CHARACTERISATION OF EXPANSIVE SOILS AND USE IN DESIGN

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ABSTRACT: This paper is concerned with the study of swelling behaviour and strength characteristics of expansive soils in order to develop new design charts. Expansive soil samples with high plasticity have been compacted at a wide range of water content and different dry densities. A new characterisation concept was developed. This is called the soil state factor which was developed for the initial and soaking state. The initial state factor is a combination of the dry density, water content and void ratio while the soaking state factor is a combination of the saturated dry density, saturated water content and amount of swelling during the soaking period. On basis of this concept, characterisation charts for swelling and initial state behaviour as well as strength and initial state behaviour were developed. The use of these charts in pavement design, evaluation and field compaction control on expansive soil areas is demonstrated.

1. INTRODUCTION

In road construction, specifications and standards normally do not permit expansive soils to be used in embankments or fill below formation level; moreover excavation below the embankment of expansive soil and replacing it by better quality materials may also be required. This is because of the large volume changes that can occur as a result of wetting and drying with seasonal changes of climate. Few roads constructed through these areas have proved satisfactory, but the majority especially in Africa and Southern Asia has failed completely.

In Sudan black cotton soils cover a wide strip along the river Nile and its tributaries, where most of the main economical and agricultural schemes and production factories are located. Most of our major highways are constructed on black cotton clays. These major engineering structures consequently suffer from series distresses and damages. According to records, the annual estimated economical losses caused by expansive soils exceed a million dollar.

When considering expansive soils as road subgrade, one of the main concerns of the design engineer should be concentrated on the swelling behaviour and strength of this soil as main factors of design. Thus, the main objective of this paper is to study the swelling behaviour and strength characteristics of this soil so as to improve the current design and construction standards used.

2. EXPERIMENTAL WORK

The laboratory tests were carried out to investigate the swelling behaviour and strength of expansive soil samples prepared at a wide range of water content an compacted to different dry densities and subjected to different testing conditions. These samples were then used to perform soil tests such as swelling , CBR and undrained triaxial tests. The measurements from these tests were able to give a useful

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indication of the relationship between the combination of the soil initial state parameters (water content, dry density and void ratio) and the measured swell percent, swelling pressure, CBR and shear strength. The soaking state parameters (saturated water content, saturated dry density and amount of swelling) and the measured soaked CBR were also illustrated.

3. RESULTS AND DISCUSSION

The tests results and the data reported by the previous researchers as indicated in Figures 3.1 to 3.11 show that the swelling of this soil is influenced by the surcharge pressure imposed on the soil as well as the initial state of the soil as described by the dry density, water content and void ratio. On the other hand, the CBR and shear strength of this soil is greatly influenced by the initial dry density, water content and void ratio of the soil as well as the testing conditions.

3.1 The Initial State Factor

Analysis of the experimental results indicated that it is possible to combine the initial state parameters such as dry density, water content and void ratio in a way reflecting the influence of each of them on the swell percent, swelling pressure, unsoaked CBR and shear strength. Therefore a new concept was developed; this is called the initial state factor.

$$Fi = \frac{\rho_d}{\rho_W} \cdot \frac{1}{\omega . e} \qquad (3.1)$$

Where:

F_i is the initial state factor

ρ_d is the initial dry density of soil

ρ_ω is the density of water

ω is the initial water content

e is the initial void ratio.

The initial state factor was empirically formulated on basis of the following reasons:

- The results of swell percent data and those reported by Chen [5] and Kassif et al [8] and shown in Figures 3.1 and 3.2 clearly indicate that a linear relationship can be drawn between the swell percent (or volume change) and the initial dry density of the samples of the same soil, having the same moisture content and subjected to the same surcharge pressure. Hence, the swell percent (S) can be assumed to be directly proportional to the dry density (ρ_d) i.e.

$$S \infty \frac{1}{\omega} \; ; \; \omega \text{ is constant} \qquad (3.2)$$

- The experimental results and the data reported by Chen [5] as indicated in Figure 3.3 suggest that an inverse linear relationship exists between the swell percent and the moisture content of the samples of the same soil, having the same dry density and subjected to the same surcharge pressure. Hence, it can be assumed that the swell percent (S) is inversely proportional to the initial moisture content (ω) i.e.

$$S \, \alpha \frac{1}{\omega} \; ; \; \rho \text{d is constant} \qquad (3.3)$$

- An inverse linear relationship exists between the swell percent and the void ratio of the samples of the same moisture content as in Figure 3.4.

So it can be assumed that the swell percent (S) is inversely proportional to the void ratio (e) i.e.

Hence from the above equations and

$$S \alpha \frac{1}{e}; \omega \text{ is constant} \quad (3.4)$$

$$S \alpha \frac{\rho_d}{\rho_\omega} \cdot \frac{1}{\omega\, e} \quad (3.5)$$

$$S \alpha F_1 \quad (3.6)$$

using $\frac{\rho_d}{\rho_\omega}$ instead of ρ_d to make the

term dimensionless results in:

From the above equation it can be concluded that the swell percent (S) is directly proportional to the initial state factor (F_i). This relationship can be expressed as:

3.2 The Soaking State Factor

It was found that saturation due to soaking has great influence on the soaked CBR values of expansive soils. Therefore the factor in the soaking state is formed by a combination of the saturated dry density, saturated water content and the amount of swelling due to soaking. This factor is termed the soaking state factor.

$$F_s = \frac{\rho_{d_{sat.}}}{\rho_\omega} \cdot \frac{1}{\omega_{sat}(1+S)} \quad (3.7)$$

Where: $\rho_{d_{sat}}$ is the saturated dry density

ω_{sat} is the saturated water content

ρ_ω is the density of water

S is the amount of swelling during the soaking period.

The soaking state factor F_s was developed on basis of the following reasons:

- ♦ The data of Bissada and Yoder [18] as shown in Figures 3.5 and 3.6 indicate that the soaked CBR values decrease with increasing in the saturated water content values (i.e. the water content values at wet of optimum side) of samples having the same saturated dry density. hence, it can be assumed that the soaked CBR is inversely proportional to the saturated water content (ω_{sat}) i.e.

$$\text{Soaked CBR } \alpha \frac{1}{\omega_{sat}}; \rho d_{sat} \text{ is constant} \quad (3.8)$$

- ♦ Based on the data reported by Yoder [18] as indicated in Figure 3.6, it can be suggested that a linear relationship may exist between the soaked CBR and the saturated dry density of the samples having the same saturated water content. thus, the soaked CBR can be assumed to have a direct proportional relationship with the saturated dry density ($\rho_{d_{sat}}$)i.e.

$$\text{Soaked CBR} \propto \rho_{d_{sat}}; \omega_{sat} \text{is constant} \quad (3.9)$$

- ♦ As reported by Yoder [18] and shown in Figure 3.6. It can be seen that increasing in the amount of swelling of expansive soils during the soaking period reduces the soaked CBR value. Whereas in granular soils swelling has no influence on the soaked CBR values during the soaking period. Hence, for different types of soil, it can be assumed that the soaked CBR is inversely proportional to the amount of Swelling (S)(as a fraction of one) as given by the term (1+S) and expressed thus:

$$\text{Soaked CBR } \alpha \frac{1}{1+S} \qquad (3.10)$$

Hence from the above relationships and using $\frac{\rho_{d\,sat}}{\rho_\omega}$ instead of $\rho_{d\,sat}$ to make the term dimensionless results in:

$$Soaked\ \ CBR \propto \frac{\rho_{d_{sat}}}{\rho_\omega} \cdot \frac{1}{\omega_{sat}(1+S)} \qquad (3.11)$$

From the above equation it can be suggested that the soaked CBR is directly proportional to the soaking state factor (F_s). This relationship can be expressed thus:

$$Soaked\ \ CBR \propto F_s \qquad (3.12)$$

3.3 The linear relationship of thefactor

The results of analysis as indicated by Figures 3.7 ~ 3.11 proved that this factor has a very good linear relationship with swell percent, swelling pressure, CBR and shear strength. This linear relationship for the swell percent and soaked CBR as examples can be expressed as follows:

$$S = M * (F_i - F_0) \qquad (3.13)$$

Where:

S is the swell percent

F_i is the initial state factor

F_0 is the value of F_i at which no swelling occurs

M is the gradient of the straight line.

$$Soaked\ \ CBR = M * (F_s - F_0) \qquad (3.14)$$

Where: F_s is the soaking state factor

4. CHARACTERISATION OF SWELLING AND STRENGTH

The linear relationship exists between swell percent, swelling pressure, CBR or shear strength and soil state factor (F_i or F_s) (as described in section 3) can be of great use in the characterisation of the swelling and strength variation with water content and dry density of a given expansive soil.

4.1 Iso-swelling lines

The isolines for the swelling and initial state behaviour of a given soil can be produced by a direct method. A limited number of swell percent tests (three to five) at a certain surcharge pressure, and swelling pressure tests can be performed, then the values of F_o and M can be determined. By using these values and linear equations for the swell percent and swelling pressure similar to equation 3.13, and by selecting various values of F_i (F_{i1}, F_{i2}, F_{i3}, ………., F_{in}), lines of swell percent and swelling pressure can be produced. Then a plot of swelling relationship with initial state variation can simply be drawn as shown by Figures 4.1 and 4.2. The data points in these figures are the measured initial state of the samples. The measured swell percent and swelling pressure values of the samples are given alongside. The comparison of the measured and calculated swell percent and swelling pressure values in these figures clearly demonstrates the validity of the iso-swelling lines concept.

4.2 Iso-CBR and Iso-Shear Strength Lines

The isolines for the CBR (soaked and unsoaked) and shear strength variation with the soil state factors (F_i and F_s) for a given soil can be produced using a similar procedure described above in Section 4.1. The relation between F_i and F_s can be expressed by the following equation.

$$F_S = \left[\frac{(G_S + e)}{(1 + 0.01S)} * \frac{\omega}{(100 + \omega)} \right] F_i \quad (4.1)$$

Where:

F_s is the soaking state factor

F_i is the initial state factor

S is the swell percent during soaking

G_s is the specific gravity

ω is the initial water content(%)

e is the initial void ratio.

Charts to show the relationship of CBR and shear strength characterisation lines with water content and dry density variations are plotted in Figures 4.3 and 4.4, repectively. When comparing the calculated CBR and shear strength values that indicated on the isolines and the measured values located alongside the data points, their values seem to be equal. This result verifies the validity of the iso-CBR and iso-shear lines produced.

5. DEVELOPMENT OF EMPIRICAL CHART

An important feature of the type of characterisation lines approach developed in the previous section is the possibility that the data regarding swelling behaviour (i.e. swell percent and swelling pressure) and soil strength (i.e. CBR and shear strength) of expansive soils can be superimposed in one characterisation line. Thus characterisation lines (isolines) of CBR, shear strength, swelling pressure and swell percent at different surcharge pressures (P_1, P_2, P_3, etc.) - Initial state (water content and dry density) behaviour of a given expansive soil could be produced. By using the procedure described in Section 4 and selecting different values of F_i and calculating the corresponding F_s values using equation 4.1, characterisation lines indicate swell percent, swelling pressure, CBR (as soaked or unsoaked) and shear strength values can be produced. Then a chart of characterisation lines indicating swelling and strength relationship with soil initial water content and dry density variations can be plotted.

The experimental results were analysed and used to demonstrate the validity of the developed chart. The result of analysis was plotted in Figure 5.1. The comparison of the measured and calculated values in this figure clearly demonstrates the validity of the chart produced.

6. UTILIZATION OF THE DEVELOPED EMPIRICAL CHART

As the aim of this paper was to improve the current specifications used in design and construction of roads on expansive soils, the empirical chart developed can be of great use in the following areas: pavement design, evaluation and field compaction control as detailed below. The methods suggested take care of both the swelling behaviour and strength characteristics of expansive soils as road subgrade.

6.1 Pavement Design

The pavement design method developed will be described in the following design steps:-

1) The road should be divided into sections, for each section take soil samples to measure the CBR and the swell percent at a surcharge pressure equivalent to an anticipated overburden pressure (i.e. the pressure exerted by the pavement layers above the subgrade). Then the empirical design chart could be produced as described in Section 5.

2) The permissible swell percent as specified by the Highway Authorities 1% to 2% depending on the class of the road is determined.

3) From the empirical chart the design CBR is determined. The design CBR should be the CBR at an initial state around which the swell percent is 50% less than the permissible swell percent.

6.2 Evaluation of Pavement

In evaluation of embankment and subgrade material to check the performance and the strength of the road. The method suggested here as outlined below:-

1) The road is divided into different sections depending on expansive soil properties.

2) Three soil samples are taken from each section to measure swelling, shear and CBR

3) Characterisation lines chart is performed as described in Section 5.

4) The field density and moisture content along each section are measured.

5) The density and moisture content data obtained in step (4) are used to determine the swelling, shear strength and CBR from the chart.

6) Comparing the determined values of the swelling and strength with the design values then sections with excessive swelling and low strength will be excluded out.

6.3 Compaction Control in the Field

This method is used for the material quality control of compacted embankment and subgrade. A new method is briefly described below: -

1) Three soil samples are taken from the field to the laboratory to determine the compaction characteristics such as optimum moisture content and maximum dry density and to measure the swelling and strength of the soil samples.

2) A chart of the dry density versus moisture content showing the characterisation lines of both the swelling and strength is formed as described in Section 5.

3) After field compaction of embankment and/or subgrade, the field density and moisture content of the material are measured.

4) A point is drawn in the chart developed in step (2) to indicate the measured field density and moisture content.

5) The point indicated in the developed chart in the above step (4), if it is located within the range of design strength and permissible swelling then the compaction

is to be accepted otherwise will be rejected.

7. CONCLUSIONS

1. It has been demonstrated that the swelling behaviour of expansive soil compacted over a wide range of water content and different dry densities depends on: the soil initial state (water content, dry density and void ratio) and applied surcharge pressure.

2. A study of the strength by the CBR and shear strength measurements of compacted expansive soil at different water contents and dry densities was conducted. It was found that the soil initial state and testing conditions greatly influenced the unsoaked CBR and shear strength. The results of the soaked (saturated) soil samples suggested that the soil soaking state (saturated moisture content, saturated dry density and amount of swelling during the soaking period) greatly influenced the soaked CBR value.

3. Initial water content, dry density and void ratio were combined in a way - reflecting the influence of each of them on swell percent, swelling pressure, unsoaked CBR and shear strength. This combination was termed the initial state Factor (F_i). On the other hand the combination of the saturated water content, saturated dry density and amount of swelling during the soaking period was termed the soaking state Factor (F_s).

4. It has been proved that a direct linear relationship between swell percent, swelling pressure, unsoaked CBR or shear strength and the initial state Factor (F_i). Similarly the relationship between soaked CBR and the soaking state Factor (F_s) was verified to be linear relationship as well. Based on this relationship, design chart of swelling and strength variations with initial water content and dry density were developed. This chart can be applied in design and evaluation of pavement as well as in compaction control in the field.

8. REFERENCES

1. AASHTO (1986) Standard Specifications for Transportation Materials and Methods of Sampling and Testing: Part II. Methods of Sampling and Testing (14th ed.). American Association of State Highway and Transportation Officials, Washington.

2. Barden, L., Madedor, A. O., and Sides, G. R. (1969): Volume change characteristics of unsaturated clay. Soil Mech. Found. Div. ASCE 95.

3. Bishop, A. W., and Henkel, D. J. (1962): The Measurements of Soil Properties in the Triaxial Test, 2nd ed. Edward Arnold, London.

4. British Standards Institution (1990) BS 1377: Methods of Test for Soils for Civil Engineering Purposes. BSI, London.

5. Chen, F. H. (1975): Foundations on Expansive Soils. American Elsevier Science Publ., New York.

6. Holtz, W. G. and Gibbs, H. J. (1956): Engineering properties of expansive clays. Trans. ASCE, Vol.121.

7. Holtz, W. G. (1959): Expansive soils, properties and problems. Quart. Colorado School of Mines, Vol. 54, No. 4.

8. Kassif, G., Komornik, A., Wiseman, G. and Zeitlen, J. G. (1965): Studies and design criteria for structures on expansive clays. Proc. 1st Res. Conf. on Exp. Soils, Texas.

9. Kassif, G., Livneh M., and Wiseman G. (1969): Pavements on expansive clays. Jerusalem Academic Press, Jerusalem , Israel.

10. El-Tayeb, M. M. (1991): Characterisation of expansive soils as road subgrade. M.Sc. thesis, Building and Road Research Institute, University of Khartoum.

11. McDonald, E. B., and Potter, A. W. (1973): Review of highway design and construction through expansive soils in South Dakota on I-95 – Missouri River West – 135 miles. Proc. Workshop Expansive Clays and Shales in Highway Design and Construction. Univ. of Wyoming. Laramie.

12. McKeen, R. G. (1977): Pavement design for swelling soils: A review. Proc. 14th Pavement Conf. University of New Mexico.

13. McKeen, R. G. and Hamberg, D. J. (1981): Characterisation of expansive soils. Trans. Res. Fc. 790, Trans. Res. Board 73 – 78.

14. Mohamed, A. E .M. (1986): Microstructure and swelling characteristics of an untreated and lime-treated compacted black cotton soil. Ph.D thesis. University of Strathclyde, Glasgow.

15. Murphy, C. P. (1966): Problems of road design and construction on the clay soils of the Fitzroy Basin. Australian Road Research Board Proc. Vol. 3 No. 2.

16. Nelson, J. D., and Miller, D. J. (1991): Expansive soils, problems and practice in foundation and pavement engineering. Colorado State University. John Wiley and Sons, New York

17. O’Connor, K. (1994). Swelling behaviour of unsaturated fine-grained soils. Ph.D. thesis, City Univ., London.

18. Yoder, E. J. and Witezak, M. W. (1975). Principles of Pavement Design. 2nd edition. John Wiley, New York.

19. Zein, A. K. M. (1985): Swelling characteristics and microfabric of compacted black cotton soils. Ph.D thesis. University of Strathclyde, Glasgow.

20. Zumrawi, M. M. E. (2000). Performance and design of expansive soils as road subgrade. Ph.D. thesis, Chang’an Univ., China.

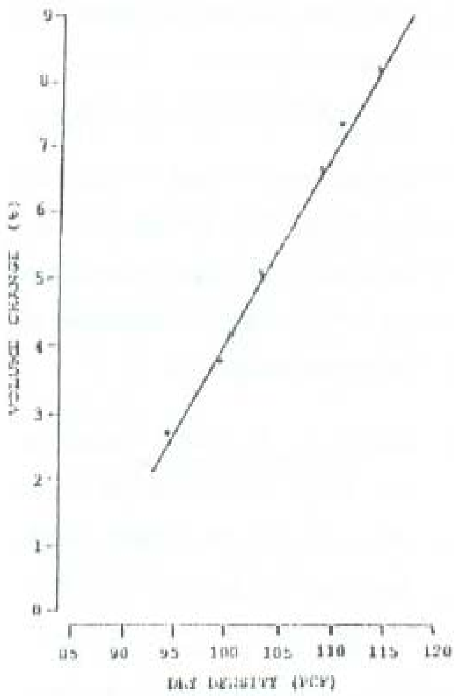

Figure 3.1 The relationship between volume change and initial dry density of expansive soil samples compacted at constant moisture content (after Chen, 1975)

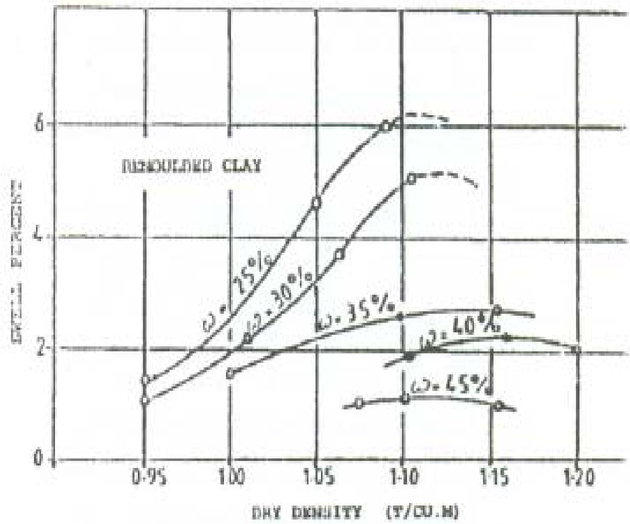

Figure 3.2 Swell percent versus dry density of samples compacted at different moisture content values (after Kassif et al, 1965).

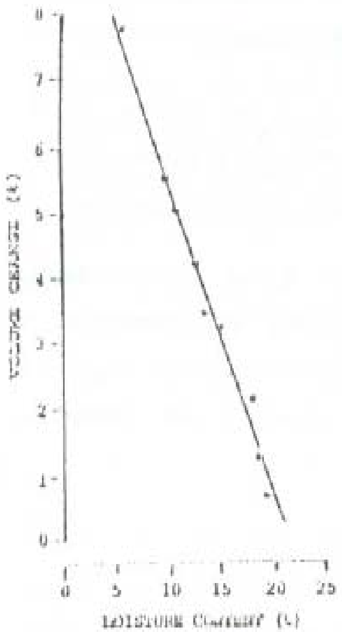

Figure 3.3 Volume change versus moisture content for samples compacted at const. dry density (after Chen, 1975).

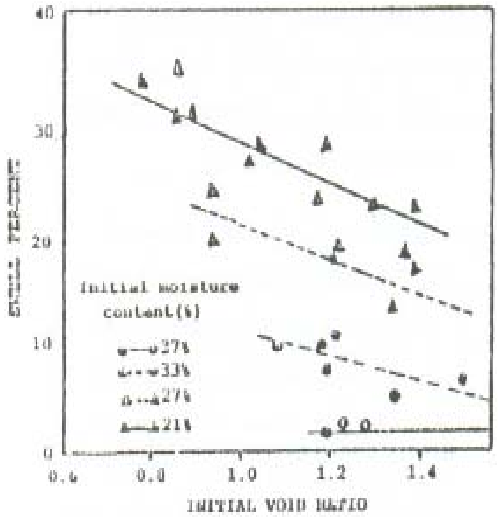

Figure 3.4 Variation of swell percent with vo ratio of samples having equal mois content values (after Brackley, 197

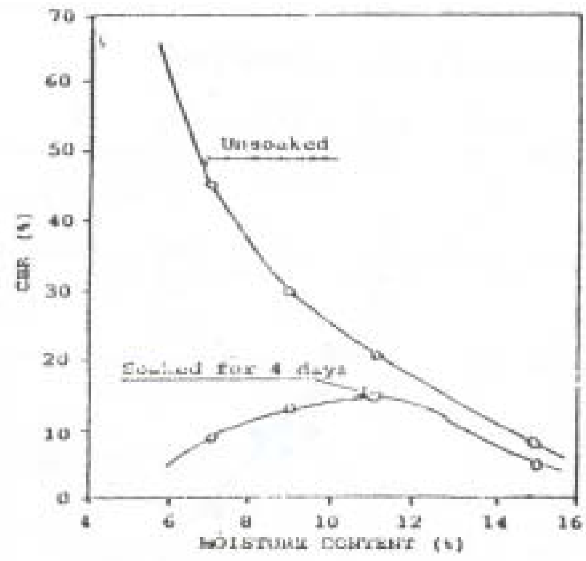

Figure 3.5 Comparison between soaked CBR and unsoaked CBR of a typical sand soil for varying moisture content values (after Bissada, 1970).

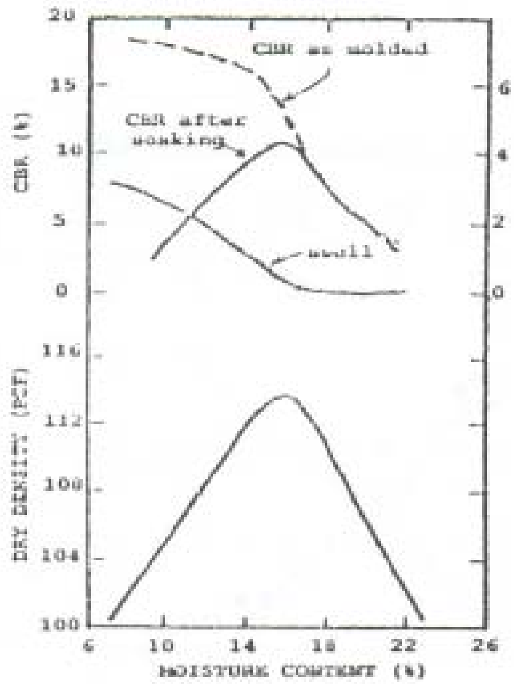

Figure 3.6 Variation of CBR moisture content for silty clay soils (after Yodar, 1975).

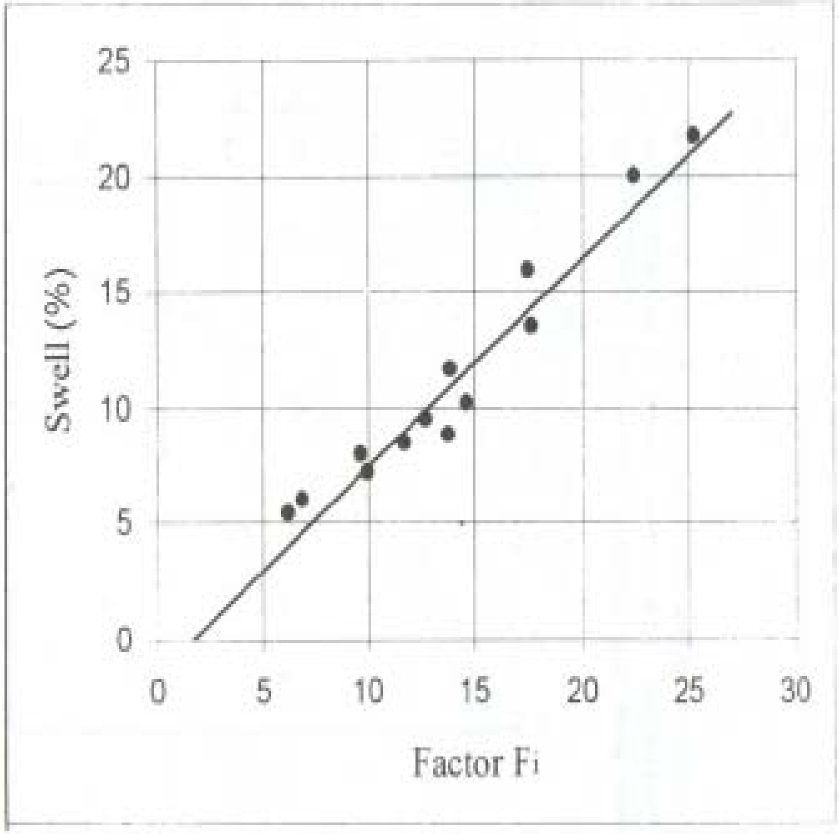

Figure 3.7: Swell percent versus factor F_i relationship for the data analysed of the present study samples tested at a surcharge pressure of 7 kPa.

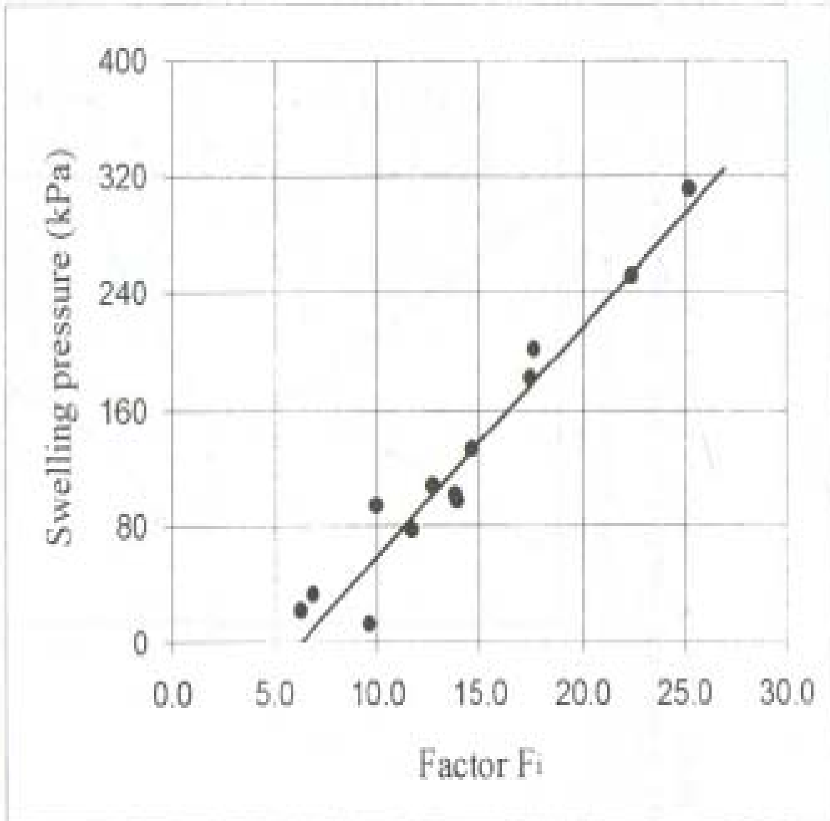

Figure 3.8: Swelling pressure and factor F_i relationship for the data analysed of the present study samples.

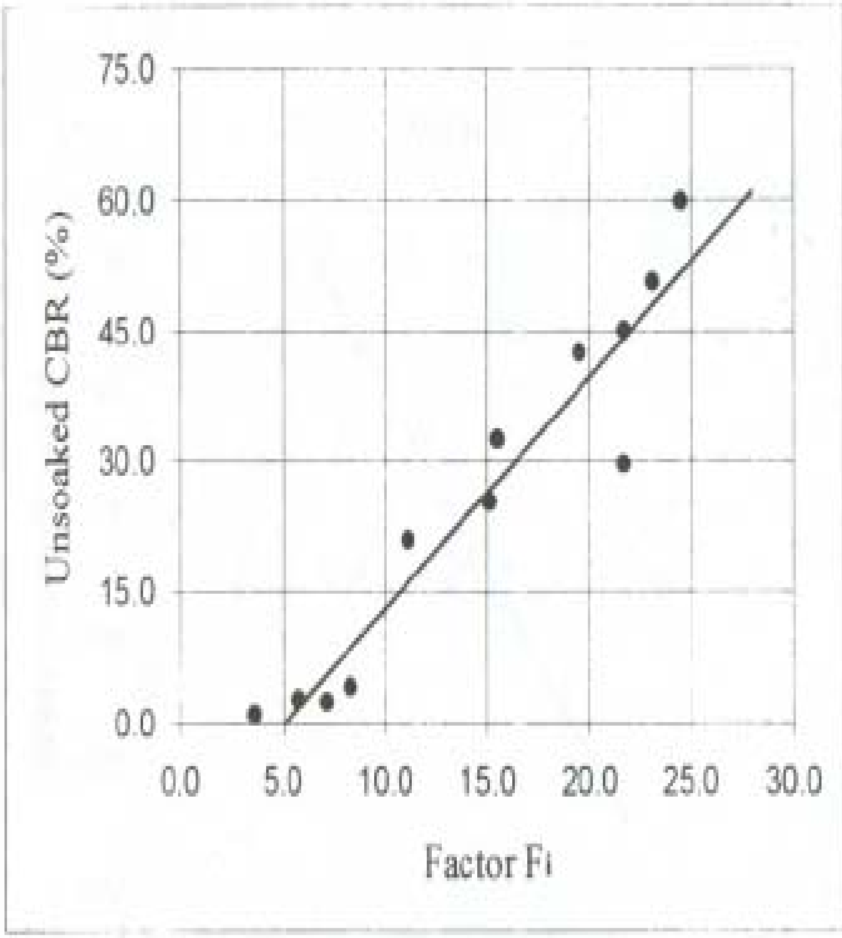

Figure 3.9: Unsoaked CBR versus factor F_i relationship for the data analysed of the present study samples.

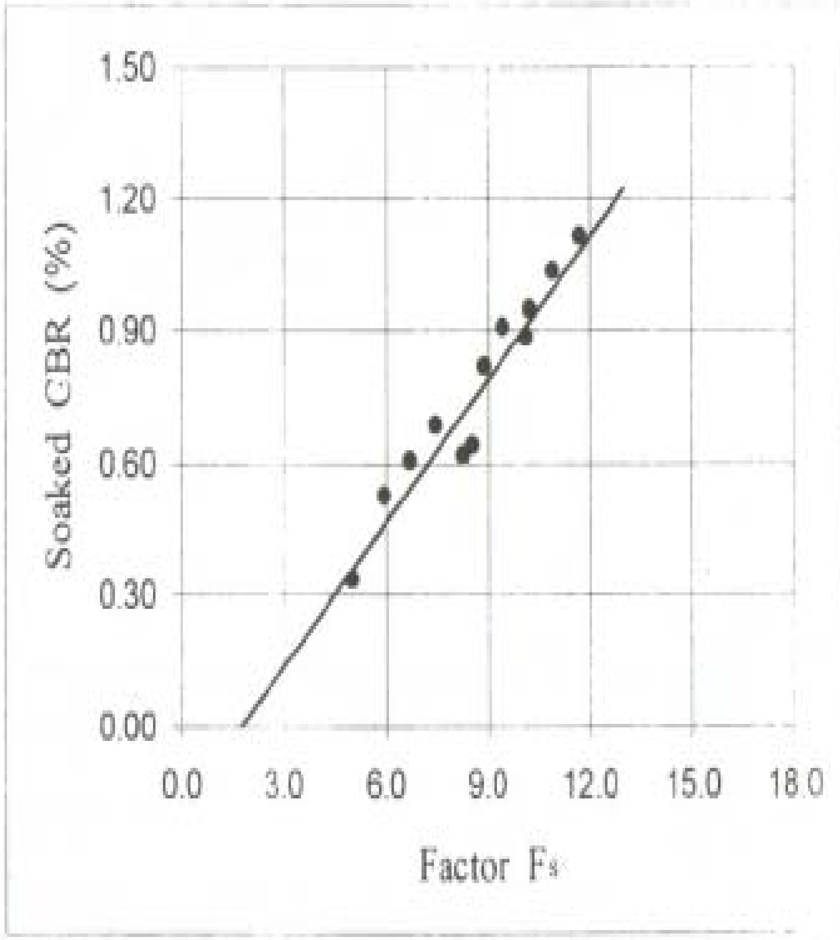

Figure 3.10: Soaked CBR versus factor F Relationship for the data analysed of the present study samples.

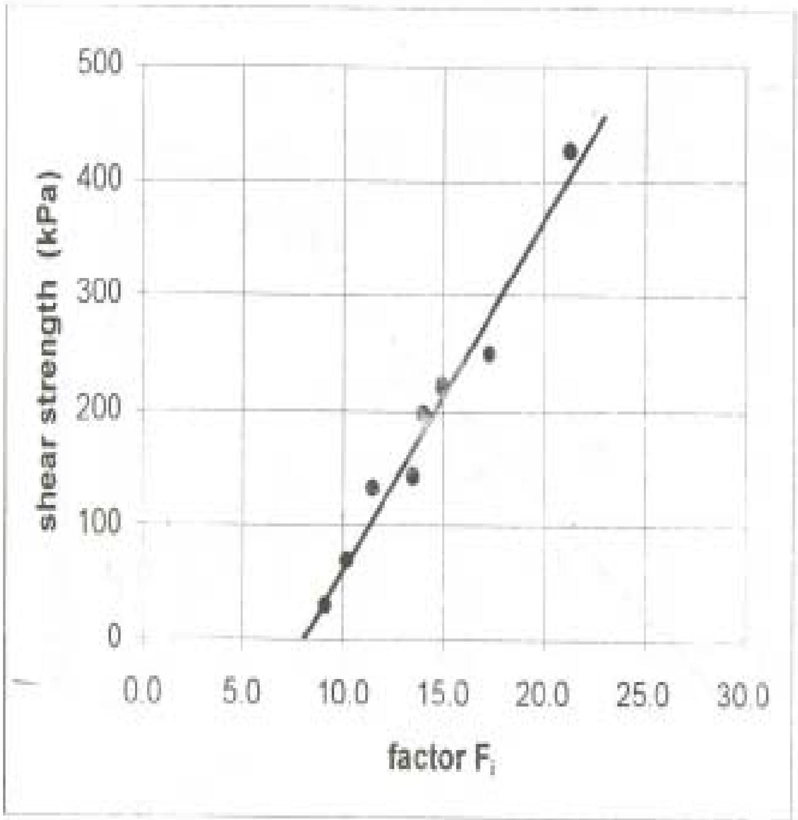

Figure 3.11: Shear strength and factor F_i relationship for the data analysed of the present study samples tested at a cell pressure of 50 kPa.

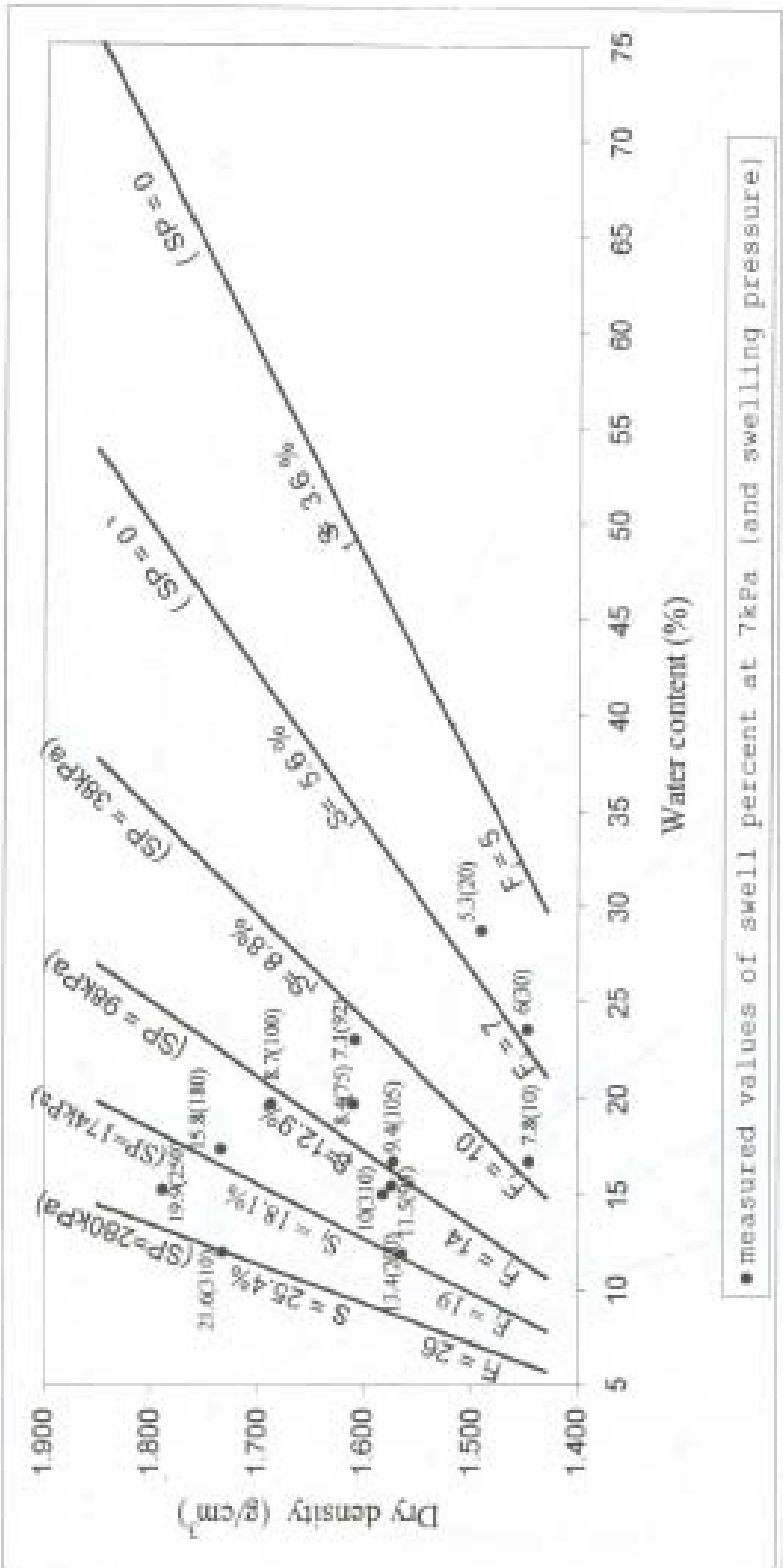

Figure 4.1: Characterisation lines chart of swelling (swell percent and swelling pressure) and initial state relationship for the studied soil.

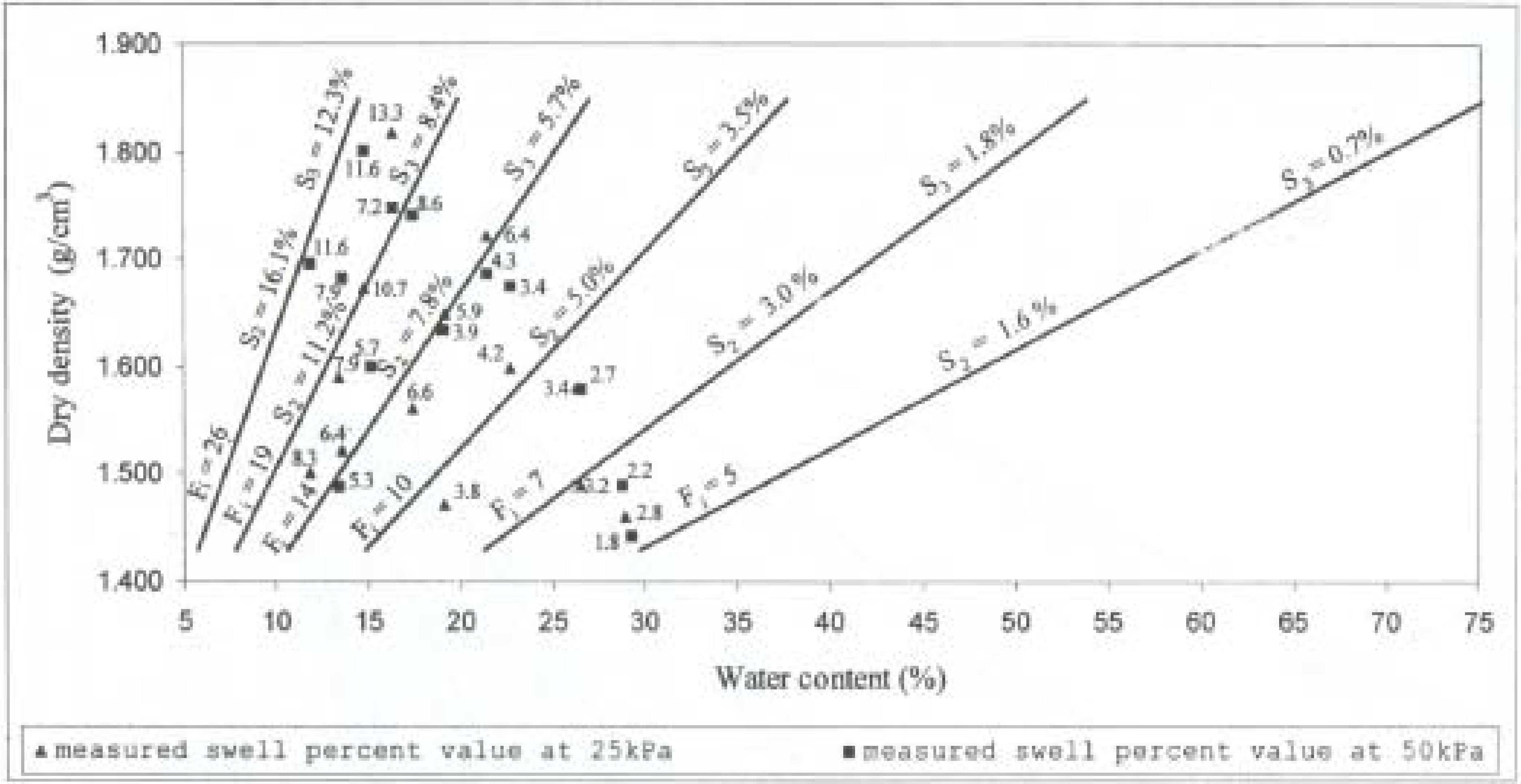

Figure 4.2: Characterisation lines chart of swell percent (measured at two different surcharge pressures) and initial state relationship for the studied soil.

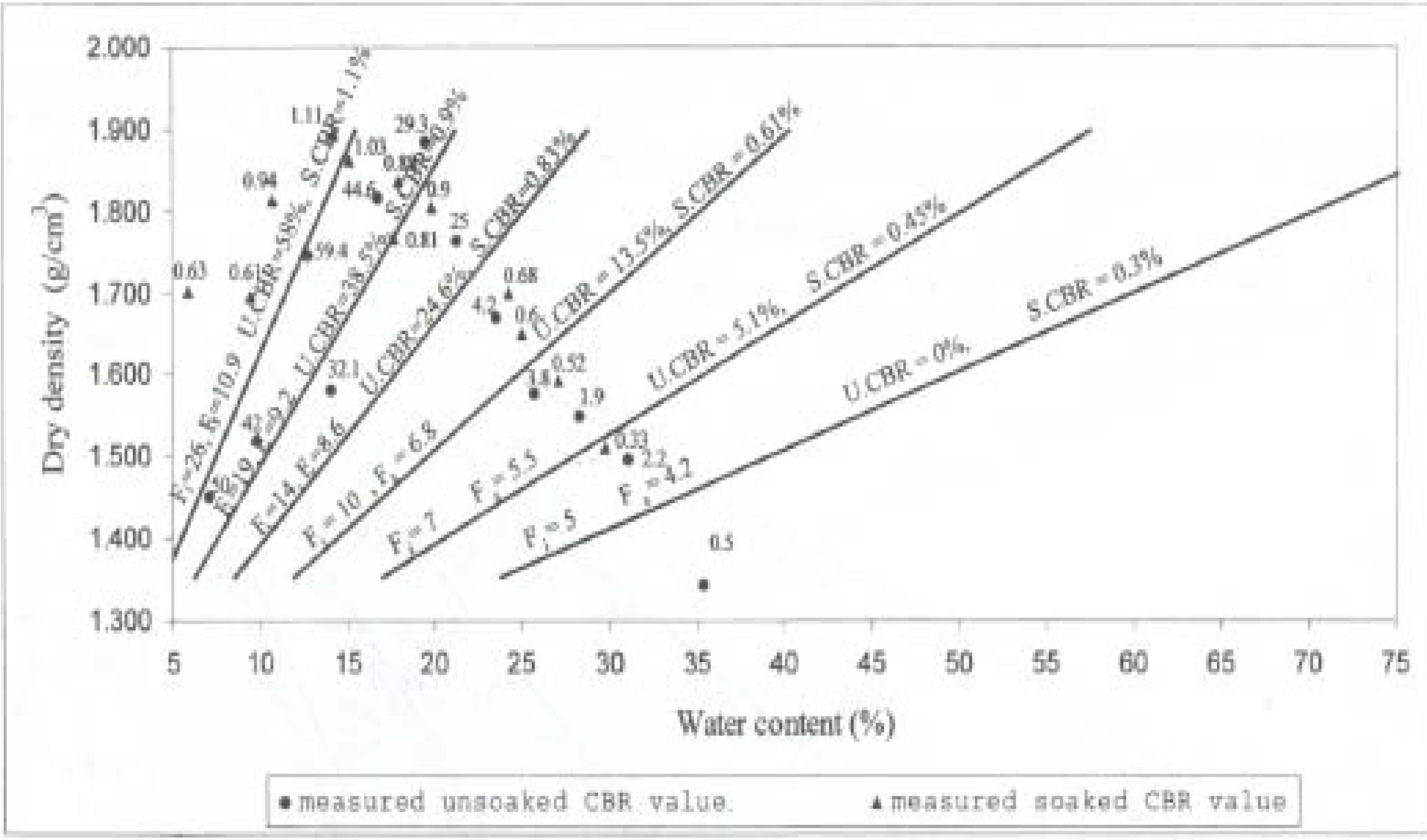

Figure 4.3: Characterisation lines chart of CBR (measured as soaked and unsoaked) and initial state relationship for the studied soil.

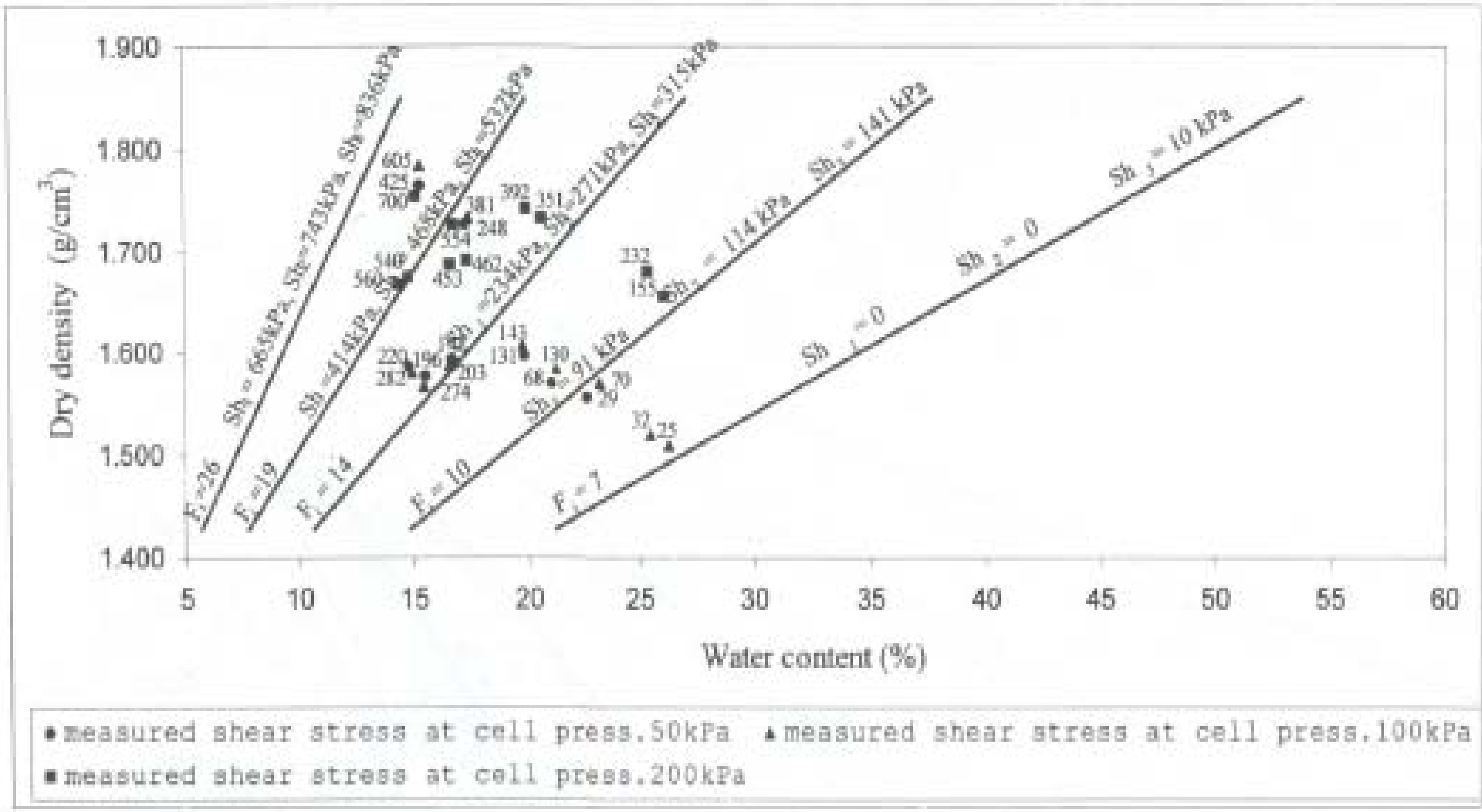

Figure 4.4: Characterisation lines chart of shear stress (measured at three different cell pressures) and initial state relationship for the studied soil.

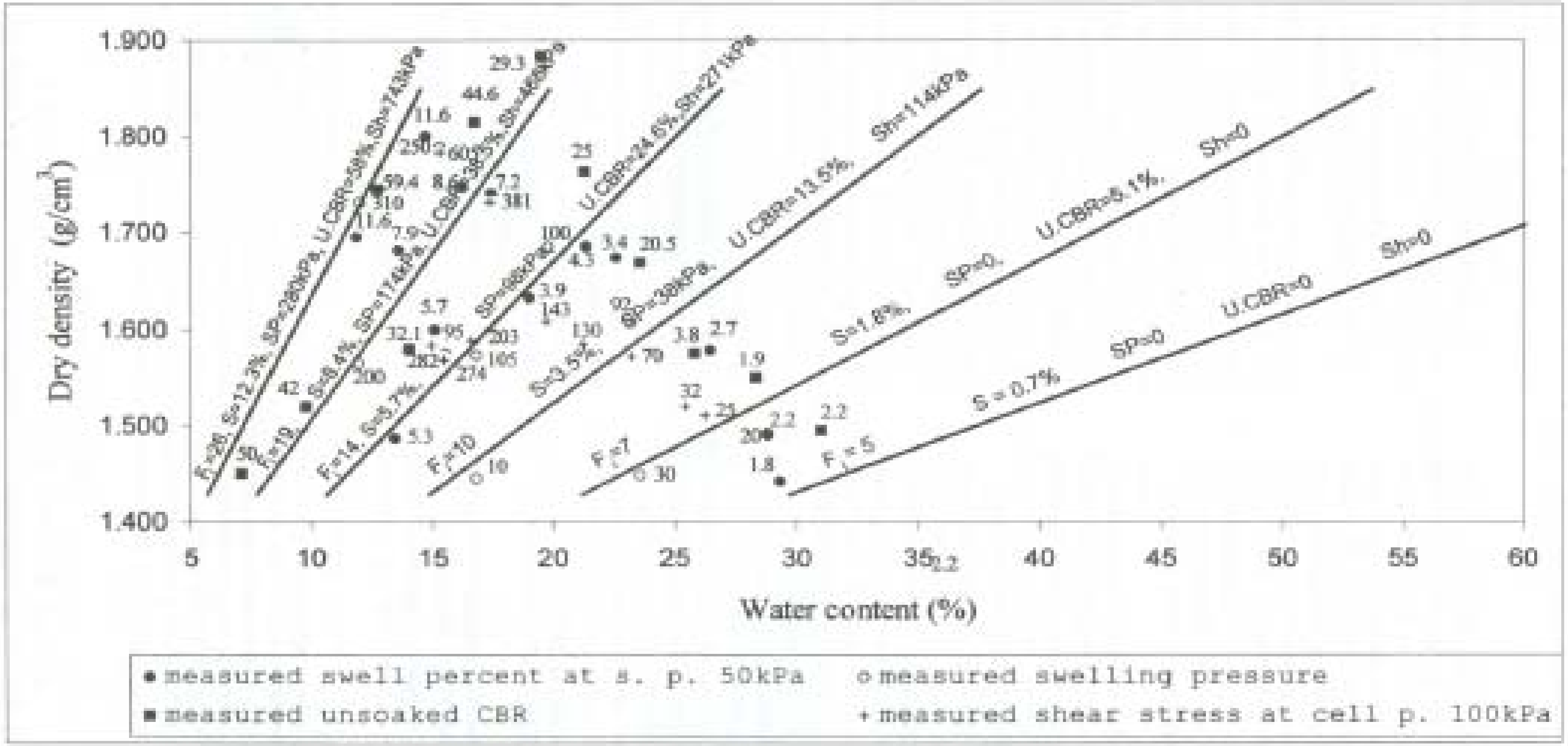

Figure 5.1: Characterisation lines chart of swelling and strength (swell percent, swelling pressure, unsoaked CBR and shear stress) versus initial state relationship for the studied soil.

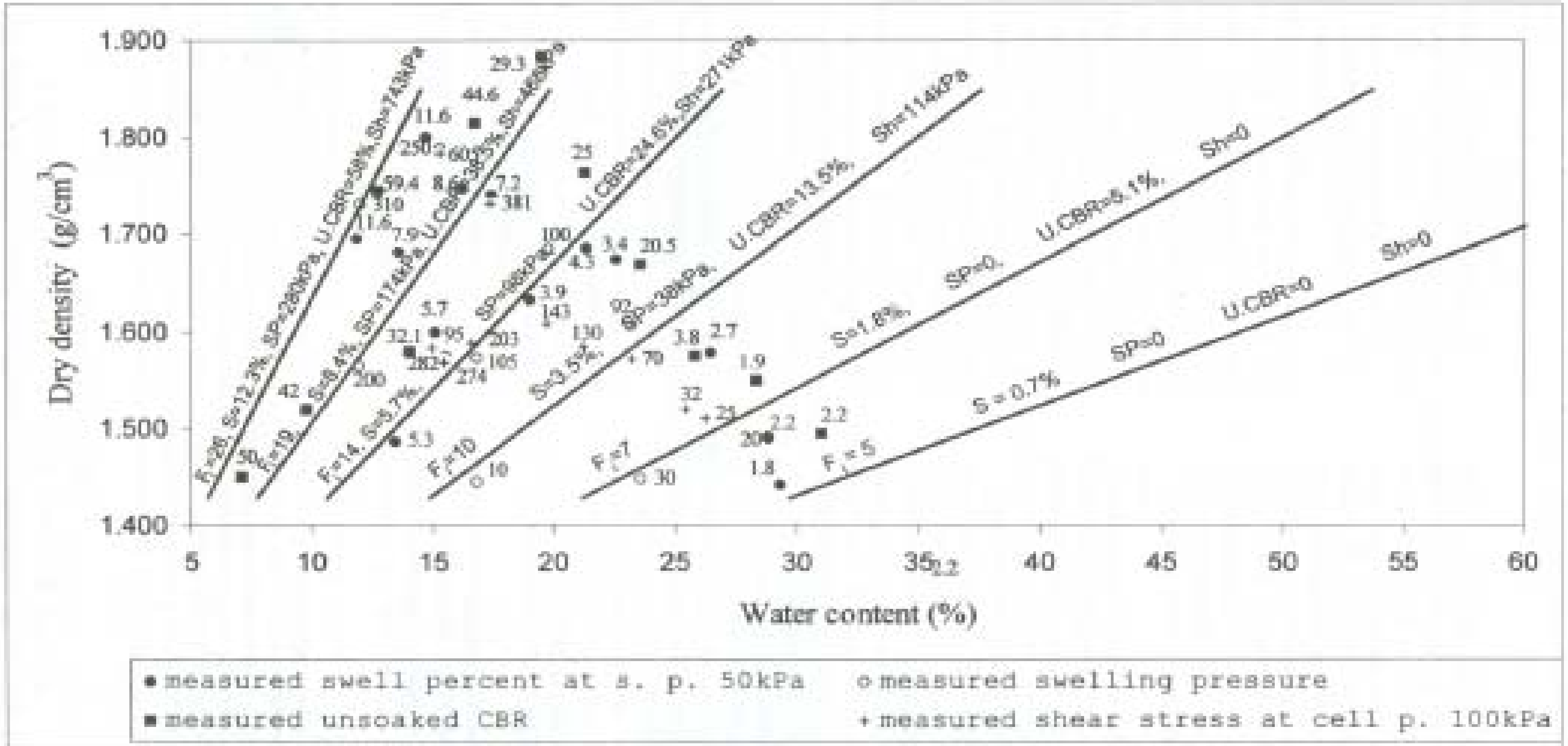

Figure 5.1: Characterisation lines chart of swelling and strength (swell percent, swelling pressure, unsoaked CBR and shear stress) versus initial state relationship for the studied soil.