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Effect of Bentonite partial density on the total suction of compacted bentonite sand mix

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ABSTRACT

Compacted bentonite owing to its low permeability, low diffusivity, high swelling ability, and high cation adsorption capacity is a favoured buffer material in deep geological repositories for the disposal of high level nuclear waste. Total suction of the compacted bentonite is an important property which determines engineering behaviour of the compacted clay in the unsaturated state. Owing to their deployment in deep geological repositories, it is important to understand how the total suction of compacted bentonites responds to variations in dry density, moisture content and clay content of the buffer. Laboratory experiments are conducted to establish relationship between total suction and degree of saturation for three compacted bentonite-sand specimens containing bentonite contents of 30 %, 50 % and 70 % respectively. The dry densities of the compacted bentonite-sand specimens ranged from 16.5 kN/m^3 to 20 kN/m^3. Further, at each dry density, samples were prepared at different degrees of saturations varying from 20 to 97 % (water content ranging from 5 to 20 %). Total suction measurements are conducted using relative humidity probes inserted in sealed specimens. The specimens are compacted with air free distilled water. The partial dry density of the bentonite in the mix is presented using a term called Effective Clay Dry Density (ECDD). Experimental results show that at high ECDDs (> 17.7 kN/m^3) the compacted specimens show the same total suction at all degrees of saturations. It is hence expected that bentonite-sand blocks compacted at high ECDDs (> 17.7 kN/m^3) will be mechanically more stable than those compacted at lower ECDDs upon exposure to variations in degree of saturation from ingress or evaporation of moisture.

INTRODUCTION

Compacted bentonite blocks are planned to be used as buffer material for sealing high level nuclear fuel waste in many countries. The favourable properties of high-density compacted bentonite blocks as sealing material in high-level radioactive waste repositories include its high swelling capacity, very low permeability, high exchange capacity, sufficient thermal conductivity and adequate mechanical resistance [1, 2]. The swelling of initially unsaturated compacted bentonite blocks upon wetting by ground water from the surrounding rock helps in filling the micro voids and thus creates an impermeable zone around the canister containing nuclear waste since the nuclear waste has to be separated from the surrounding environment [3]. The low permeability and high exchange capacity of the buffer material prevents the migration of the ground water and diffusion of cations from the surrounding rock to waste containing canister and thus reduce the corrosion susceptibility of the canister [4]. The high thermal conductivity helps the buffer material to withstand the high temperature arising from the nuclear waste and the high mechanical resistance makes the buffer stable under high stresses arising from overburden, swelling pressure and thermal stresses [5]

The unsaturated compacted bentonite blocks consist of three phases namely, soil solids, water and the air, which interact with each other to produce negative pressure known as suction. The suction present in the unsaturated soil makes its behaviour highly transient as compared to the steady state behaviour of saturated soils. As a result of this, the characterisation of unsaturated soil is based on a set of soil functions [6] as against a set of soil parameters for saturated soils.

Soil suction can be broadly divided into two types: matric suction and osmotic suction. Matric suction is developed due to the adsorptive and capillary forces existing in the soil matrix whereas the osmotic suction is the result of salts or contaminants present in the porewater [7,8] The sum of matric and osmotic suction is termed as total suction and hence, in the absence of any contamination, matric suction becomes equal to total soil suction.

Previous researchers have indicated that the suction developed is mostly a function of water content (either, gravimetric or volumetric) or soil saturation [9,10] and dry density. The degree of saturation of the buffer blocks is not stable during the life time of the repository due to the infiltration of ground water from the surrounding rock and evaporation due to the high temperature from the nuclear waste canister. Hence total suction developed in the compacted bentonite buffer material keeps changing with time. Delage et al. [11] studied the effect of suction on the swelling properties of the bentonite compacted at a dry density equal to 18.5 kN/m^3. Tang et al. [12] studied the suction in the bentonite compacted at a dry density equal to 16.7 kN/m^3. Mata [13] studied the behaviour of unsaturated bentonite buffer compacted at a dry density equal to 16.7 kN/m^3. However, the behaviour of compacted bentonite as a function of dry density is relatively unexamined.

This paper presents the total suction response of three bentonite sand mixes compacted at various dry densities for a range of degrees of saturation values. The impact of variations in clay content and dry density on the total suction is interpreted in terms Effective Clay Dry Density (ECDD).

EXPERIMENTAL PROGRAMME

Preparation Of The Samples

Bentonite samples from North West India and the river sand from the state of Karnataka were used in the present study. The properties of bentonite and sand are presented in Table 1 and Table 2 respectively. The particle size distribution of bentonite and sand are presented in Fig 1. Oven dried bentonite was mixed with three different proportions (on weight basis) of oven dried sand, namely, 70 %, 50 % and 30 % respectively. Each mix is compacted with distilled water. The tests were done at three different dry densities of 16.5, 17.5 and 20 kN/m^3. At each dry density, samples were prepared at different degrees of saturations varying from 20 to 97 % (water content ranging from 5 to 20 %). The mass of water required to achieve a desired saturation was calculated by trial and error basis. The wet samples are kept in dessicator for 24 hours to have a uniform distribution of moisture content throughout the sample. The water content of each mix is then accurately determined by oven drying method. The samples were statically compacted in a metallic ring of diameter 0.08 m and height 0.03 m.

Table 1: Properties of Bentonite

Property	Values
Liquid Limit	408 %
Plastic Limit	40 %
Shrinkage Limit	11 %
Plasticity index	368 %
Unified Soil Classification	CH
Specific gravity	2.69
Exchange capacity of cations (meq/100g)	
Na^+	51.35
K^+	1.18
Ca^{2+}	12.36
Mg^{2+}	16.56
Total Cation Exchange Capacity (CEC)	81.45 meq/100g

Table 2: Properties of the sand

Property	Values
Specific gravity	2.64
C_u	3.33
C_c	0.83
Unified Soil Classification	SP

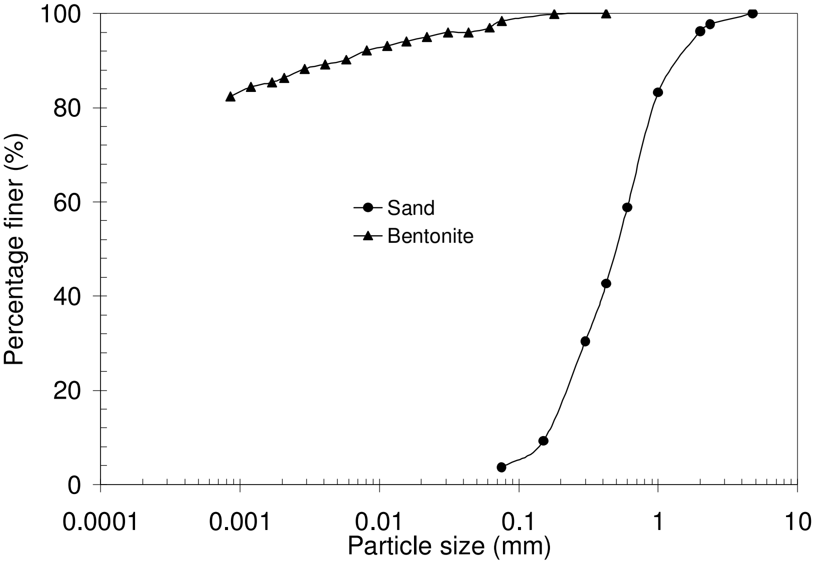

Fig 1: Particle size distribution curves of bentonite and sand used in the present study

Measurement Of Total Suction

Total suction of the sample was indirectly measured using a hygroclip by measuring the relative humidity of the compacted sample. Hygroclip used in this study is Hygroclip CPXXPVC, which is a commercially available sensor made by Rotronic Ag, Switzerland. The probe has a diameter of 0.015 m and sensing length of 0.03 m. The total length of the probe is 0.10 m. The humidity sensor inside the probe is Hygomer c-94 and the temperature sensor is Pt 100 1/3 DN which is the standard measuring elements for the scientific applications as per Swiss standards. The hygroclip has humidity range of 0 to 100 % with an accuracy of ±1.5 % and the temperature range of -40 to 80 ºC with an accuracy of ± 0.3 K. Fig 2 shows the photograph of the sensor.

The bentonite sand mix compacted in the metallic ring was tightly enclosed in the base and the top assembly and a small hole of diameter 0.015 m was drilled into the soil using a hand auger to insert the hygroclip. The hygroclip was then inserted into the soil and sealed air tight at the top of the metallic container. The temperature and the relative humidity of the samples were monitored at the constant time interval until the relative humidity reaches a constant value. This takes almost 18 to 20 hours. The relative humidity is converted to the total suction using the Eq.1, which relates total suction (ψ) with the universal gas constant (R), absolute temperature (T), specific volume of water (ν_{wo}), molecular mass of water vapour (ω_v) and the relative humidity (RH), given by Fredlund & Rahardjo [7]

$$\psi = -\frac{RT}{\nu_{wo}\omega_v}\ln(RH) \tag{1}$$

The readings were taken at the room temperature. Fig 3 shows the photograph of the test set up.

Fig 2: Photograph of the hygroclip used in the present study

Fig 3: Photograph of the test set up

RESULTS AND DISCUSSIONS

Fig 4 plots the variation of relative humidity of compacted 70 % bentonite + 30 % sand specimens with time. The specimens were compacted at a dry density of 17.5 kN/m^3 for a range of S_r values (16-97 %). It can be seen that in all specimens the sensor developed constant relative humidity values in about 18 to 40 hours. This equilibrium value of relative humidity was recorded and converted to total suction using Eq.1. Since the hygroclip responded similarly in all specimens, the time variation of relative humidity of other specimens is not presented in this paper. Fig 5 to 7 plot the total suction response of 30 %, 50 % and 70 % bentonite specimens. Each specimen was compacted to three different dry densities (16.5, 17.5 and 20 KN/m^3 respectively); additionally at each density, the S_r values were varied between 20 and 98 %.

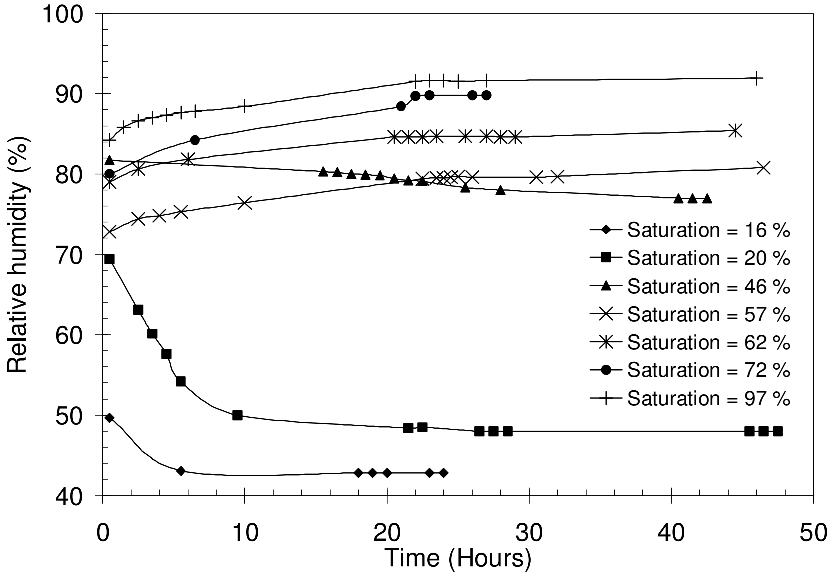

Fig 4: Variation of the relative humidity with time in samples compacted with DW at dry density 17.5 kN/m^3.

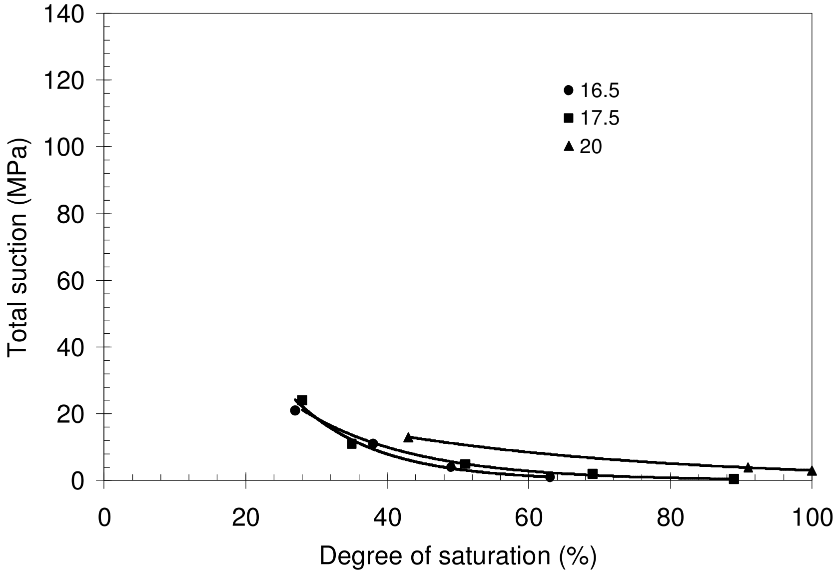

Fig 5: Suction response of the samples with degree of saturation at three different dry densities (30 % Bentonite)

It is observed from the graphs that the total suction reduces with an increase in the degree of saturation. This is attributed to reduction in matric suction of the compacted clays with increase in saturation. The maximum value of total suction in the drier state is (almost 120 MPa) exhibited by the 70 % bentonite specimen and least (almost 20 MPa) by the 30 % bentonite specimen. The results are understandable as the total suction of the mix is mainly contributed by bentonite content, due to the high specific surface area and small diameter of interparticle pores of the clay. To account for the effect of clay content on the dry density of the mix, a term called Effective Clay Dry Density (ECDD) has been introduced. ECDD is defined as the partial dry density of the clay in a compacted clay sand mix. This is defined by the Eq.2 by Kurosawa et al. [14]

$$\rho_b = \frac{\rho_{bs}(100 - R_s)}{100 - \rho_{bs}(\frac{R_s}{\rho_s})} \quad (2)$$

Where ρ_b is the partial density of the bentonite (ECDD), ρ_{bs} is the dry density of the bentonite sand mix, ρ_s is the density of the sand and R_s is the fraction of the sand in the mix.

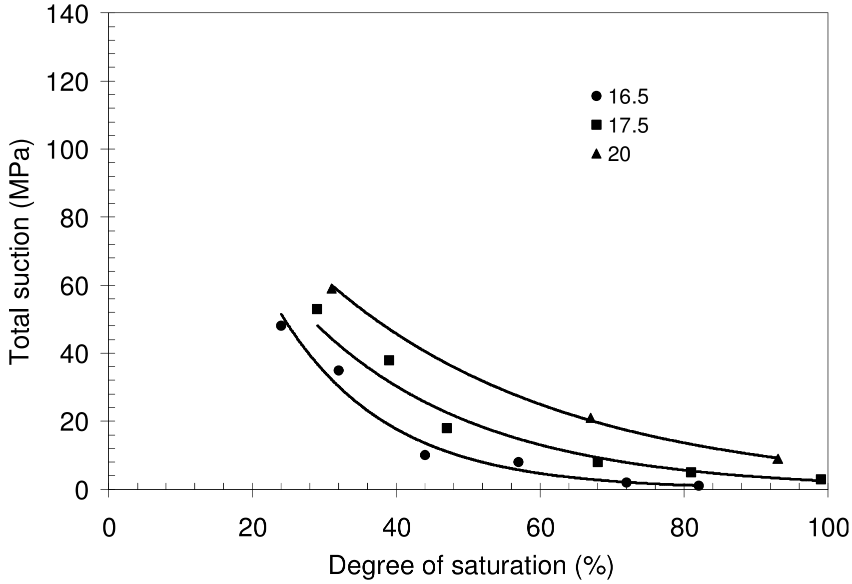

Fig 6: Suction response of the samples with degree of saturation at three different dry densities (50 % Bentonite)

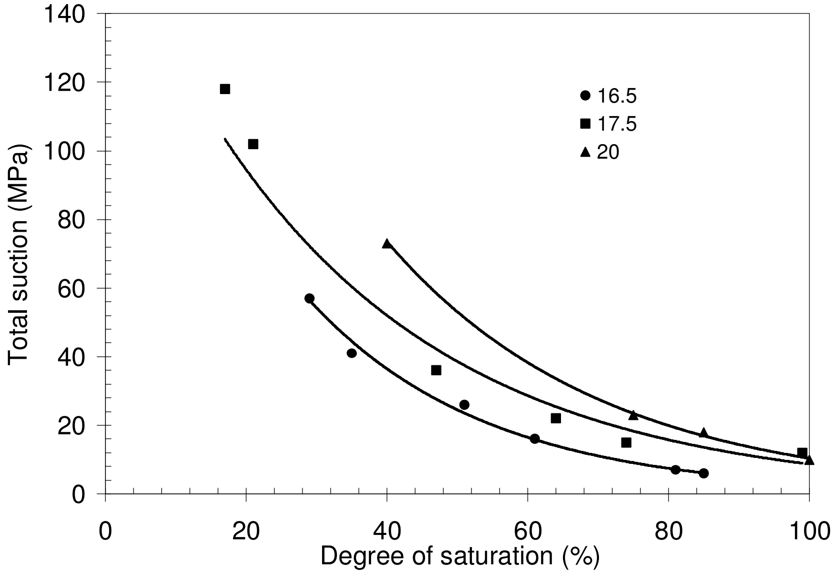

Fig 7: Suction response of the samples with degree of saturation at three different dry densities (70 % Bentonite)

ECDD is calculated in each case and the variation of the total suction with ECDD at three different degrees of saturation has been plotted in fig 8 for all three mixes. Table 3 provides the ECDD of the three compacted mixes and Table 4 provides the total suction values at different ECDDs and three different degrees of saturation.

Table 3: ECDDs of the specimens at different dry densities

Bentonite fraction (%)	Dry density (kN/m^3)	ECDD (kN/m^3)
30	16.5	9.0
	17.5	9.7
	20.0	12.7
50	16.5	12.1
	17.5	13.2
	20.0	16.0
70	16.5	14.2
	17.5	15.3
	20.0	17.7

Table 4: Values of total suction at different ECDDs.

ECDD(kN/m^3) →	9.00	9.70	12.10	12.70	13.10	14.20	15.10	16.00	17.70
S$_r$ (%)	Total suction (MPa)								
40	7.94	9.97	17.68	14.12	30.30	36.52	51.96	45.73	73.45
60	1.43	2.84	4.66	8.51	13.06	16.51	28.57	25.00	38.19
80	0.26	0.81	1.23	5.13	5.63	7.46	15.71	13.66	19.86

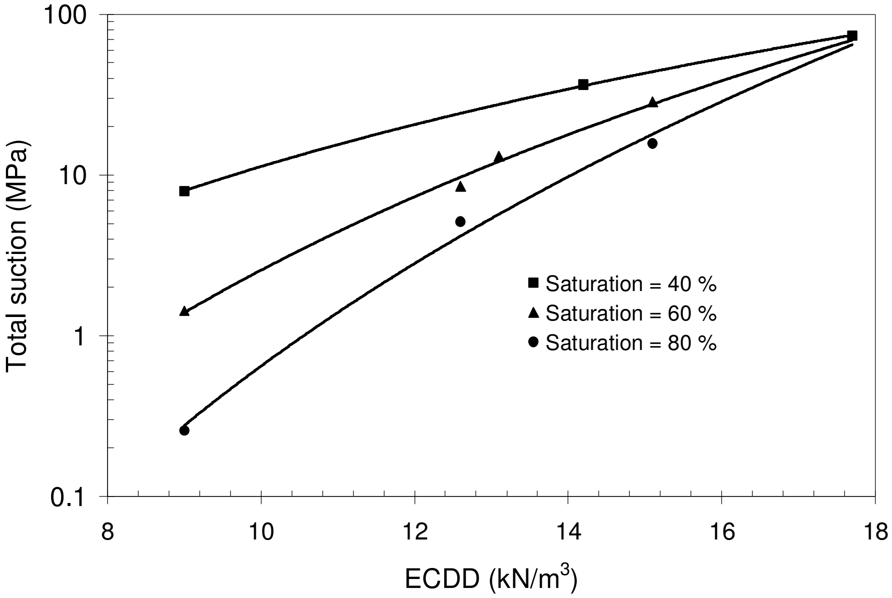

Fig 8: Variation of the total suction with ECDD at three different degrees of saturation

Fig 8 exhibits that the total suction increases with an increase in the ECDD of the compacted specimens. The three curves representing three different saturations converge at ECDD of 17.7 kN/m^3, i.e., when the mix is compacted at ECDDs > 17.7 kN/m^3, the total suction becomes independent of the degree of saturation. This may be because at high ECDDs, the bentonite particles are very closely spaced and thus the number of continuous capillary pores, participating in the growth of matric suction are very less. Since, matric suction is mainly contributed by the capillary action in continuous interparticle pores, the volume of water required to satisfy this capillary potential will be very less when the number of such pores become very small at high ECDDs (> 17.7 kN/m^3). It is probable that at S_r of 40 %, the compaction water content satisfies capillary potential in the continuous interparticle pores and the addition of excess water may fill the discontinuous interparticle pores that do not significantly contribute to capillary potential. Thus the suction will be the same in the entire range of saturation at ECDDs > 17.7 kN/m^3. It is hence desirable to compact bentonite-sand mixes at ECDDs > 17.7 kN/m^3, since the suction and hence engineering properties may not be sensitive to variations in degree of saturation.

CONCLUSIONS

The effect of dry density and the clay content on the total suction of bentonite sand mix has been presented. The term Effective Clay Dry Density (ECDD) was used to present the effect of both dry density and clay content on the total suction of the bentonite-sand mix. Total suction was found to increase with ECDD at all ranges of saturations. At high ECDD (> 17.7 kN/m^3), the suction was found to be independent of the degree of saturation. It is hence expected that bentonite-sand blocks compacted at high ECDDs (> 17.7 kN/m^3) will be mechanically more stable than those compacted at lower ECDDs.

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