

# Role of microfabric in matrix suction of residual soils

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## Abstract

Residually derived red soils are present in Bangalore District of Karnataka State. The red soils of Bangalore District are generally unsaturated with bulk of the specimens having degree of saturation ( $S_r$ ) from 20% to 70%. In unsaturated soils, pores with small radii act as capillary tubes and retain water in a state of reduced pressure with respect to atmospheric pressure. The reduced pressure of capillary water is termed as matrix suction. Factors influencing matrix suction of unsaturated soils are water content/degree of saturation, relative compaction and particle size. Besides the above-mentioned factors, the microfabric is expected to influence matrix suction ( $u_a - u_w$ ) of unsaturated soils as it determines the relative abundance of different categories of pores in a soil. The study examines the influence of the microfabric on the matrix suction of residual soils from Bangalore District by referencing the matrix suction of undisturbed residual soil specimens to their remolded state. The matrix suction of the undisturbed and remolded soil specimens is determined by the ASTM filter paper method. Information on microfabric of the residual soil specimens is obtained from mercury intrusion porosimetry (MIP) experiments. Experimental results suggest that the matrix suctions of the undisturbed and remolded residual soil specimens are greatly influenced by the relative abundance of the inter-aggregate porosity and intra-aggregate porosity.

*Keywords:* Residual soils; Microfabric; Matrix suction; Porosity

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## 1. Introduction

Residually derived red soils are distributed over the Indian States of Kerala, Tamil Nadu, Karnataka, Andhra Pradesh, Madhya Pradesh, Maharashtra, Goa, Orissa, West Bengal and Northeastern States and

Union Territories of Andaman, Nicobar and Pondicherry. Red soils are also present in Bangalore District of Karnataka State. The physical and chemical weathering of gneissic parent rock formed the red soils of Bangalore District (Ramaiah and Rao, 1969). It has been pointed out that the gneissic rocks of Bangalore region were formed by the invasion of Dharwar schist by granitic material (Ramaiah and Rao, 1969). The region exhibits the characteristic smooth rolling topography of the gneissic terrain. The climate is hot semi-

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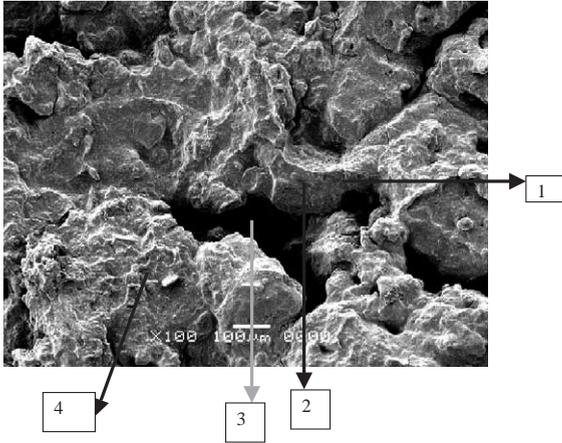


Fig. 1. SEM showing microfabric of undisturbed red soil sample: (1) inter-granular contact, (2) sand particle, (3) macropore, (4) clay aggregate.

arid and characterized by alternate wet and dry seasons. The period from June to October constitutes the wet season, while the period from November to May represents the dry season. The mean temperature in the warmest month (April) is 27 °C and in the coldest month is 20 °C. The average annual rainfall in Bangalore region corresponds to 780 mm. The residual soil profile in Bangalore District can be divided into three zones: (1) the upper zone—a crust of stiff red sandy clays, (2) the intermediate zone—a thick bed of loose to firm micaceous sandy silts and silty sands, (3) the partially weathered zone—the transition to unweathered rock consisting of gravelly silty sands with lenses of relatively sound rock.

A review of literature by [Revanasiddappa \(2000\)](#) showed that the red soils of upper zone (average thickness of upper zone, 1 to 4 m) are generally unsaturated with bulk of the specimens having degree of saturation ( $S_r$ ) from 20% to 70%. In unsaturated soils, the pores with small radii act as capillary tubes and retain water in a state of reduced pressure with respect to atmospheric pressure. The reduced pressure of capillary water is termed as matrix suction as it is related to soil properties within the whole matrix of the soil. At low degrees of saturation, the matrix suction in a soil can be as high as 7000 kPa ([Olsen and Langfelder, 1965](#)). Though matrix suction is also referred to as matric suction, the former nomenclature is adopted in this study. Factors influencing matrix suction of unsaturated soils include water content/

degree of saturation, relative compaction and particle size ([Olsen and Langfelder, 1965](#); [Krahn and Fredlund, 1972](#); [Houston et al., 1994](#); [Rao and Revanasiddappa, 2000](#)). Besides the above-mentioned factors, the microfabric is expected to influence matrix suction ( $u_a - u_w$ ) of unsaturated soils as it determines the relative abundance of different types of pores (large, small, etc.) in a soil. The microfabric of an unsaturated undisturbed soil is made up by (a) arrangement of bulky sand particles along with aggregates of clay platelets and (b) arrangement of clay platelets in the clay aggregates. Capillary bonds and chemical cementation bonds buttress the inter-granular contacts that comprise of sand-sand contact, sand-clay aggregate contact or clay aggregate-clay aggregate contact. Coulombic forces buttress the clay platelet contacts in a clay aggregate. The large pores between sand particles and clay aggregates comprise the macropores of the soil. The pores between clay platelets of a clay aggregate constitute the micropores of the soil ([Dudley, 1970](#); [Barden et al., 1973](#); [Carvalho and Simmons, 1997](#)). The assemblage and bonding that occur between microfabric units determines the relative abundance of macropores and micropores in an undisturbed soil. Visual illustration of microfabric features of an undisturbed red soil specimen from Bangalore District is presented by the scanning electron micrographs (SEM) in [Figs. 1 and 2](#). The SEM in [Fig. 1](#) shows how granular sand particles and clay aggregates arrange to form macropores. The SEM in [Fig. 2](#) illustrates the arrangement of clay platelets within a clay aggregate and the constituent micropores.

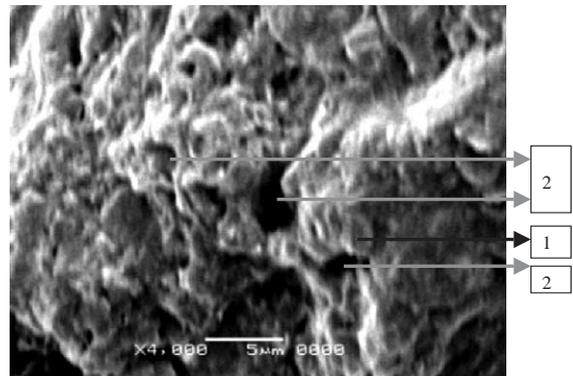


Fig. 2. SEM of clay aggregate: (1) clay platelet, (2) micropore.

The role of microfabric in the matrix suction of unsaturated residual soils has not been examined. Such a study is important as matrix suction has an important bearing on the engineering response of unsaturated soils. Structural stability is imparted to an unsaturated soil by matrix suction that stabilizes the inter-granular contacts in the partially saturated condition. Addition of water destroys the capillary bonds and causes the inter-granular contacts to fail in shear, resulting in volumetric and shear deformations (Burland, 1961; Toll, 1990; Alonso and Gens, 1994; Wheeler, 1994; Gallipoli et al., 2003).

The study examines the influence of microfabric on the matrix suction of residual soils by referencing the matrix suction of undisturbed residual soil specimens to their remolded state. Remolding alters the relative distribution of macropores and micropores in a soil specimen with reference to its undisturbed counterpart. The matrix suction of the undisturbed and remolded soil specimens is determined by the ASTM filter paper method. Information on soil microfabric of the residual soil specimens is obtained from mercury intrusion porosimetry (MIP) experiments.

## 2. Materials and methods

### 2.1. Collection and properties of soil specimens

Undisturbed soil specimens were obtained from 2-m deep test pits at two locations in Bangalore District

Table 1  
In-situ properties of undisturbed soil specimens

Location	Property	Specimen			
		U1-1	U1-2	U1-3	U1-Average
1	Void ratio	0.77	0.81	0.84	0.81
	Water content (%)	16.3	16.0	16.5	16.3
	Degree of saturation (%)	57	54	53	55
Location	Property	Specimen			
		U2-1	U2-2	U2-3	U2-Average
2	Void ratio	0.97	0.92	0.94	0.94
	Water content (%)	17.7	16.9	17.2	17.3
	Degree of saturation (%)	49	50	50	50

Table 2  
Index properties of residual soils

Location	Grain size distribution (%)			Liquid limit (%)	Plastic limit (%)	Indian soil classification system, symbol
	Sand	Silt	Clay			
1	43	34	23	45	20	CI
2	36	23	39	59	26	CH

(Hosur Bandi—location 1 and Indian Institute of Science Campus—location 2) by manually pushing standard oedometer ring (76 mm diameter, 25 mm high)+extension collar (76 mm diameter, 25 mm high) assembly into the base of the pits. The specimens contained in the oedometer rings were packed in airtight polyethylene bags, transported to the laboratory and used in laboratory tests immediately. Sufficient quantity of representative (disturbed) soil was also collected from each test pit.

Table 1 details the in-situ properties of the undisturbed soil specimens from the two locations and Table 2 their index properties. The six undisturbed specimens (three from each location) were employed in matrix suction tests. Undisturbed specimens from location 1 are designated as U1-1 to U1-3 and undisturbed specimens from location 2 are designated as U2-1 to U2-3. In-situ properties of void ratio, water content and degree of saturation of the three undisturbed specimens from each location are reported in Table 1. Void ratio of a soil sample is defined as the ratio of volume of voids to volume of soil solids. Thus, densely packed soils have a low void ratio. Typical values in the field range from 0.1 to 2.5. Water content of a soil is defined as the ratio of mass of water to mass of soil solids. Small water content indicates a dry soil, while large water content indicates a wet one. Values in the field are between 3% and 70%, but values greater than 100% are sometimes found in sedimentary deposits, below the groundwater table, which simply means that soil has more water than solids. A similar parameter is the degree of saturation, which is the percentage of voids filled with water. This is similar to water content in that both are equal to zero when there is no water. However, degree of saturation has a maximum value of 100% when all the voids are filled with water. The term saturated is used to describe this condition. Soils below the groundwater table are saturated. Soils above

the groundwater table are unsaturated, meaning only part of the voids is filled with water and the remainder contains air. Values of degree of saturation above the water table are usually between 5% and 100%.

Index property tests such as grain size distribution and Atterberg limit tests were performed on representative soils collected from the test pits. Two laboratory tests are commonly used to determine the grain size distribution of soils, namely the sieve analysis and hydrometer test. The sieve analysis determines the grain size distribution of particles larger than 75  $\mu\text{m}$  (gravel and sand termed as coarse-grained soils). Hydrometer analysis gives insight in the distribution of finer particles (silts and clays termed as fine-grained soils). Natural soils almost always contain a variety of particle sizes mixed together. The Atterberg limits assess the plasticity of a soil and its consistency at various moisture contents. The commonly performed Atterberg limits tests are the liquid limit test and the plastic limit test. The liquid limit (LL) of a soil represents the water content at which a soil transits from liquid to plastic state. The plastic limit (PL) of a soil represents the water content at which a soil transits from plastic to semi-solid state. Plasticity index (PI) defined as the difference between liquid limit and plastic limit represents the range of water content in which the soil is plastic, i.e., can be easily molded without cracking or breaking. Soils with large clay content remain plastic over a wide range of water content and thus have large plasticity index. The plasticity index is important in classifying fine-grained soils based on Casagrande's plasticity chart. The important feature of this chart is the empirical A-line that is given by the equation:

$$PI = 0.73(LL - 20) \quad (1)$$

The A-line separates the inorganic clays from inorganic silts. The inorganic clays plot above the A-line. Values for inorganic silts plot below the A-line. For example, laboratory results show that the red soil specimens from the two locations classify as inorganic clays of intermediate to high plasticity (Indian Soil Classification System Symbol, CI and CH).

The grain size distributions of the representative soil specimens were determined as per Indian Standards procedure, IS: 2720-1985 (Methods of test for soils—grain size analysis). Atterberg limits of the representative soil specimens were determined as per

Indian Standards procedure, IS: 2720-1985 (Methods of test for soils—determination of liquid and plastic limit). Air-dried soil fractions finer than 425  $\mu\text{m}$  were used in determination of the Atterberg limits.

X-ray diffraction analysis of representative soil specimen showed kaolinite as the dominant clay mineral and montmorillonite as a secondary clay mineral in its #75  $\mu\text{m}$  fraction. Quartz, mica and feldspar comprised the non-clay mineral fraction of the soil.

## 2.2. Matrix suction measurement

The ASTM Filter Paper Method (ASTM D5928-94 Standard Test Method for Measurement of Soil Suction) determined the matrix suction of the undisturbed and remolded specimens in the unsaturated state. Three undisturbed specimens belonging to the same location (U1-1 to U1-3 location 1 and U2-1 to U2-3 location 2) contained in oedometer rings (76 mm diameter) were trimmed to 25 mm thickness and quickly transferred to three airtight containers of 160 ml capacity. Remoulded specimens were prepared by displacing six additional undisturbed specimens (three from each location) from oedometer rings. The displaced specimens were thoroughly hand-remoulded at their natural water contents that approximately ranged between 16% and 18% (Table 1), then sealed in polyethylene covers and kept in airtight containers. The remoulded specimens used in matrix suction tests were not subjected to any drying prior to compaction. Portions of the remoulded specimens were kept for moisture content determinations. Adding requisite volume of water to the remoulded specimens made up any deficiency in moisture content of the remoulded specimens with respect to their undisturbed counterparts due to evaporation loss. After moisture content adjustment if any (maximum evaporation loss corresponded to 0.5%), the remoulded specimens were statically compacted in oedometer rings (diameter=76 mm and height=25 mm) to the void ratios of their undisturbed counterparts. The remolded specimens from location 1 are designated as R1-1 to R1-3 and from location 2 are designated as R2-1 to R2-3 (Table 3). The six remolded specimens (three for each location) were also transferred to six airtight containers (capacity of each container=160 ml) for matrix suction measurements.

Table 3  
Matrix suction of residual soil specimens

Undisturbed specimens	Matrix suction (kPa)	Remolded specimens	Matrix suction (kPa)
U1-1	290	R1-1	860
U1-2	280	R1-2	820
U1-3	255	R1-3	790
U1-Average	275	R1-Average	823
U2-1	5750	R2-1	8380
U2-2	6125	R2-2	8445
U2-3	5895	R2-3	8175
U2-Average	5923	R2-Average	8333

Filter paper disks (Whatman No. 42, 45 mm diameter) were used as sensors to measure the matrix suction of the soil specimens. Contact between an undisturbed/remolded soil specimen and the filter paper disk was achieved by placing the filter paper disk at the base of the container and the specimen above it. To prevent soil contamination, the filter paper disk was sandwiched between two sacrificial filter papers that had slightly larger diameter than the central disk. The sealed containers were transferred to a desiccator and allowed to equilibrate for 10 days at 24 °C in an incubator. After 10 days of equilibration, the equilibrium moisture content of the filter paper was determined. The equilibrium moisture content of the filter paper was converted to matrix suction of the unsaturated specimen by referring to the ASTM calibration curve for Whatman No. 42 filter paper.

Matrix suction measurements were made in triplicate on the undisturbed and remolded specimens from each location. The matrix suctions of undisturbed specimens U1-1, U1-2 and U1-3 from location 1 correspond to 290, 280 and 255 kPa, respectively, at moisture contents of 16.3%, 16.0% and 16.5%, respectively (Table 3). The matrix suctions of undisturbed specimens U2-1, U2-2 and U2-3 from location 2 correspond to 5750, 6125 and 5895 kPa, respectively, at moisture contents of 17.7%, 16.9% and 17.2%, respectively (Table 3). The matrix suctions of undisturbed specimens from location 2 are commensurate with their moisture contents. However, the matrix suctions of undisturbed specimens from location 1 do not follow the expected trend of variations of suction and water content. For example, sample U1-2 shows the lowest water content and intermediate value of suction. Conversely, sample U1-1 shows the highest value of suction but intermediate water content.

The matrix suctions of undisturbed specimens from location 1 do not follow the expected trend of variations of suction and water content presumably due to errors associated with contact efficiency between filter paper sensors and soil specimens and measurements of small masses of the filter papers. The average matrix suctions of the undisturbed and remolded specimens are used in the study.

### 2.3. Mercury intrusion porosimetry (MIP)

The pore-size distributions of the undisturbed and remolded specimens were determined using the Autoscan mercury intrusion porosimeter. The mercury intrusion porosimeter had a pressurizing capacity of 2 psi to 60,000 psi (14 to 413,685 kPa). Cylinders approximately 5 mm in diameter and 15 mm in length were trimmed from additional set of undisturbed specimens (U1-4 and U2-4) from locations 1 and 2 that had in-situ void ratios of 0.81 and 0.94 and water contents of 16.3% and 17.3%, respectively.

The remaining portion of the undisturbed specimens from locations 1 and 2 (U1-4 and U2-4) were thoroughly hand-remolded at their natural water contents (16.3% to 17.3%), sealed in polyethylene covers and kept in airtight containers. The remoulded specimens used in porosimeter tests were not subjected to any drying process. Portions of the remoulded specimens were kept for moisture content determinations. Adding requisite volume of water to the remoulded specimens made up any deficiency in moisture content of the remoulded specimens with respect to their undisturbed counterparts due to evaporation loss. After moisture content adjustment if any, the remoulded specimens were statically compacted in oedometer rings (diameter=76 mm and height=25 mm) to the void ratios of their undisturbed counterparts. The remolded specimens from locations 1 (R1-4) and 2 (R2-4) were trimmed from these compacted samples. The trimmed undisturbed/remolded specimens were freeze-dried.

The freeze-dried specimen was surrounded by mercury in the sample tube and pressurized in small increments. The volume of mercury entering the specimen after each increment was automatically recorded. Each pressure increment forced mercury into the accessible soil pores of a diameter larger

than or equal to that calculated by the Washburn (1921) equation for the given pressure. In this manner, cumulative mercury volume intruded per gram of soil (cc/g) versus entrance pore radius (micrometer or microns, symbol— $\mu\text{m}$ ) curves were generated for the undisturbed and remolded specimens.

### 3. Results and discussion

#### 3.1. Matrix suction results

Table 3 reports the matrix suction of residual soil specimens from the two locations in their undisturbed and remolded states. The residual soil specimens from both locations exhibit higher matrix suctions in the remolded state (823 and 8333 kPa, corresponding to R1-Average and R2-Average, Table 3) than in the undisturbed state (275 and 5923 kPa corresponding to U1-Average and U2-Average, Table 3). The remolded specimens in Table 3 were compacted at the same void ratios and water content as their undisturbed counterparts, despite which the matrix suctions of the undisturbed and remolded specimens are largely different. The void ratios and water contents of the undisturbed specimens from locations 1 and 2 employed in matrix suction experiments are reported in Table 1. The largely different matrix suctions of the residual soil specimens from a given location in the undisturbed and remolded conditions imply that the

microfabric has a major influence on the matrix suction of the undisturbed residual soil specimens.

The influence of microfabric on the matrix suction of the undisturbed residual soil specimens is also illustrated by vastly different matrix suctions of the undisturbed specimens from the two locations (U1-Average=275 kPa, U2-Average=5923 kPa). The undisturbed specimen from location 2 has a slightly lower degree of saturation ( $S_r=50\%$ , U1-Average) than the undisturbed specimen from location 1 ( $S_r=55\%$ , U2-Average). Besides the lower degree of saturation, it is anticipated that differences in soil structure also contribute to the large difference in matrix suctions of the undisturbed residual soils from the two locations in Bangalore District. The role of microfabric in impacting the matrix suction behaviour of the residual soil specimens is explained from the mercury intrusion porosimetry results.

#### 3.2. Mercury intrusion porosimetry results

##### 3.2.1. Effect of remolding

Fig. 3 plots the cumulative volume of mercury intruded per gram of soil versus entrance pore radius of the undisturbed and remolded specimens from location 1 (U1-4 and R1-4). Owing to the existence of different categories of pores, the cumulative distribution curves of the undisturbed and remolded specimens approximate into three regions of near constant slopes, namely, a coarse pore region from

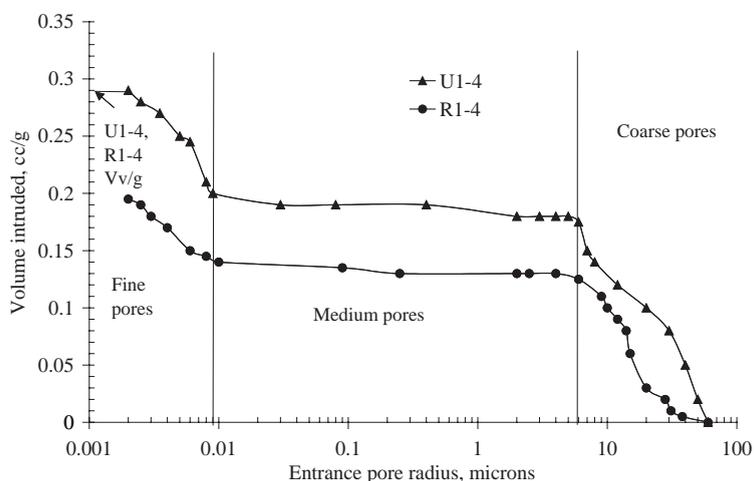


Fig. 3. Cumulative pore-size distribution curves of undisturbed and remolded specimens from location 1.

60 to 6  $\mu\text{m}$ , medium pore region from 6 to 0.01  $\mu\text{m}$  and fine pore region from 0.01 to 0.002  $\mu\text{m}$  (Fig. 3). The total pore space available per unit mass of the undisturbed and remolded specimen ( $V_v/g$ ) is 0.29 cc/g and is represented as a horizontal line in Fig. 3. The entire pore space available in unit mass of the undisturbed specimen was intruded by mercury at the maximum pressure employed (413,685 kPa). Comparatively, only 70% of the total pore space available per unit mass of the remolded specimen (0.29 cc/g) was intruded by mercury at the maximum pressure employed (413,685 kPa). Lesser mercury intrusion occurred into the pore space of the remolded specimen, presumably as pores finer than 0.002  $\mu\text{m}$  (termed very fine pores) contribute to its pore space. Intrusion of very fine pores needs application of pressure larger than 413,685 kPa. The volume of very fine pores in unit mass of specimen is computed as the difference between total pore space available in unit mass of specimen (0.29 cc/g) minus the total intruded volume (0.20 cc/g). This difference representing the volume of very fine pores ( $< 0.002 \mu\text{m}$ ) in unit mass of remolded specimen equals 0.09 cc/g.

Fig. 4 plots the differential volume of mercury intruded per gram of soil versus the entrance pore radius for the undisturbed and remolded specimens from location 1. The differential plot depicts the bimodal character of the pores in the undisturbed and remolded specimens. One of the modes is a large pore mode contributed by the coarse pores ranging

from 60 to 6  $\mu\text{m}$ . The other mode is a small pore mode that encompasses the medium and fine pores. The very fine pores ( $< 0.002 \mu\text{m}$ ) would also contribute to the small pore mode of the remolded specimen. Based on a synthesis of MIP and scanning electron microscopy results, Lefebvre and Delage (1986) interpreted that the large pore mode contributes to the inter-aggregate pores and the small pore mode to the intra-aggregate pores of soil samples. Extending this interpretation to bimodal pore-size distribution of residual soils, large pore mode apparently contributes to the inter-aggregate porosity constituted by the macropores. Comparatively, the small pore mode contributes to the intra-aggregate porosity constituted by the micropores.

Fig. 5 plots the frequency distribution of pores of the undisturbed and remolded specimens from location 1. The coarse pores constitute 60% of the total pore space (0.29 cc/g) and medium and fine pores constitute the remaining (40%) pore space in the undisturbed specimen. The frequency distribution in Fig. 5 also shows that the remolded specimen has smaller coarse pore content than the undisturbed specimen. The MIP data in Figs. 3 and 5 hence bring out that, despite similar void ratio, the remolded specimen is characterized by a different pore-size distribution than the undisturbed specimen. The smaller coarse pore content (0.13 cc/g) and occurrence of very fine pore content (0.09 cc/g) imparts higher matrix suction to the unsaturated remolded specimen than its undis-

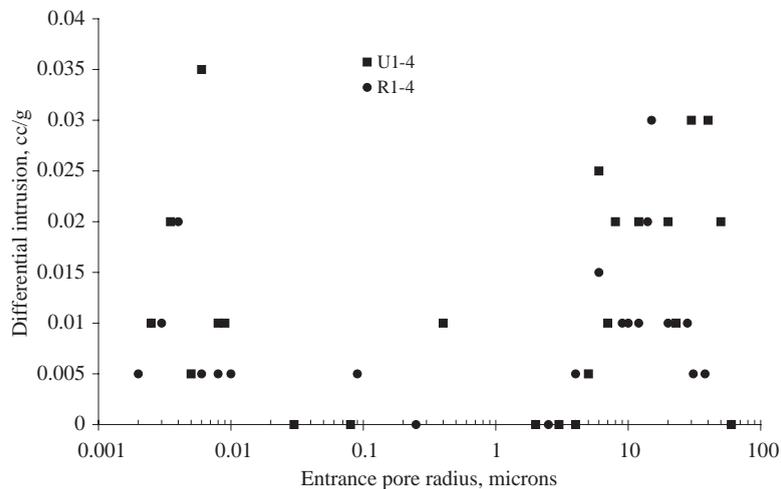


Fig. 4. Differential pore-size distribution curves undisturbed and remolded specimens from location 1.

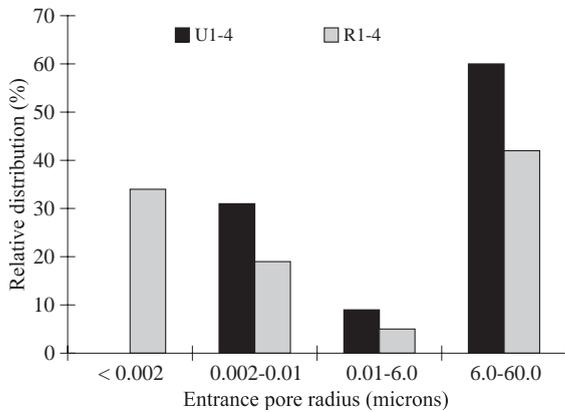


Fig. 5. Frequency distribution of pores in undisturbed and remolded specimens from location 1.

turbed counterpart. Further, the higher matrix suction of the remolded specimen from occurrence of pores finer than 0.002  $\mu\text{m}$  and smaller coarse pore content implies that the matrix suction of residual soil specimens depend on the relative abundance of intra-aggregate and inter-aggregate porosity.

Fig. 6 plots the cumulative volume of mercury intruded per gram of soil versus entrance pore radius ( $\mu\text{m}$ ) for the undisturbed and remolded specimens from location 2 (U2-4 and R2-4). Similar to location 1 specimens, the cumulative pore-size distribution curves of location 2 specimens approximate into a coarse pore region from 60 to 6  $\mu\text{m}$ , medium pore region from 6 to 0.01  $\mu\text{m}$  and fine pore region from

0.01 to 0.002  $\mu\text{m}$ . The total pore space available per unit mass of the undisturbed and remolded specimens from location 2 ( $V_v/g$ ) is 0.35 cc/g. Relatively small fraction (17%) of this available pore space (0.35 cc/g) is intruded by mercury in the remolded specimen in comparison to the undisturbed specimen (29%). Differences in cumulative intrusions occur as the undisturbed specimen has larger coarse (0.04 cc/g), medium (0.04 cc/g) and fine (0.02 cc/g) pore contents and smaller very fine pore content (0.25 cc/g) than its remolded counterpart (coarse, medium, fine and very fine pore contents=0.032, 0.016, 0.012 and 0.29 cc/g).

The much smaller cumulative intrusions in location 2 specimens (17% to 29%) imply a preponderance of very fine pore content (71% to 83%) in the undisturbed and remolded specimens from location 2. The predominance of very fine pore content also agrees with the relatively large matric suctions of location 2 specimens (5923 to 8333 kPa, Table 3). The location 2 specimens also exhibit bi-modal nature as depicted by the differential intrusion plots in Fig. 7.

### 3.2.2. MIP results of undisturbed specimens

Fig. 8 compares the cumulative mercury volumes intruded per gram of soil (cc/g) versus entrance pore radius ( $\mu\text{m}$ ) of undisturbed specimens from locations 1 and 2. The total pore spaces available per unit mass ( $V_v/g$ ) correspond to 0.29 cc/g and 0.35 cc/g for U1-4

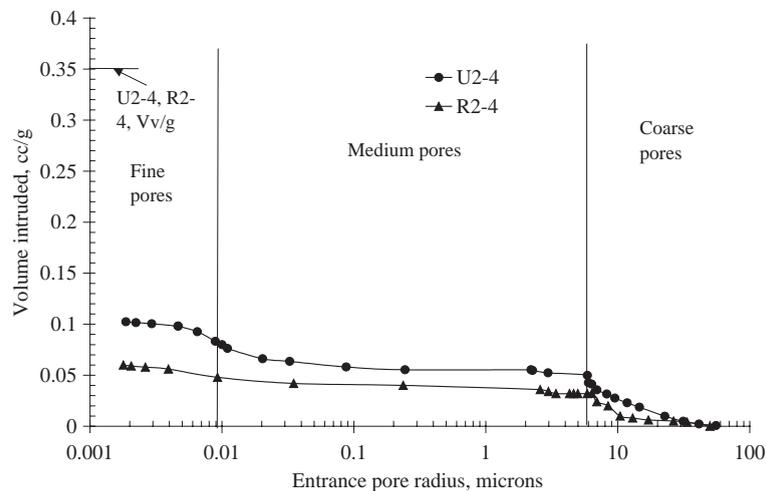


Fig. 6. Cumulative pore-size distribution curves of undisturbed and remolded specimens from location 2.

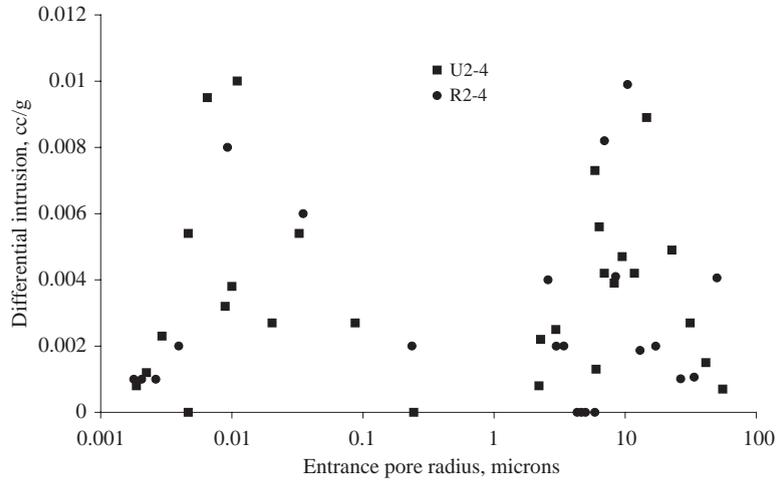


Fig. 7. Differential pore-size distribution curves undisturbed and remolded specimens from location 2.

and U2-4 specimens (indicated by horizontal lines on the graph). The U1-4 specimen approximately has five-fold higher coarse pore content (60–6 μm range) than the U2-4 specimen. Further, only 30% of the available pore space (0.35 cc/g) is intruded by mercury in U2-4 specimen presumably as pores <0.002 μm predominate this specimen. The U1-4 specimen has slightly higher degree of saturation (55%) than the U2-4 specimen that would act to somewhat lower the matrix suction of the U1-4 specimen (Rao and Revanasiddappa, 2000). Major differences in the matrix suctions of U1-4 and U2-4 specimens apparently arise from the pronounced dif-

ferences in their pore-size distributions. The predominance of very fine pores (71%) at the expense of coarse pore content in the undisturbed specimen from location 2 is apparently responsible for its relatively high matrix suction (average matrix suction=5923 kPa) in comparison to the undisturbed specimen from location 1 (average matrix suction=275 kPa). The higher matrix suction of the undisturbed specimen from location 2 owing to occurrence of pores finer than 0.002 μm highlights the importance of the relative abundance of intra-aggregate and inter-aggregate porosity on the matrix suction of undisturbed residual soils.

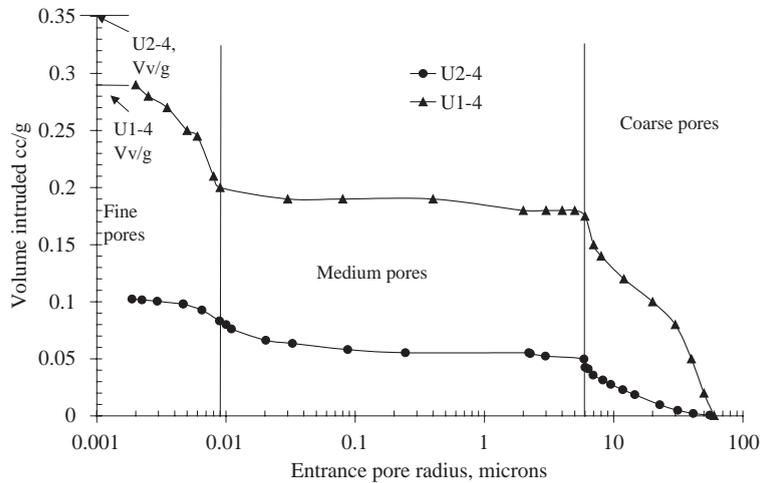


Fig. 8. Cumulative pore-size distribution curves of undisturbed specimens from locations 1 and 2.

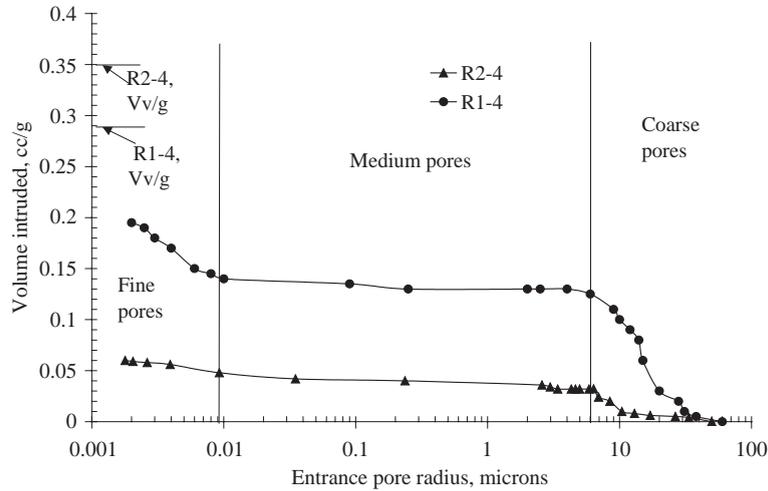


Fig. 9. Cumulative pore-size distribution curves of remolded specimens from locations 1 and 2.

### 3.2.3. MIP results of remolded specimens

Fig. 9 compares the cumulative mercury intrusion curves of the remolded specimens from the two locations. The R1-4 specimen has approximately four-fold larger coarse pore content (0.13 cc/g) than the R2-4 specimen (0.032 cc/g). Only 17% of the available pore space (0.35 cc/g) is intruded by mercury in R2-4 specimen, while 70% of available pore space (0.29 cc/g) is intruded in the R1-4 specimen. Much smaller intrusion occurs in the R2-4 specimen presumably as pores  $< 0.002 \mu\text{m}$  predominate (83%). The predominance of very fine pores ( $< 0.002 \mu\text{m}$ ) and smaller coarse pore content of the remolded specimen from location 2 concurs with its relatively high matrix suction (average matrix suction = 8333 kPa) in comparison to the remolded specimen from location 1 (average matrix suction = 823 kPa).

## 4. Conclusions

Differences in matrix suctions and pore-size distributions of (a) undisturbed and remolded residual soil specimens from the same location, (b) undisturbed residual soil specimens from different locations and (c) remolded residual soil specimens from different locations imply that the microfabric has a major influence on the matrix suction of the residual soil specimens in the undisturbed and remolded conditions. Microfabric determines the relative abundance of dif-

ferent types of pores in a soil. Mercury intrusion porosimetry indicated that the pore-size distribution of the undisturbed and remolded residual soil specimens has bi-modal character. One mode is the large mode embracing the coarse pore region (from 60 to 6  $\mu\text{m}$ ). The other is the small pore mode embracing the medium (from 6 to 0.01  $\mu\text{m}$ ), fine (from 0.01 to 0.002  $\mu\text{m}$ ) and very fine ( $< 0.002 \mu\text{m}$ ) pore regions. Based on the findings of the earlier researchers, it is inferred that the large pore mode contributes to the inter-aggregate porosity constituted by the macropores. The small pore mode contributes to the intra-aggregate porosity constituted by the micropores. The matrix suction of the undisturbed residual soil specimens is greatly influenced by the relative abundance of the inter-aggregate porosity and intra-aggregate porosity suggested by the matrix suction and MIP results of the residual soil specimens in the undisturbed/remolded conditions. For example, the smaller coarse pore content and occurrence of very fine pore content ( $< 0.002 \mu\text{m}$ ) imparted higher matrix suction to the unsaturated remolded specimens from locations 1 and 2 than their undisturbed counterparts. The predominance of very fine pores (71% to 83%) at the expense of coarse pore content in the undisturbed and remolded specimens from location 2 were responsible for their relatively higher matrix suctions in comparison to the undisturbed and remolded specimens from location 1. The dependence of matrix suction on the relative abundance of inter-aggregate and intra-aggregate porosity

suggests that microfabric plays an important role in determining the matrix suction magnitudes of undisturbed and remolded soils.

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