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Matric Suction, Swelling and Collapsible Characteristics of Unsaturated Expansive Soils
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Matric Suction, Swelling and Collapsible Characteristics of Unsaturated Expansive Soils

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Abstract

Unsaturated expansive soils are recognized as one of the most problematic soils owing to its swelling-shrinkage characteristics. The presence of such soils in highway/railway embankments, slopes and earthen dam sites manifests various critical issues during and after the construction of structures. The current research aims on the evaluation of the suction, swelling and collapsible characteristics of four expansive soils possessing different expansiveness and mineralogical composition. A series of constant volume swell pressure, double-oedometer and in-contact filter paper tests were performed on four different expansive soils to acquire swelling pressure, collapse potential and matric suction at different degree of saturation. Swelling pressure, collapse potential and matric suction of all expansive soils degraded substantially with increment in the degree of saturation. The results revealed significant impact of magnitude of matric suction on volumetric deformation (swell and collapse) behavior of expansive soils. Swelling and collapse potential were observed to be higher for the expansive soils with larger matric suction. Higher matric suction governed the water intake within interlayer spacing of the Montmorillonite mineral present in expansive soil, which contributed to higher crystalline swelling response. Larger collapse potential indicated development of larger localized deformations within the soil mass owing to higher matric suction.

Keywords: Expansive, Unsaturated, Matric suction, Swell Pressure, Collapse Potential

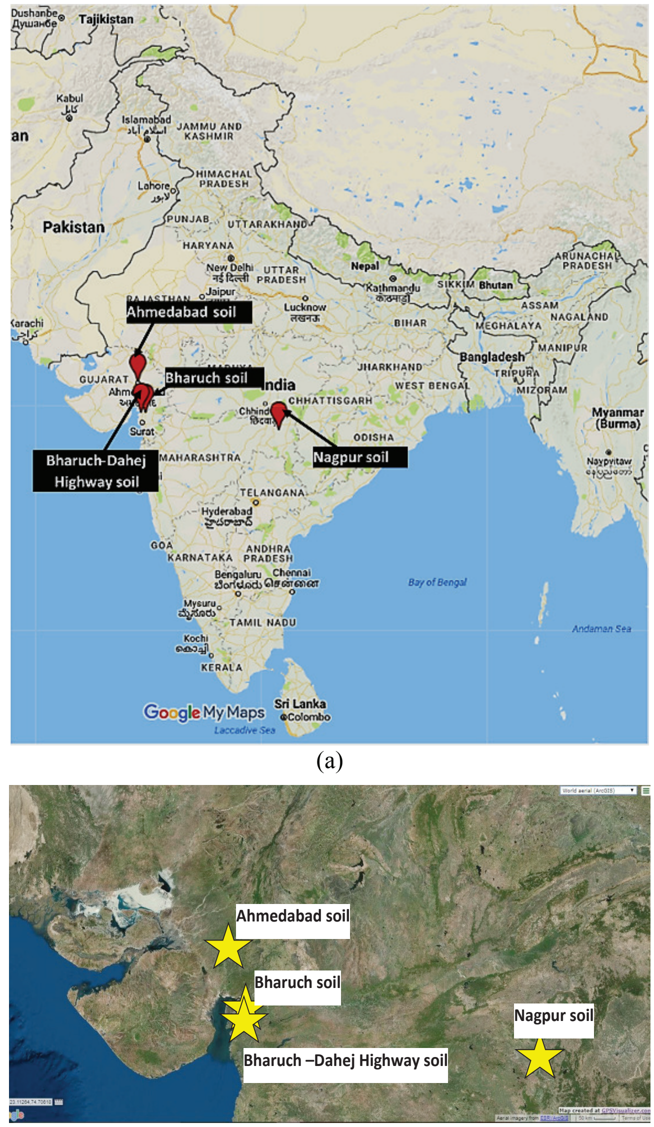
1. Introduction

Natural soils (Black cotton soils) possessing tendency to swell (in the presence of water) and shrink (in the absence of water) are referred as expansive soils. Such soils in unsaturated state (S_r < 100%) experiences severe swelling and shrinkage owing to transient variation in degree of saturation of soil mass in the active zone/ vadose zone subjected to climatic cycles. Formation of expansive soils is caused due to chemical weathering of basaltic rocks. The lower amount of precipitation, high condensation due to high temperature and fluctuating drying & wetting cycles are accountable for predominantly leaching and chemical weathering of rocks. Expansive soil covers large portion of earth surface usually in the semi-arid and arid environmental regions (Nalbantoglu and Gucbilmez, 2001). Around 20% of regions in India comprises of shrinkage-swelling (expansive) soils. Expansive soils are found in several parts of Gujarat, Uttar Pradesh, Andhra Pradesh, Karnataka, western Madhya Pradesh and Maharashtra (Verma and Maru, 2013). The critical problem related to expansive soils was found to be associated with induced deformations. Developed deformations in expansive soils were reported to be severely greater than the elastic deformations, which could not be anticipated by classical elastic and plastic theory (Nelson and Miller, 1997). Extent of volumetric deformation would cause severe upheaving and large cracks in embankments & pavements; destruction to the floor slabs; basement buckling due to increased lateral stresses; concrete and steel plinths failure; deterioration of water pipelines; and damages to retaining walls etc. (Charlie et al. 1984). These detrimental volumetric changes would be governed by clay mineralogy, plasticity, soil-water chemistry, depth of ground water table, vegetation cover, temperature, amount of moisture variation over space and time, permeability, soil profile etc. (Nelson and Miller, 1997; Houston et al. 2009). Rapid urbanization has triggered the growth of potential sources of water content upsurge within soil strata; broken sewer and water lines, poor surface drainage, ground water recharge, landscape irrigation, damming due to fill/cut construction, cessation of pumping after building occupation etc. (Houston et al. 2009). Sudden increase of water quantity or overburden stress buildup would cause hydroconsolidation/ collapse of the soil skeleton stimulating excessive damages to the structures and hefty differential settlements. Presence of expansive soils in highway/railway embankments and pavements could lead to detrimental failures owing to swelling followed by collapse response of unsaturated expansive soil due to sudden saturation and vehicular vertical stress. Matric suction would influence the hydro –mechanical behaviour of unsaturated soil (Nowamooz and Masrouri, 2010). Matric suction would control the geometric arrangement of particles within the soil mass, which could induce the volume change behaviour (Swelling and Collapse) within the expansive soil skeleton. The present research focuses on the investigation of the swelling, collapsible and matric suction characteristics of four expansive soils. The effect of mineralogical composition of expansive soils on matric suction, swelling pressure and collapse potential was studied. Both swelling and collapse behaviour of the unsaturated expansive soil were dominated by the amount of matric suction in soil mass at different degree of saturation. Relationship between matric suction of expansive soil with its swelling pressure and collapse potential was also assessed. The role of matric suction governing the mechanism behind swelling and collapsible characteristics of expansive soil were also comprehensively illustrated in the current research.

2. Material properties and specimen preparation

In the current research, four expansive soils (S1, S2, S3 and S4) were collected from Nagpur (Gosikhurd dam site, Maharashtra), Bharuch (Gujarat), Bharuch-Dahej Highway soil (Gujarat) and Chandkheda (Gujarat) respectively. Fig 1. (a) and (b) presents the locations of soil collection sites in political and topographical map of India respectively. Expansive Soils were collected from 0.5m depth to avoid the presence of organic matter on the upper portion of the soil strata. Grain size distribution curves of collected expansive soils are shown in Fig 2. The soil classification, Atterberg limits (*LL*, *PL* and *SL*) and specific gravity (G_S) are presented in Table 1. Differential free swell index (*DFSI*) of Nagpur soil, Bharuch soil, B-D highway soil and Ahmedabad soil were obtained to be 134%, 104%, 70% and 30% respectively. X-Ray diffraction analysis was performed on all four expansive soil specimens to determine their mineralogical compositions. The percentage of Montmorillonite mineral was obtained to be largest for Nagpur soil and lowest for Ahmedabad soil (Table 1). Relationship of Atterberg limits with *DFSI* of four expansive soils is presented in Fig 3. Percentage of Montmorillonite mineral and *DFSI* values indicated Nagpur soil to be most expansive and Ahmedabad soil to be non-expansive in nature.

Moist tamping technique was opted for preparing specimens to perform filter paper, double oedometer and constant volume swell pressure tests. Detailed descriptions regarding the procedure incorporated for moist tamping method was described in Pandya and Sachan (2017a). Specimens were prepared at 1.46 g/cc dry density with different degree of saturation (S_r) values varying from 30% to 97%. Detailed information regarding specimen preparation of different expansive soils is given in Table 2.



(a) (b)

Fig 1. Google map representing locations of expansive soils. (a) Location on political map of India, (b) Location on topographical map of India

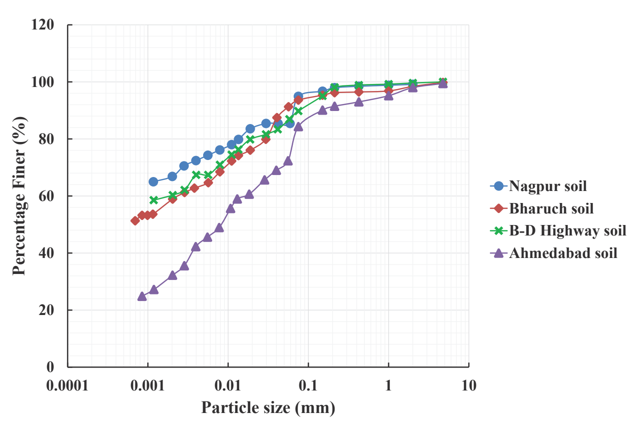


Fig 2. Grain size distribution curves of expansive soils.

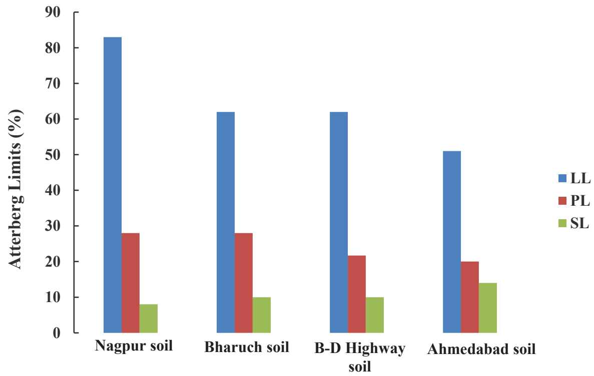


Fig 3. Relationship of Atterberg limits with *DFSI* of expansive soils

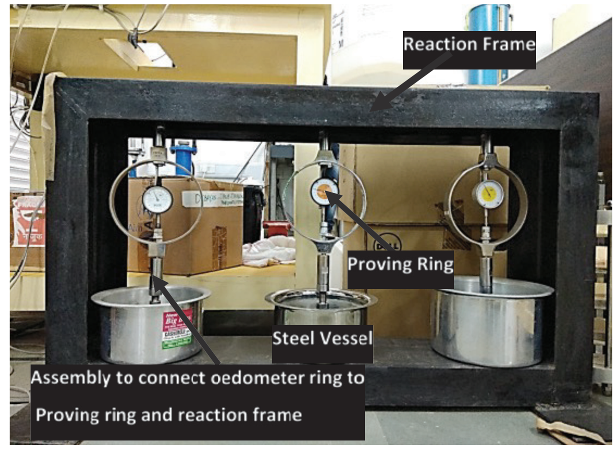


Fig 4. Constant volume swell pressure apparatus

3. Experimental program

Matric suction, swell pressure and collapse characteristics of four expansive soils were determined by performing filter paper, constant volume swell pressure and double oedometer tests respectively.

3.1 Matric suction

Filter paper method was employed to determine matric suction for four expansive soils (S1, S2, S3 and S4). In-contact filter paper method covers large range of suction from 10kPa to 100 MPa. Method has been designated as the most efficient, low costing and accurate for measurement of matric suction for all types of soil. Filter paper method was performed as described in ASTM D5298-10 (2013) using Whatman 42 ashless filter paper. Detailed procedure and complete description of methodology of filter paper tests were explained by Pandya and Sachan (2017a). Calibration curve for Whatman 42 (ASTM D5298-10, 2013) was used for determination of matric suction in current study.

3.2 Swell Pressure

Swelling pressure (P_s) can be designated as the pressure exerted by the expansive soil, when change in the volume of soil is restricted. Swelling pressure (P_s) of expansive soils were determined employing constant volume swell pressure tests (Fig 4). In this test, the specimen was prepared in the ring (*d*- 60mm and *h* -20mm) using moist tamping method. The ring was then placed in a thick steel vessel with flat base and wider diameter. The specimen was then attached to the proving ring to restrict volume change (Fig 4). Proving ring was attached to reaction frame with capacity of 1 tonne. After the test setup, the water was poured in the container to allow the specimen saturation. Water penetration inside the specimen instigated swelling in the soil and the pressure exerted by the soil was reflected from proving ring under constant volume conditions. The swelling pressure of the soil was recorded from the proving ring at different time intervals till the reading became constant.

3.3 Collapse potential

Collapse potential indicates the amount of collapse of soil skeleton exposed to sudden inundation or vertical stress application. In the current research, collapse potential (*CP*) of four expansive soils (S1, S2, S3 and S4) were determined by employing double-oedometer test. In the test, two similar compacted (same dry density and water content) specimens of expansive soil were placed in the oedometer mould of two different testing devices. One out of them was loaded under unsaturated conditions and the other one was initially soaked (saturated) for 24 hrs under seating load of 5 kPa. Both the specimens were further loaded sequentially; 10 kPa, 20kPa, 50kPa, 100 kPa, 200kPa, 400 kPa and 800 kPa. Detailed procedure regarding the double oedometer test was presented by Pandya and Sachan (2017b). Each specimen (as-compacted & saturated) was reached at equilibrium under applied vertical stress in 24 hrs, and the specimen was further loaded sequentially. Equilibrium void ratio (after 24 hrs) representing volumetric strain under each vertical stress increment was assessed for both the specimens. Collapse potential of soil was stated as the difference between volumetric strains at a specific vertical stress normalized by initial void ratio of the specimen. It was ascertained using expression demonstrated in Equation1 (from Medero et al. 2009)

$$CP = \frac{e_i - e_f}{1 + e_0} \quad (1)$$

Where, e_i = equilibrium void ratio from *1D* consolidation oedometer test of as-compacted specimen, e_f = equilibrium void ratio from *1D* consolidation oedometer test of saturated specimen (inundated specimen), e_0 = initial void ratio of the specimen corresponding to the dry density of the sample, *CP* = collapse potential.

Table 1: Geotechnical and mineralogical properties of expansive soils

Soil No.	Soil Name	DFSI (%)	Q (%)	M_o (%)	K/H (%)	G (%)	Sand (%)	Silt (%)	Clay (%)	PI (%)	G_s
S1	Nagpur	134	45	55	0	0	5	28	67	55	2.77
S2	Bharuch	104	43	40	17*	0	6	35	59	34	2.74
S3	B-D highway	70	50	34	17*	0	10	30	60	40.3	2.72
S4	Ahmedabad	30	86	12	2#	1	15	52	32	31	2.70

*Halloysite, # Kaolinite, *G*-Gravel

Table 2: Swelling, matric suction and collapse potential response of unsaturated expansive soils

Soil Name	**Soil Name**	***DFSI* (%)**	**S_r (%)**	**P_S (kPa)**	**u_a-u_w (kPa)**	***CP* (%) @400kPa**	***CP* (%) @800kPa**
S1	Nagpur	134	30	90	34386	9.23	13.56
			43	76	13348	7.12	12.59
			52	71	12460	6.27	9.21
			62	59	3653	4.6	6.67
			75	43	2654	0.27	1.91
S2	Bharuch	104	30	68	21000	9.17	12.87
			43	57	10436	6.57	9.17
			53	36	6852	5.31	6.67
			66	33	3990	3.80	5.75
			75	29	3580	3.54	5.63
			84	17	1560	2.45	5.60
			97	6	340	0.78	4.6
S3	B-D Highway Soil	70	30	65	13733	9.17	12.6
			43	51	5941	2.70	7.90
			52	28	4288	2.49	6.53
			62	25	1748	-1.49	1.49
			75	10	732	0.15	0.32
S4	Ahmedabad	30	30	13	7781	6.59	7.07
			43	10	5442	4.29	4.09
			52	8	4101	3.18	3.91
			62	5	618	0.93	1.03
			75	4	124	0.16	0.42

4. Results and Discussions

The research focuses on the evaluation of matric suction, swelling and collapsible characteristics of expansive soils along with their *DFSI* and mineralogical composition.

4.1 Influence of DFSI on matric suction characteristics of expansive soil

Matric suction in a soil develops as a result of adhesive and cohesive forces associated with the soil particle assembly (soil matrix). It could also be defined as force attracting the soil water to the soil matrix. Particle size within the soil mass would govern these phenomena. Relationship of matric suction and degree of saturation of expansive soils with varying *DFSI* are shown in the Fig 5. It could be identified that Matric suction was found to decrease with increase in the degree of saturation for all the expansive soils. It could be observed that the matric suction for the present study followed corresponding pattern S1>S2>S3>S4; as represented in Table 2. The results were analogous for all values of degree of saturation. Matric suction of the soil reduced with decrease in *DFSI* of the soil. About 4.42 times reduction in the matric suction values were observed for the lowest degree of saturation (S_r = 30%) between Nagpur soil (Highest *DFSI*) and Ahmedabad soil (Lowest *DFSI*), as shown in Table 2. Matric suction of soil S4 was found to be 21.4 times lesser as compared to that of soil S1 for 75% degree of saturation. Matric suction was found to be the function of particle size (Fredlund and Rahardjo 1993; Likos and Lu (2004). Smaller the particle size, larger is the matric suction of soil. Higher DFSI values, higher clay content, lower shrinkage limit and higher Montmorillonite content indicated that Nagpur soil (S1) contained larger amount of smaller size particles leading to higher matric suction. However, Ahmedabad soil possessing lesser *DFSI* (30%) comprised of lower amount of smaller size particles and hence resulted into lower matric suction.

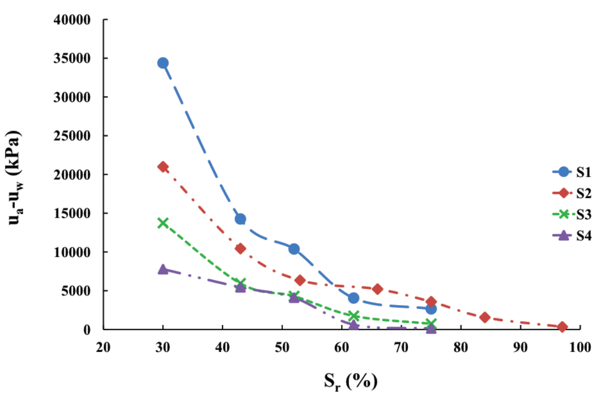


Fig 5. Variation of matric suction of expansive soils with degree of saturation.

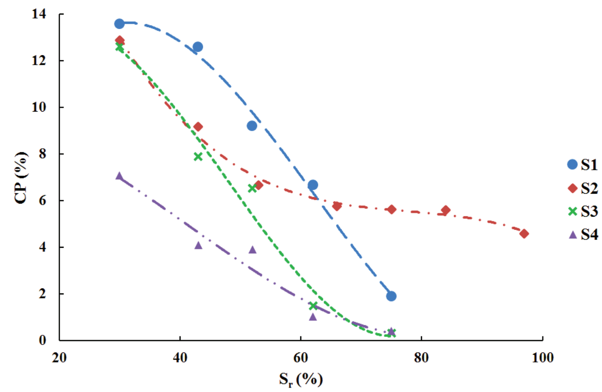


Fig 8. Collapse potential variation with degree of saturation for soils S1, S2, S3 and S4.

4.2 Influence of DFSI on swelling characteristics of expansive soils

Differential free swell index (*DFSI*) denotes the swelling prospective for a soil. Swelling pressure indicates the quantitative amount of pressure exerted by the expansive soil under saturated conditions, when volume change of soil mass is restricted. Increment in the swelling pressure with time has been displayed for soils S1, S2, S3 and S4 in Fig 6 (a), (b), (c) & (d) respectively. Trend of swelling pressure enhancement with time was found to be similar for all four soils. Swelling characteristics of all four expansive soils with respect to degree of saturation has been shown in Fig 7. A linear variation of swelling pressure (P_S) with degree of saturation (S_r) was attained for all four expansive soils (S1, S2, S3 and S4). Swelling pressure was observed to decrease with increment in the degree of saturation for all four soils (Table 2). Swelling pressure obtained from constant volume method was observed to be the maximum for S1 soil and minimum for S4 soil. Increase in the degree of saturation might lead to gradual fulfillment of affinity of water in the expansive soils yielding to lower values of suction. Montmorillonite appeared as the dominant clay mineral in S1, S2 and S3 soils (Table 1). Presence of higher clay content denoted larger negative charge due to presence of higher Montmorillonite content. Hence, the soil possessing higher clay content would require more cations to balance the negative charge for an equilibrium state (Mitchell and Soga, 2005), which would possess higher affinity for water. Therefore, the Nagpur soil contained higher capability to swell at all degree of saturation values as compared to Bharuch and B-D highway soil. Dominant mineral in Ahmedabad soil was obtained to be Quartz resulting in lowest affinity for water leading to smaller values of swell pressure for S4 soil.

4.3 Influence of DFSI on collapsible characteristics of expansive soil

Collapse potential of soil designated the degree of soil skeleton crumbling due to gradual increment in the vertical load or due to sudden upsurge of water content within the soil mass. It specified the magnitude of volume deterioration experienced by the soil specimen. Collapse potential variation in all expansive soils with their degree of saturation values at vertical stress of 800kPa are shown in Fig 8. It could be examined that the collapse potential significantly reduced with the increase in saturation values of the soil at 800kPa vertical stress. It was also identified that maximum collapse potential was obtained for the Nagpur soil (S1) at 800kPa vertical stress (Table 2). On the contrary, lowest collapse potential was determined for Ahmedabad soil.

Soil in unsaturated state would be tightly held by the additional interparticle resistive force due to presence of air-water interface /contractile skin in unsaturated state (Pandya and Sachan, 2017b). Presence of greater amount of smaller size particles and higher percentage of Montmorillonite gave rise to the higher intensified additional inter-particle resistive force. Inter-particle resistive force would be directly proportional to matric suction, which would inversely vary with particle size. As degree of saturation increased the particles which were held tightly by intensified resistive force might lead to sudden and higher magnitude of volume change for Nagpur soil. However, as the magnitude of inter-particle resistive force decreased with the reduction in amount of clay particles (smaller size particles), the collapse potential of soil was found to reduce (Table 2).

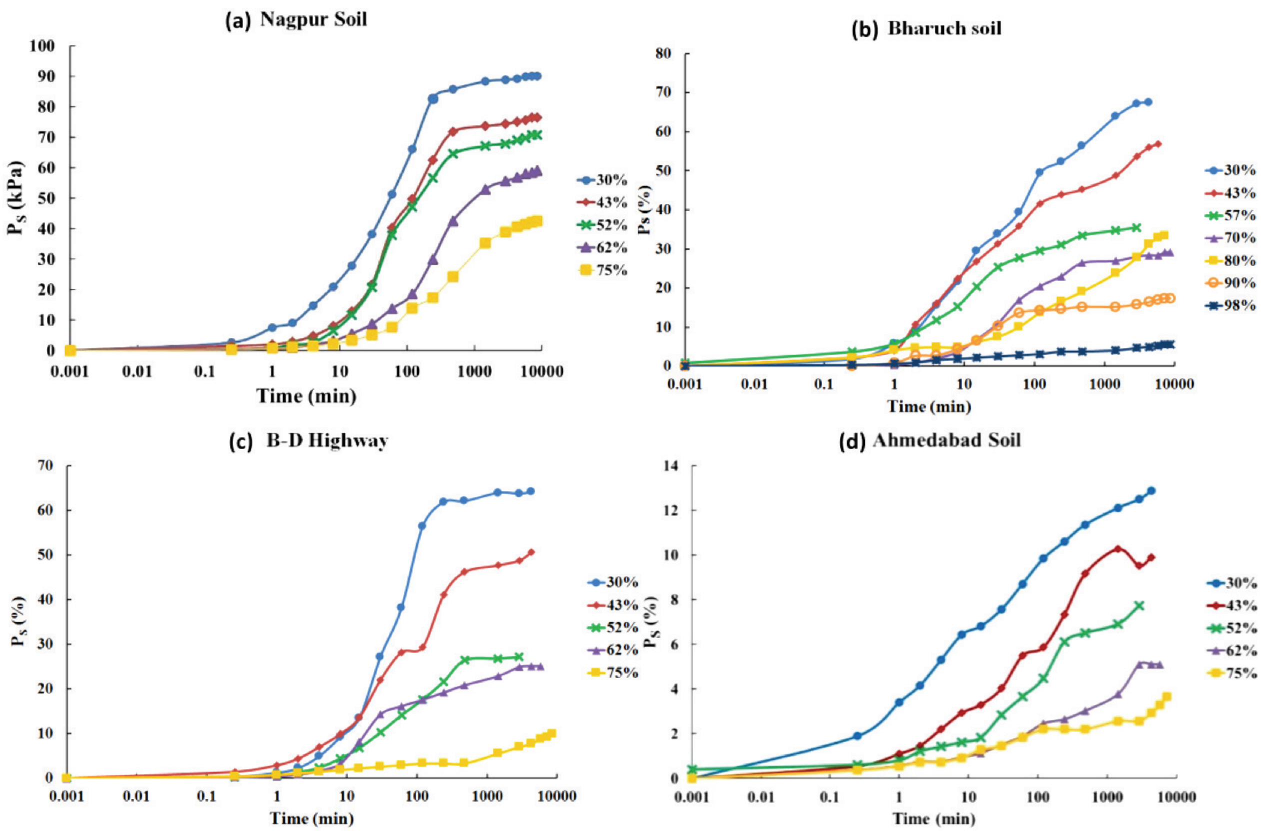


Fig 6. Transient variation of swelling pressure of expansive soils at different degree of saturation. (a) Nagpur soil, (b) Bharuch Soil, (c) Bharuch-Dahej Highway soil, (d) Ahmedabad soil

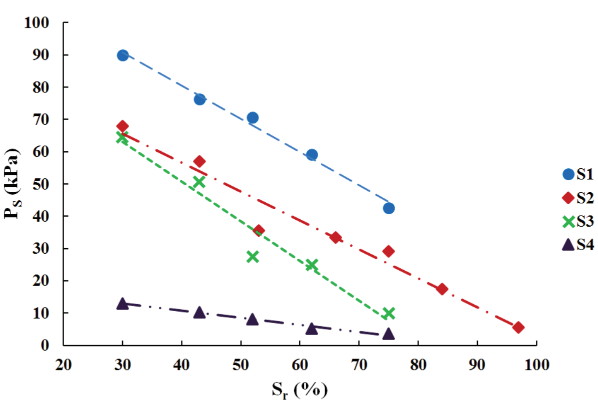


Fig 7. Variation of maximum swelling pressures of expansive soils with degree of saturation

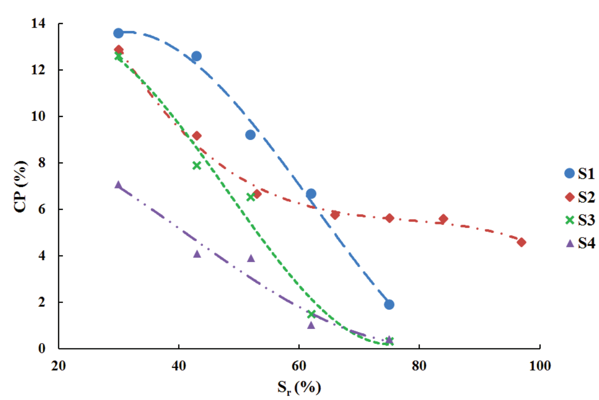


Fig 8. Collapse potential variation with degree of saturation for soils S1, S2, S3 and S4

4.4 Relationship of matric suction with swelling pressure of expansive soils

Matric suction of soil could be expressed in the form of pressure, at which the unsaturated soil would attract the water from the positive hydraulic datum (water table). Variation of matric suction with the swelling pressure of expansive soils with different *DFSI* at varying degree of saturation is shown in Fig 9. It could be attributed from the results that specimens with higher matric suction exhibited larger swelling pressure. Existence of matric suction due to presence of air-water interface gave rise to the capillary force (Pandya and Sachan, 2017b). Soil possessing large amount of Montmorillonite clay content revealed the presence of larger quantity of small size clay particles. For platy particles, Laplace equation relating matric suction of the soil to the surface tension and spherical radii (r_1 and r_2) could be reduced to the following form represented in Equation 2 (Cho and Santamarina, 2001). Schematic sketch representing the meniscus (air-water interface), spherical radii (r_1 and r_2) and distance between two platy particles are presented in Fig 10.

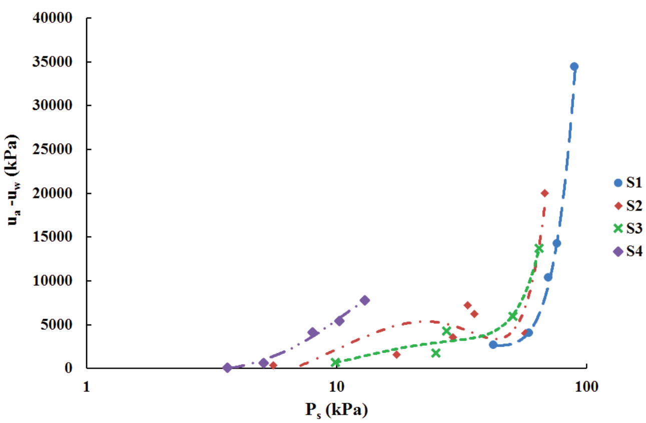


Fig 9. Relationship of swelling pressure with matric suction of expansive soils

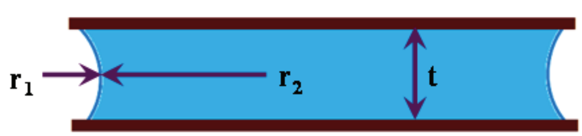


Fig 10. Schematic representation of meniscus, spherical radii (r_1 and r_2) and distance between platy clay particles (t)

$$\Delta u = T_S\left(\frac{1}{r_1}\right) \quad (2)$$

For platy particles $r_1 << r_2$, the term ($1/r_2$) remained negligible; thus it can be neglected. The distance (t) between two platy clay particles can also be described as $t = 2*r_1$. Water content in the space between two platy particles can be described in Equation 3 (Cho and Santamarina, 2001).

$$\Delta u = \frac{W_w}{W_s} = \frac{A(2r_1)\gamma_w}{W_s} = \left(\frac{2A}{W_s/g}\right)r_1\frac{\gamma_w}{g} = \frac{S_S r_1 \gamma_w}{g}$$

……………… (3)

Where, A = surface area of one platy particle, W_s and W_w = solids and water weights, Ts = surface tension, S_S indicates specific surface area, γ_w = unit weight of water, w = water content and g = acceleration due to gravity. This formulation indicated that the matric suction between two platy particles is a function of specific surface area of soil, as shown in the Equation 4 (Cho and Santamarina, 2001).

$$\Delta u = T_S\left(\frac{S_S\gamma_w}{wg}\right) \quad (4)$$

Soils consisting of larger amount of clay particles acquired higher specific surface area; hence this might have proceeded to the development of high matric suction within the soil mass. This would have resulted in the development of intensified additional inter-particle resistive force due to larger matric suction as represented in Equation 5 (Likos and Lu, 2004).

$$F_e = (u_a - u_w)\pi r_2^{\,2} + T_s 2\pi r_2 \quad (5)$$

This might lead to the intense attraction between two platy particles together which would cause reduced interlayer spacing between two individual Montmorillonite structural units (Tan and Kong, 2001). Hence, this would have contributed to development of higher overall unbalanced negative charge on the surface of clay particle, which would result in higher affinity for water to reach equilibrium. This would foster higher crystalline swelling among two structural units, which would lead to higher swelling pressure in the soil possessing high matric suction with large *DFSI*.

4.5 Relationship of matric suction with Collapse Potential of expansive soils

Collapse of the soil skeleton occurs due to removal of the cementing agents bonding the soil particles together within soil mass due to upsurge in quantity of water in soil specimen or due to rise in the overburden (vertical stress). Transient variation in the environmental and climatic conditions could exhibit changes in matric suction of the soil mass which would instigate alterations inside the soil fabric arrangement. Variation of collapse potential with matric suction of the soil has been evaluated and signified in Fig 11. Polynomial variation of collapse potential with matric suction was observed for all expansive soils (S1, S2, S3 and S4). The schematic diagram to understand the collapse mechanism of unsaturated soil skeleton on saturation and vertical stress augmentation has been shown in Fig 12 (a) & (b) respectively. It could be acclaimed from the quantitative estimation of collapsible and matric suction characteristics of the expansive soils (S1, S2, S3 and S4) that collapse potential of the soil was found to be maximum for the soil possessing more matric suction (Table 2). Collapse potential decreased with reduction in the matric suction of soil irrespective of the degree of saturation.

Soil possessing higher matric suction contributed to the development of higher capillary pressure causing intensified hold amongst soil particles. Nagpur soil underwent extreme volumetric deformation due to sudden inundation and vertical stress augmentation. When soil specimen with high capillary pressure was subjected to larger vertical stress and sudden saturation, it would cause greater magnitude/amount of localized deformation due to sudden disappearance of air-water interface leading to weakening of additional inter-particle resistive force within the soil skeleton causing enormous collapse. However, smaller matric suction would create lower capillary force, which would cause lower magnitude of collapse due to little change in volumetric arrangement within the soil mass.

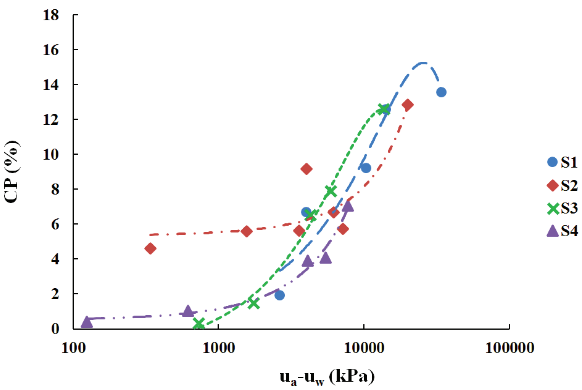


Fig 11. Relationship of collapse potential of expansive soils with matric suction

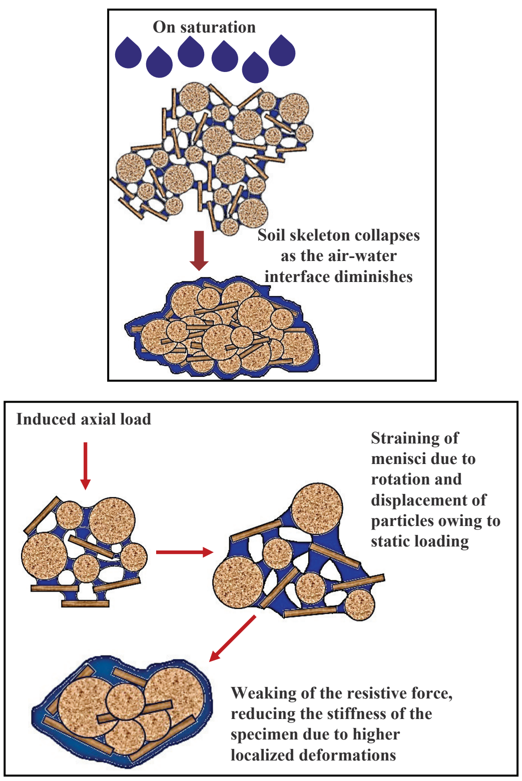


Fig 12. Conceptual sketch representing collapse mechanism within soil skeleton, (a) On saturation, (b) On vertical stress augmentation

5. Conclusions

Extensive experimental research was performed to evaluate the swelling, collapsible and matric suction characteristics of four different expansive soils with different mineralogical composition and *DFSI*. These soil samples were collected from Nagpur, Bharuch, Bharuch-Dahej Highway and Ahmedabad soil. Main observations drawn from the study are as follows:

1. Matric suction was obtained to be the maximum for soils with largest *DFSI* regardless of their degree of saturation. At lowest degree of saturation, the matric suction of Nagpur expansive soil was attained to be 4.42 times higher as compared to Ahmedabad soil.
2. The linear relationship of swelling pressure with degree of saturation was obtained for expansive soils with *DFSI* varying from 30% to 134%. Minimum swell pressure was obtained for the expansive soil with lowest *DFSI*. Nagpur expansive soil exhibited highest percentage of Montmorillonite and the maximum matric suction. This revealed larger swelling pressures due to large amount of crystalline swelling owing to the development of intense capillary pressure within soil mass.
3. Larger magnitude of volumetric deformation due to the collapse of soil skeleton was observed for soil with higher *DFSI*, higher matric suction and larger amount of Montmorillonite. Largest collapse potential (14%) was obtained for Nagpur soil specimen prepared at lowest degree of saturation, which was obtained to be two times higher than Ahmedabad soil specimen at same degree of saturation.

The results and findings from the current study signifying the swelling and collapsible characteristics of four expansive soils could be applicable for any expansive soils possessing equivalent grain size distribution and *DFSI* values.

Acknowledgements

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Notation

u_a-u_w = Matric suction
1D = One dimensional
CP = Collapse potential
CH = Cohesive soil with high ccompressibility
e_0 = Initial void ratio of the specimen
e_i = Initial void ratio
e_f = Equilibrium void ratio of saturated specimen
S_r = Degree of saturation
w = Water content
LL = Liquid limit
PL = Plastic limit
SL = Shrinkage limit
d = Diameter
h = Height
DFSI = Differential free swell index
P_s = Swell Pressure
ρ_{di} = Initial dry density
w_i = Initial water content
u_w = Pore water pressure
R = Radius of curvature
T_S = Surface tension
α = Contact angle
θ = Wetting angle
p = Vapour pressure
p_0 = Saturation vapour pressure
T = Temperature
M = Molecular mass
Q = Quartz
K = Kaolinite
H = Halloysite
M_o = Montmorillonite
G = Gravel