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Measures for Rehabilitation of Distressed Structures Founded On Expansive Soils

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ABSTRACT: *Expansive soil also known as shrink- swell soil is a very common cause of foundation problems. Foundation soils which are expansive will "heave" and can cause lifting of a building or other structures during periods of high moisture. Conversely during periods of falling moisture, expansive soil will "collapse" and can result in building settlement. Either way damage can be extensive. This work analyses a typical problem where expansive soil was suspected to be the cause of distress to the structures. Soil samples collected at different depths were tested according to the conventional geotechnical investigations to ascertain the swelling potential of the soil. The paper also reviewed innovative solutions along with conventional foundation practices to counteract the dual problem of swelling and shrinking posed by expansive soils. Besides, the paper throws light on causes of distress in lightly loaded structures founded on expansive soils as well as measures to rehabilitate the distressed structures founded on them.*

KEY WORDS: *Expansive Soil; Distress; Structures; Rehabilitation; Shrink-Swell.*

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I. INTRODUCTION

Expansive soils are present throughout the world and are found predominantly in Nigeria in the North Eastern region, where they occupy an estimated area of 104,000km^2. (Osinubi *et al*, 2012). [9] In Nigeria, expansive soils have liquid limit values ranging from 50 to 100%, plasticity index from 20 to 65% and shrinkage limit from 9 to 14 % (Chen *et al*, 2015). [5] The amount of swell generally increases with increase in the plasticity index. The swelling potential depends on the type of clay mineral, crystal lattice structure, cation exchange capacity, ability of water absorption, density and water content. Swell in the vertical direction is called heave. Among the illite, kaolinite and montmorillinite clay minerals, the montmorillinite possesses the greatest ability to swell.

Studied soil properties by various researchers and their proposed relation to degree of expansion are summarized in table1.

Table 1 *Swelling Potential Prediction*

Parameter	Reference	Degree of expansion			
		Low	medium	High	Very high
LL%	Chen, 1975 [4]	<30	30-40	40-60	>60
PI%	Chen, 1975 [4]	<10	10-35	35-55	>55
	Holtz and Gibbs, 1956 [6]	<1 2	12-34	34-45	>45
Clay content (%)	Holtz and Gibbs, 1956[6]	< 17	17- 27	27-37	>37
Clay content (%)	Holtz 1959 [7]	-	13- 23	24-31	>31
Swell percent (%)	Thomas *et al*, 2000 [13]	< 3.0	3.0- 6.0	6.0- 9.0	>9.0
Swell pressure (kN/m^2)	Thomas *et al*, 2000[13]	< 81	81- 153	153- 225	>225
Activity	Skempton, 1953[11]	< 0.75	0.75- 1.25	-	>1.25

1.1 Problems with Expansive soils

The problem is more in case of light structures, those that cannot counteract the upward thrust posed by expansive soils. The damage will be apparent, usually, several years after construction. The soil below will exert swelling pressure both upwards and laterally. As a result, the floor slab is lifted up, leading to cracking of floor. Cracking is normally evident at the corners of window and door openings. This usually assume in the form of diagonal cracks – a consequence of differential settlement in the wall. (Fig.1)

Fig 1. Views of cracks in exterior walls as a result of upward soil expansion

Often, utilities buried in soil such as water pipelines and sewage lines, get damaged due to displacement in the soil in which they are buried. The ensuing leakage further aggravates the situation. Roads that pass through expansive soil sub-grade are subjected to heaving and shrinkage settlement of these treacherous soils. Both the lined and unlined canals are subjected to the vagaries of expansive soil. The unlined canal slopes erode and become soft. Canal beds heave up obstructing the functioning of the canal. The concrete lining splinter like glass pieces on account of the deleterious cyclic movement of background swelling clay. This results in seepage losses.

II. MATERIALS AND METHODS

2.1 Materials

The expansive soil used in this study is the black cotton soil obtained from Baure, Gombe state, North–eastern Nigeria. Representative disturbed samples were collected every 0.5m from three boreholes drilled up to 2.5m depth under the distressed buildings, at the end of the dry season. A typical view of the soil is shown in Fig. 2

Fig 2. Views of expansive soil with Polygonal pattern of surface cracks in the dry season.

2.2 Methods

2.2.1 Experimental programme

An experimental study to evaluate the swelling characteristics of the soil was performed on all the soil samples collected. Laboratory analyses included particle –size distribution, liquid limit (LL), plastic limit (PL), clay content, natural moisture content, dry unit weight, degree of saturation (S) and expansibility potential. These tests were accomplished according to the standards of the American society for testing and materials (ASTM [2], while the mineral composition was determined by X-ray diffraction (XRD) analysis.

2.2.2 Foundation Practices on Expansive Soils

The following conventional foundation practices and innovative techniques can provide solutions to problematic soils

(i) Sub Excavating or Replacing the Expansive Soil by Cushions

In this technique the expansive soil is replaced either in part or full (Fig.4) with a material that does not undergo swell. The load of the cushion provides the load necessary to counter heave.

Fig. 4 Sub Excavating or Replacing the Expansive Soil by Cushions

(ii) Sand Cushion Method

The entire depth of the expansive soil stratum or a part thereof may be removed and replaced with sand cushion, compacted to the desired density and thickness. Swelling pressure varies inversely as the thickness of the sand layer and directly as its density. Therefore, generally sand cushions are formed in their loosest possible state without, however, violating the bearing capacity criterion. The basic advantage of the sand cushion method is its ability to adapt itself to volume changes in the soil. However, the sand cushion method has several limitations particularly when it is adopted in deep strata.

Most of the foundation engineers often suggest some arbitrary thickness for the sand cushion without consideration to the depth of the zone of potential volume change which itself is difficult to determine. The high permeability of sand creates conditions conducive to easy ingress and accumulation of water from surface run off.

(iii) Cohesive Non –swelling soils (CNS) Layer Method

Replacement by soils with relatively impervious material may, to a great extent offset the disadvantages of sand cushion method. Katti (1978) [8] developed a technique where by removal of about 1m of expansive soil and replacement by CNS layer beneath foundations has yielded satisfactory results. He successfully adopted it for prevention of heave and resultant cracking of canal beds and linings and recommends it for use in foundations of residential buildings also. The approximate value of CNS thickness to be used for soils in different swelling pressures is shown in Table 2.

` **Table 2**: *Thickness of CNS layer to be used for lining over expansive soil sub-grade*

Swell pressure of soils (kN/m^2)	Thickness of CNS material (cm)
50 – 150	75 – 85
200 – 300	90 – 100
350 – 500	105 – 125

Source: Rama (2012) [10]

(iv) Providing a Granular Bed and a Granular Cover Below and Round Foundation.

Fig.5 shows a strip footing under an outside wall constructed on an expansive soil. The excavation of the expansion soil is carried out for a width greater than the width of the footing proper. Generally an extra width of 15cm is excavated on either side. A freely-draining granular soil, such as gravel, sand or a mixture of gravel or sand is placed in the trench up to the base level of the footing and compacted. The footing usually of reinforced concrete is then constructed at this level and the wall is raised. The freely-draining soil is filled on the sides of and the top of the footing up to the ground level.

The foundation on expansive soil is usually constructed during hot season when the soil has shrunk to its minimum level. A cushion of freely- draining soil below the foundation acts as a barrier and the effect of swelling on the foundation is reduced. A reinforced concrete apron of about 2m wide is provided around the outer walls of the building to prevent the entry of water into the foundation. Suitable arrangements should be made to drain the water away from the granular base during the raining season. The reinforced concrete beam should have an air gap over the ground surface to prevent effects of the soil.

Arora (2008) [1] suggests that instead of a reinforced concrete apron, a flexible water proof apron made of bituminous concrete about 2m wide and 75mm thick can be constructed around the building. He stressed that the flexible apron should not crack when it is pushed up by the swelling soil. If it cracks or if their connection with the main structure is damaged, it should be properly sealed before the next rainy season. The flexible apron is covered with soil and given an outward slope of 1 in 30.

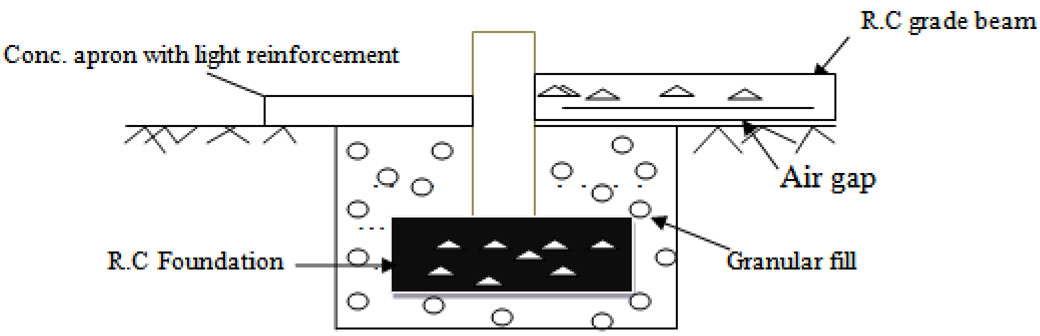

Fig. 5 Foundation on granular cover below and around the foundation

III. RESULTS AND DISCUSSION

3.1 Basic Geotechnical Properties

The results of the average basic geotechnical properties of the samples tested at different depths is presented in table 3

Table 3. *Average basic geotechnical properties*

Depth (m)	LL (%)	PL (%)	PI (%)	C (%)	S (%)	w (%)	γ_d (g/cm^3)
0.5	54.4	34.3	22.1	22.7	0.44	12.2	1.576
1.0	54.4	26.5	27.9	25.0	0.75	15.8	1.693
1.5	55.0	30.5	24.5	21.0	0.92	15.2	1.714
2.0	52.5	27.7	24.8	21.1	0.80	14.7	1.820
2.5	51.5	28.5	23.0	19.8	0.71	14.9	1.821

KEY: LL (liquid limit); PL (plastic limit); PI (plasticity index); C (clay content,<$2\mu m$);
w (natural moisture content) and γ_d (dry unit weight)

From the result it can be seen that an average value of 53.6% was obtained for the LL and mean value found for PI was 24.5% for all samples collected. Similar values have been reported by other researchers (Beni Lew, 2010 [3]; Sridharan and Prakash, 2000[12] and Thomas *et al*, 2000) [13]. A comparison between Atterberg's limits (Table 1) and the studied samples shows that this soil can be classified as highly expandable.

3.2 Swelling Potential Properties

Direct estimation of the swelling potential (swell percent and swell pressure) of expansive soil in the laboratory is important for the prediction of ground heave. The average swell percent and swell pressure of the samples collected at different depths are shown in table 4. At 0.5m depth the swell percent of the samples was low, around 2.1%. According to this value the soil has a low swell potential. However, swell percent increases to 12.7% at 1.0m (very high swell potential). On average the soil showed a high swell percent value indicating a highly to very highly expansive soil. The low swell percent observed at 0.5m depth was probably not accurate.

Table 4 *Average swelling potential properties of the samples tested*

Depth (m)	Activity	swell percent (%)	swell pressure (kN/m^2)
0.5	1.05	2.1	45.0
1.0	1.12	12.7	38.3
1.5	1.17	10.1	35.2
2.0	1.17	7.4	28.5
2.5	1.16	6.2	24.4

A swell pressure (Table 4) value of 45kN/m^2 was observed at 0.5m, which is classified as a low degree of swelling potential. Moreover the swell pressure decreases with the depth up to 24.4kN/m^2 at 2.5m. This decrease was probably caused by the increase in dry unit weight with the depth, an indication of soil resistance to swelling with increasing depth. All samples have a low degree of swelling according to the values of table 4. However, these values are higher than the bearing capacity of the residential foundations (around 20kN/m^2)

3.3 XRD Analysis

Results of XRD showed the presence of kaolinite, quartz, microcline, offretite bentonite (a mineral from the montmorillonite group) and illite in all samples. (Fig.6)

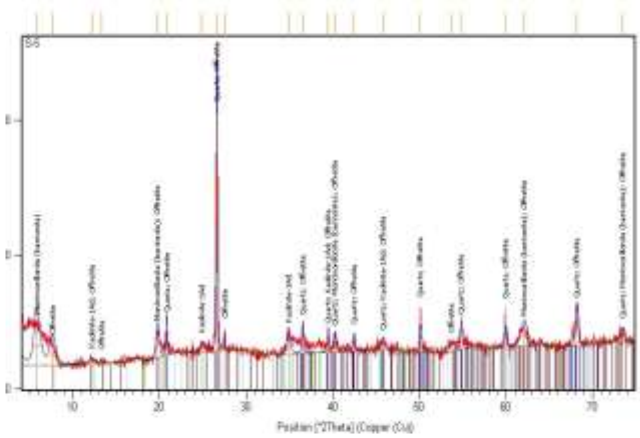

Fig. 6 X- ray diffraction result of natural sample.

Kaolinite, offretite and quartz having a stable structure (due to the strong bonds) react with water to a minimum extent, in contradiction to montmorillonite (bentonite) and microcline which are regarded as very hydrophilic due to their mobile structure, making them highly expansive. Illite in turn is a mineral that reacts with water to a limited extent.

Quantitative analysis of XRD results revealed that the average percentages of different clay minerals in the samples are 51% montmorillonite, 32% illite, 8% offretite, 4% kaolinite, 3% microcline and 2% quartz.

3.4 Visual Observation from Field Investigation

The following causes of distress to the structures were observed

(i) The construction of buildings was on marshy area and water table was observed at a shallow depth below the ground level
(ii) There is no flagging/plinth protection around the buildings
(iii) Growth of vegetation was noticed around the buildings
(iv) Sump tank and sewage pipes are very close to the foundation
(v) Waste water and rainwater are disposed directly on the ground very close to the foundations
(vi) Cracks at plinth, sill lintel levels and differential heaving of flooring, shifting of walls, extensive cracks were observed in internal and external walls of the buildings. It is due to high swelling and shrinking characteristics of expansive black cotton soil in the foundation region.

3.5 Measures for Rehabilitation of Distressed structures

The following restoration measures are suggested to counteract the dual problem of swelling and shrinking behaviour of expansive clay.

(i) Construction of additional one or two floors above the existing building should be done so that the loading on the foundation would be more than the existing swelling pressure;
(ii) The plinth beam should be separated from the natural ground by leaving an air gap of 8 to 10cm between the plinth beam bottom and natural ground. If the gap is not provided the plinth beam have at least to be designed for upward pressure due to swelling;
(iii) A flexible water proof apron (plinth protection) of about width 2.0m wide should be provided all round the buildings;
(iv) Installation of horizontal/vertical moisture barriers should be provided around the perimeter of the buildings;
(v) The internal non-load bearing walls with wide multiple cracks and dislocations should be removed completely and rebuilt. Before dismantling, the complete roof should be supported by either steel or timber props;

(vi) Flooring shall be redone after removing existing filled up soil up to about 1.5m from the floor level and replacing the same with well compacted non- expansive materials placed in layers not exceeding 30cm thickness;
(vii) The sewer pipes with leak proof joints close to the foundation should be placed beyond the foundation media;
(viii) Sump tank should be provided far from foundation region;
(ix) Plantation of trees, plants and hedges within 3m distance around the building should be avoided. This is because excessive watering of plants close to the building contributes to swelling;
(x) Rain water collected from roof should be discharged at a distance of about 1m from the structure.

IV. CONCLUSION

Adequate geotechnical investigations are imperative for the characterization of expansive soil. By evaluating the properties of expansive soils accurately, it is feasible to choose the proper foundation technique with a good construction quality. The distress in the lightly loaded structures was essentially due to the shrinking characteristics of expansive soils in the foundation media. The light loaded structures founded on expansive soils must be designed in such way to observe that the load coming on the structure is sufficiently more than the swelling pressure of the expansive soil. Furthermore, Plinth protection apron and curtain walls should also be constructed round the structures. This would control moisture migration and help to maintain equilibrium moisture in soils beneath the structures.

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