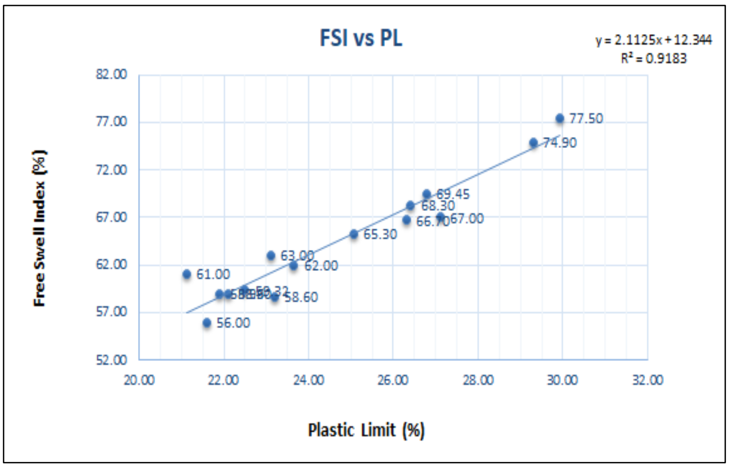

Fig. 1(b)

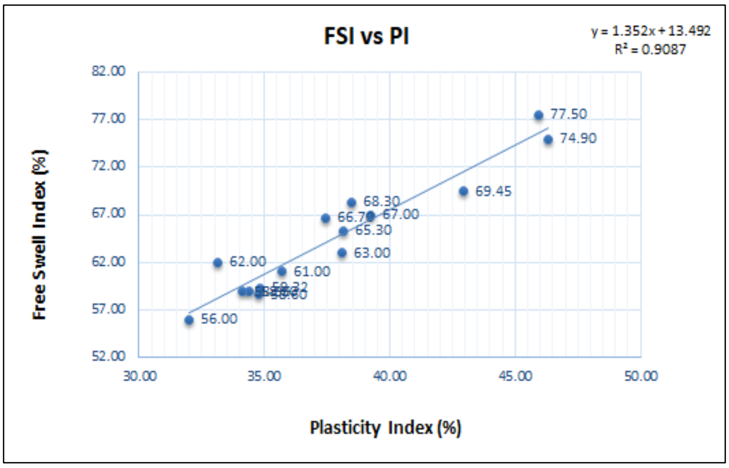

Fig. 1(c)

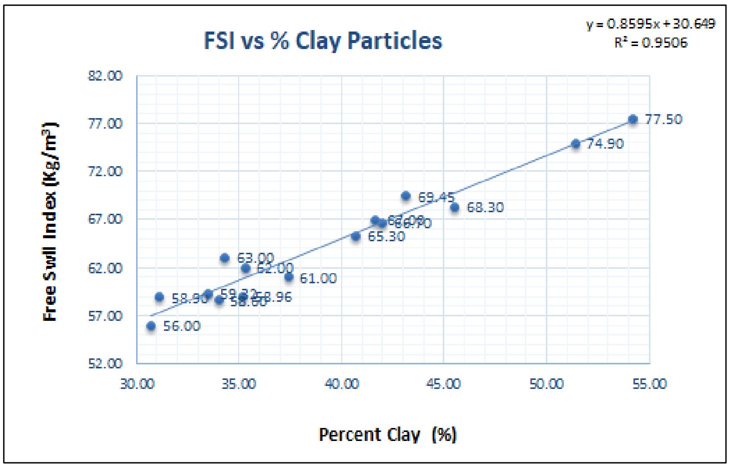

Fig. 1(d)

Fig 1(a), 1(b), 1(c) and 1(d). Predictive models developed for Free Swell Index; based on Liquid Limit, Plastic Limit, Plasticity Index and Percentage clay particles respectively.

All the models developed using data set-1, showing good values of R^2, ranging from 0.9580 to 0.9087. The developed equations are given below in equations 1 to 4.

Equation obtained for prediction of Free Swell Index (FSI) with the Liquid Limit (LL) with R^2 value of 0.9580:

- *FSI = 0.8655 LL + 10.478* [1]

Equation obtained for prediction of Free Swell Index (FSI) with the Plastic Limit (PL) with R^2 value of 0.9183:

- *FSI = 2.1125 PL + 12.344* [2]

Equation obtained for prediction of Free Swell Index (FSI) with the Plasticity Index (PI) with R^2 value of 0.9087:

- *FSI = 1.352 PI + 13.492* [3]

Equation obtained for prediction of Free Swell Index (FSI) with the Percentage Clay Particles with R^2 value of 0.9506:

- *FSI = 0.8595 (% Clay size) + 30.649* [4]

4.3 MODEL VALIDATION STUDY

For validating the developed predicted models, another five numbers of similar type of expansive soil were taken as a data set-2 from the same area but different borrow area locations. The collected soil samples were further subjected to detailed laboratory investigations to determine their index and physical properties in accordance with relevant Indian Standard (IS) codes. Grain size distribution analysis (IS 2720 Part 4) was performed to quantify the percentage of clay-sized particles. Atterberg limits tests (IS 2720 Part 5) were conducted to determine the liquid limit, plastic limit and plasticity index. The swelling characteristics of the soils were assessed by conducting the Free Swell Index (FSI) test in accordance with IS 2720 Part 40.

The linear equations developed based on observed values of first set of 15 nos. of tested soil samples are utilized for calculation of predictive values of swelling parameters for another 5 numbers of similar type of expansive soil. The predictive swelling values of the second set of soil samples were obtained with respect of physical properties such as LL, PL, PI and percent clay particles. The data for validation of model is presented in table-2. The correlation between the actual observed values of second set of five numbers of soil samples and its calculated predicted values are given with the obtained R^2 values in Fig.2 (a) to 2 (d) respectively.

Table 2: Consensus of the Data for Validation

S. No.	Lab Sample No.	LL (%)	PL (%)	PI (%)	% Clay Size	Actual FSI (%)	L.L. Based Predicted FSI value	P.L. Based Predicted FSI value	P.I. Based Predicted FSI value	% of Clay Based Predicted FSI value
1	Sample-21	56.60	25.28	31.32	38.50	57.85	59.47	65.75	55.84	63.74
2	Sample-22	67.30	28.00	39.30	43.30	67.75	68.73	71.49	66.63	67.87
3	Sample-23	67.05	29.94	37.11	44.14	68.85	68.51	75.59	63.66	68.59
4	Sample-24	72.50	31.50	41.00	47.19	73.54	73.23	78.89	68.92	71.21
5	Sample-25	72.40	30.54	41.86	45.30	72.56	73.14	76.86	70.09	69.58

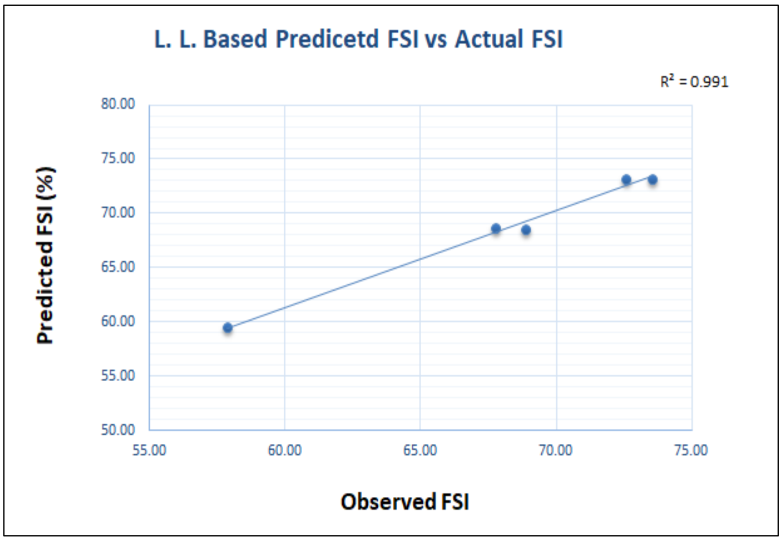

Fig. 2 (a)

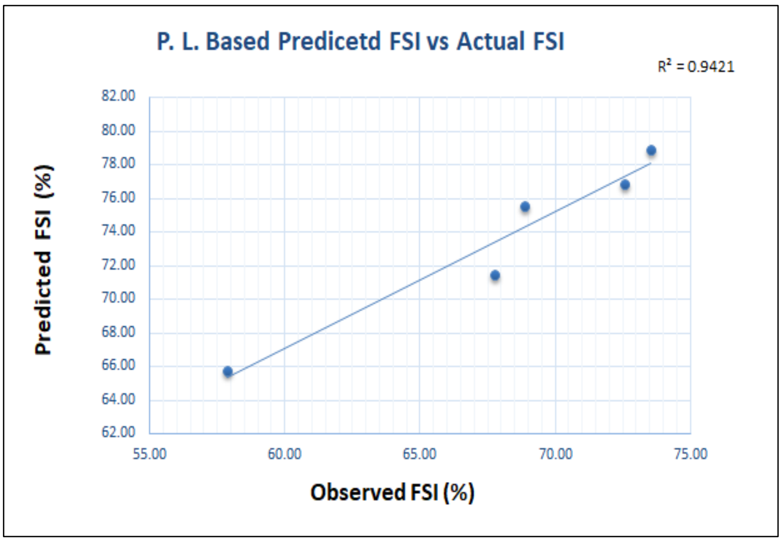

Fig. 2(b)

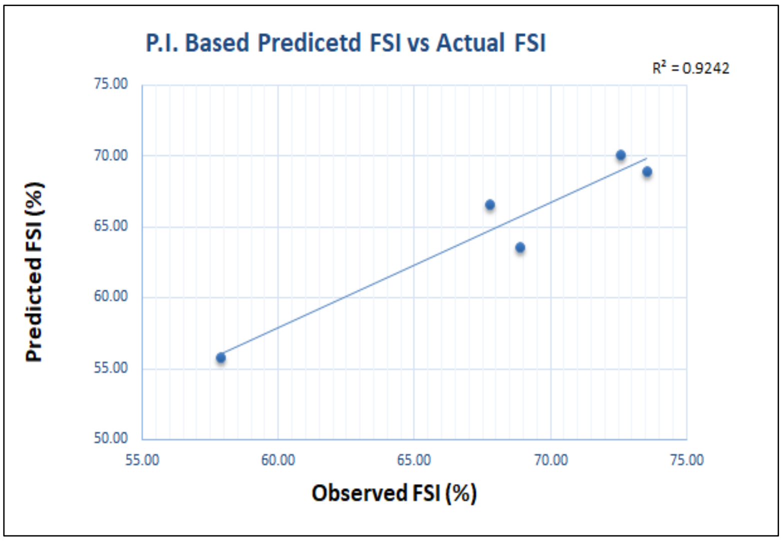

Fig. 2(c)

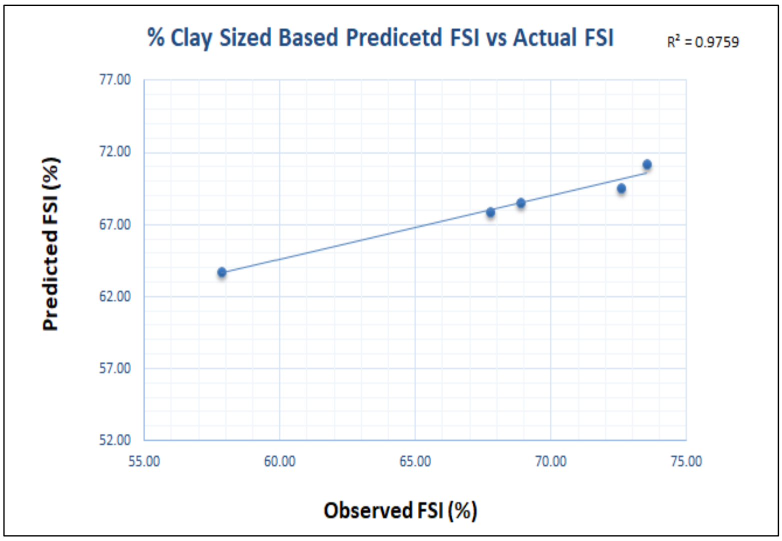

Fig. 2 (d)

Fig 2(a), 2(b), 2(c) and 2(d). Predictive models obtained for Free Swell Index; based on Liquid Limit, Plastic Limit, Plasticity Index and Percentage clay particles respectively.

From the validation study, the results obtained for the first set of data as shown in figure-1(a), 1(b), 1(c) and 1(d). It can be observed that the maximum R^2 value of 0.9580 is obtained for the Liquid Limit based model with respect to observed Free Swell Index Value. The other correlation graphs showed a varying tendency of R^2 values ranging from 0.9087 to 0.9506.

The results of predicted FSI value in the validation study using the second set of data are shown in graphical form from Fig. 2(a) to 2(d). The obtained correlation prominent between the predicted value and observed values for the models developed based on Liquid Limit (with R^2 value 0.9910) and percentage of clay particles (with R^2 value 0.9759), based on Plastic Limit (with R^2 value 0.9421), based on Plasticity Index (with R^2 value 0.9242).

The consensus of the validation study is shown in Table-3 below, with the R^2 values obtained for the second set of 5 numbers of similar types of soil samples from the same region.

Table 3: Consensus of the Validation Study

Details	Values of R^2 Obtained from Data Set-2 Samples
Models based on Liquid Limit	0.9910
Models based on Plastic Limit	0.9421
Models based on Plasticity Index	0.9242
Models based on % of Clay Particles	0.9759

On comparison of the two different sets of data with validation studies, it can be inferred for data set-1, the Liquid Limit and percentage of clay particles based model gave maximum accuracy with R^2 value 0.9580 and 0.9506, while Plastic limit and Plasticity Index Based Model gave R^2 value 0.9183 and 0.9087 respectively.

On the other hand, for data set-2; it was observed that the Liquid Limit and percentage of clay particles based predicted FSI model gave maximum R^2 value 0.9910 and 0.9759, while plastic limit and plasticity index based model gave R^2 value 0.9421 and 0.9242 respectively.

However, in correlation-based analyses of developed empirical models, the predictive accuracy is significantly influenced by the range and variability of the dataset used during model formulation. Consequently, the applicability of a given set of equations is largely confined to the specific dataset from which it is derived, ensuring optimal performance within that domain. Nevertheless, such models may still provide generalized insights into the swelling behavior of the selected soil types and the governing parameters affecting it.

V. CONCLUSION

According to present study, the following major conclusions are arrived:
Based on laboratory testing of fifteen selected expansive soil samples, predictive models were successfully developed to estimate the Free Swell Index (FSI) using four independent variables, namely Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI) and Percentage Clay Fraction. The developed models exhibited satisfactory coefficients of determination (R^2), indicating good predictive performance. The corresponding empirical relationships are presented as follows:

- $FSI = 0.8655\ LL + 10.478$ (with R^2=0.9580)
- $FSI = 2.1125\ PL + 12.344$ (with R^2= 0.9183)
- $FSI = 1.352\ PI + 13.492$ (with R^2= 0.9087)
- $FSI = 0.8595$ (% Clay size) + 30.649 (with R^2= 0.9506)

The validation study for the developed model when conducted with another set of data with 5 numbers of different soil samples.

- The data set-2 for another 5 numbers of soil samples selected from the same region showed that maximum accuracy for the predicted values of FSI. The FSI value predicted based on actual observed values of data set-2 gave prominent result with R^2 value=0.9910 for Liquid Limit based FSI model, R^2 value=0.9421 for Plastic Limit based FSI model, R^2 value=0.9242 for Plasticity Index based FSI model and R^2 value=0.9759 for % clay based FSI model.
- A primary limitation of empirical modelling lies in its strong dependence on the size, range and representativeness of the dataset used for model development. Consequently, the generalizability of such models to other datasets or field conditions may be restricted. However, validation against independent datasets, yielding satisfactory coefficients of determination (R^2), enhances the reliability and confidence in applying the developed equations to different but comparable domains.

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