Macroscopic and microscopic study of unsaturated shear strength behaviour of type-F fly ash

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\textbf{ABSTRACT}

Fly ash is a by-product of thermal power plant generated due to the combustion of coal. The silt size hollow spherical particles of fly ash have low specific gravity and high crushability. Fly ash is used as a structural fill in highway/railway embankments that remain unsaturated during most of the year, and its behavior under unsaturated conditions has not been explored yet. The current research explains a procedure to determine unsaturated shear strength parameters of type-F fly ash by using conventional shear strength parameters and matric suction. A series of filter paper tests and consolidated undrained (CU) triaxial tests were conducted to obtain the soil water characteristic curve (SWCC) and effective shear strength parameters ($c'$ & $\phi'$) of fly ash respectively. Unconfined compression (UC) test series at varying degree of saturation was performed to determine unsaturated shear strength (USS) of fly ash as a function of matric suction. USS of fly ash was observed to increase with matric suction until it reached the residual zone of unsaturation, after which it was observed to reduce. The angle of internal friction with respect to matric suction ($\phi^b$) increased and stiffness decreased with the increment in degree of saturation. Additionally, the effect of crushability of fly ash particles on matric suction evolution was also analyzed using Scanning Electron Microscope (SEM) images to evaluate its microscopic behavior. The reduction in matric suction with increasing crushing cycles could be attributed to the breakage of cenospheres and deformation of plerospheres.

\textbf{Keywords:} fly ash, unsaturated, matric suction, shear strength, cenospheres, plerospheres

\textbf{1 INTRODUCTION}

Thermal power plants fulfil the major electricity requirements of the country (India) by burning coal to produce electricity. Fly ash is generated as a by-product in the process of coal combustion. The disposal and consumption of this fly ash is a major environmental concern. Every coal plant has different types of coals and its burning process, which lead to generation of different types of fly ash. Few researchers (Martin et al., 1990; Pandian, 2004; Kim et al., 2005) studied the basic geotechnical properties of fly ash to understand its nature. They tried to determine the suitability of fly ash material as structural fills, an alternative of natural soils. Fly ash can be used in bulk as a backfill material in retaining walls, reinforced fill material in geosynthetic reinforced soil walls, earthen embankments, sub-base material in road-railway construction, etc (Toth et al., 1988; Pandian et al., 1998; Pandian, 2004; Kim et al., 2005; Gupta and Sachan, 2018).

Shear strength is an important engineering property required for the design of geotechnical structures. Several researchers worked on the shear strength behaviour of fly ash under saturated conditions. Sherwood and Ryley (1966), Digioia and Nuzzo (1972), Yudbir and Honjo (1991), and Singh (1996) studied the effect of free lime content present in the fly ash and its effect on shear strength properties. Few researchers (Martin et al., 1990; Singh and Panda, 1996; Kim et al., 2005; Kim and Prezzi, 2008) studied the behaviour of saturated shear strength parameters and concluded that major component in the shear strength of fly ash is due to internal friction angle. Most of the geotechnical structures remained unsaturated during most part of the year, thus unsaturated behaviour of fly ash needs to be explored. Stability and strength during unsaturated conditions can be governed by the matric suction fluctuations. A series of tests was conducted in the current research work to study the variation in shear strength of unsaturated fly ash with matric suction under uncrushed state. The unsaturated shear strength parameter ($\phi^b$) was estimated from matric suction ($u_a-u_w$) and conventional shear strength parameters ($c'$ and $\phi'$) by using methodology proposed by Vanapalli et al. (1999).

Fly ash particles are mainly spherical in nature and they can be either cenospheres or plerospheres. Hollow fly ash particles are called as cenospheres, whereas plerospheres are hollow particles filled with many other small size particles (Fisher et al., 1978). These particles undergo crushing with time as fly ash highway/railway

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embankments are subjected to heavy traffic loading conditions. The geotechnical properties of fly ash are modified due to the breakage and deformation of its particles. Thus, it is important to study the effect of crushing and incorporate these changes in design procedures. Gupta and Sachan (2018) conducted experimental study to evaluate the effect of crushing on compactability, compressibility and shear strength of type-F fly ash. They found significant variation in these properties with crushing. Matric suction is also an important engineering property of fly ash in unsaturated state. The current research work further assessed the effect of crushing on matric suction evolution. Impact loading in the form of compaction energy was applied to crush the fly ash particles. A series of in-contact filter paper tests were conducted on fly ash specimens at different degree of crushing cycles. Scanning electron microscope (SEM) images were taken for each crushing cycle and analysed to relate the macroscopic behaviour (matric suction) of type-F fly ash with its microscopic behaviour (particle’s shape and size).

2 EXPERIMENTAL SCHEME

2.1 Material properties

Fly ash used for the current study was collected from Gandhinagar Thermal Power Plant (Gujarat, India). The basic geotechnical properties of fly ash sample (S0) in its uncrushed state were obtained by conducting grain size distribution test (GSD), liquid limit, specific gravity, Standard Proctor test, consolidation and falling head permeability tests. These properties are tabulated in Table 1. The majority particles of the fly ash lied in the range of 2 to 75 μ particle size, which is the range of silt size particles. Due to non-cohesive nature of fly ash, the liquid limit was determined through cone penetration method and plastic limit test could not be performed. Chemical composition of fly ash material was determined through X-ray diffraction (XRD) analysis. XRD pattern of fly ash indicated the presence of quartz, mullite, corundum and hematite minerals. The details regarding relative percentages of various minerals present in fly ash is given in Gupta and Sachan (2018). The fly ash sample was classified as type-F fly ash, as per ASTM classification since the combined relative percentage of silica, alumina, and iron oxide was found to be greater than 70%. The spherical shape of uncrushed fly ash particles was observed from scanning electron microscope (SEM) images of uncrushed fly ash.

2.2 Experimental program

The unsaturated shear strength parameters of type-F fly ash were determined using methodology proposed by Vanapalli et al. (1999). A series of unconfined compression (UC) tests were performed on uncrushed fly ash specimens (S0) having dry density of 1.16 g/cm³ and degree of saturation (Sₚ) varying from 30% to 90% (Sₚ = 30%, 40%, 50%, 60%, 70%, 79%, & 90%). The corresponding water content values are mentioned in a Table 2. All the specimens for UC tests were prepared by moist tamping method in four equal layers in a cylindrical mould of 100 mm height and 50 mm diameter. Consolidated undrained (CU) triaxial compression tests were performed on specimens of fly ash at three different confining pressures of 100, 200, and 300 kPa. The samples (50 mm diameter & 100 mm height) were prepared at OMC and MDD of 31% and 1.16 g/cm³ respectively using moist tamping method. The specimens was saturated in three stages as CO₂ flushing, water flushing and forced saturation. CO₂ flushing was performed to replace entrapped air inside the specimen with CO₂ as it is soluble in water. Water flushing was then performed at 20 kPa effective confining pressure followed by forced saturation. Forced saturation was conducted till the value of Skempton’s pore pressure parameter B was achieved greater than 0.95. All the CU specimens were saturated at the back pressure of 470 kPa. All the saturated specimens were consolidated and then sheared at a strain rate of 0.1%/min. A series of in-contact filter paper tests were conducted to determine matric suction (uₐ-uₚ) values of specimens at varying degrees of saturation and to establish material water characteristic curve (SWCC) for uncrushed fly ash samples. All the filter paper tests were performed in accordance with the procedure given in ASTM code (ASTM D5298-10). Whatman 42, ashless filter papers were used in the procedure. These experiments were performed on the specimens of 1.16 g/cm³ constant dry density with varying degrees of saturation (Sₚ = 30%, 40%, 50%, 60%, 70%, 79%, & 90%). Two filter papers of 60 mm diameter and one with 55 mm diameter were used. Smaller filter paper was sandwiched between the two bigger papers and this stack of filter papers was further sandwiched between two fly ash cakes of height 75 mm and diameter 25 mm. Both the fly ash cakes were prepared by moist tamping method and same dry density and water content was maintained. This whole assembly was then tightened properly to maintain proper contact between soil cake and filter paper by tied them (from the sides and top) with the help of electric tape. The tied specimen was carefully transferred to a glass jar and the cap of the glass jar was also sealed properly with the electric tap. The glass jar was further

| Table 1. Basic geotechnical properties of type-F fly ash |
|-----------------------------------------------|
| Geotechnical properties                     | Values |
|-----------------------------------------------|
| Specific gravity, Gₛ                         | 2.14   |
| Liquid limit, wₐ (%)                         | 44     |
| Maximum dry density, MDD (g/cm³)             | 1.16   |
| Optimum moisture content, OMC (%)            | 31     |
| Permeability, k (cm/s)                       | 7.14 * 10⁻⁵ |
| Compression index, Cc                         | 0.057  |

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placed in the temperature and humidity controlled incubator for 7 days to ensure equilibration at constant temperature of 20 °C. After 7 days of equilibration time, the assembly was removed and the water content of the central filter paper (dia. = 55 mm) was calculated with great precision. Matric suction value was then determined from the calibration chart given in the ASTM code for Whatman 42 ashless filter paper at particular water content value. This procedure was repeated for all specimens with different degree of saturation ranging from 30% to 90% and repeatability was ensured by comparing results of two similar tests.

Additionally, the effect of crushability of fly ash particles on matric suction evolution was also analyzed. To prepare the specimens with different degrees of crushing, type-F fly ash samples were subjected to several cycles of impact loading. The uncrushed fly ash specimen denoted as S0. When S0 specimen compacted as per Standard Proctor test procedure in three equal layers for one round, the energy imparted was 592 kJ/m³. Similar to that, 13 such compaction rounds were required to generate one cycle of the Standard Proctor test. Total compaction energy transmitted was 7702 kJ/m³ to prepare S1 specimen, as mentioned in Table 3. S1 specimen was then kept for oven-drying for 24 hours, and one more cycle of impact loading was applied on it to generate S2 specimen. Similarly, S3 and S4 specimens were obtained. S0, S1, S2, S3, and S4 specimen indicated the zero, one, two, three and four number of impact loading cycles on fly ash respectively. Table 3 lists the imparted compaction energy to generate fly ash specimens (S0-S4) at different degrees of crushing along with their MDDs and OMCs. Grain size distribution and liquid limit tests were performed to calculate the effect of crushing on index properties of fly ash. Their values are listed in Table 3 for uncrushed specimen (S0) to highly crushed specimen (S4). The in-contact filter paper tests were conducted on all the specimens from S0 to S4 by keeping the dry density and water content constant as 1.16 g/cm³ and 31%, respectively. Scanning electron microscope (SEM) images were taken for S0 to S4 specimens to determine the effect of crushing cycles on cenospheres and plerospheres.

### 3 RESULTS AND DISCUSSION

The first series of tests were focused on the determination of unsaturated shear strength parameters of type-F fly ash by using conventional UC and CU triaxial testing along with matric suction measurements by filter paper tests. The second series was performed to evaluate degree of crushability of fly ash particles and its effect on matric suction generation. An attempt has been made to correlate the macroscopic behaviour of fly ash with its microstructural modification through SEM image analysis.

#### 3.1 Effect of matric suction variation on unsaturated shear strength parameters of type-F fly ash

The unsaturated shear strength is a function of two separate stress state variables i.e. net normal stress ($\sigma_n$-$u_i$) and matric suction ($u_i$-$u_a$). Fredlund et al. (1978) proposed an equation (1) to determine shear strength of unsaturated soils by extending the concept of traditional Mohr-Coloumb equation with consideration of two stress state variables.

$$\tau_f = c' + (\sigma_n - u_i)\tan\varphi' + (u_i - u_a)\tan\varphi_b$$

Where, $c'$ is effective cohesion and $\varphi'$ is effective angle of internal friction. Both these parameters are saturated shear strength parameters. $\varphi_b$ is the angle of shearing resistance with respect to matric suction. ($\sigma_n$-$u_i$) and

| Sample no. | No. of crushing cycles (N) | Energy imparted (kJ/m³) | OMC (%) | MDD (g/cm³) | LL, wL (%) | (u_i-u_a) (kPa) |
|------------|---------------------------|-------------------------|---------|-------------|------------|-----------------|
\((u_a-u_w)\) represents the net normal stress on the plane of failure and matric suction at failure respectively. Experimental determination of unsaturated shear strength using suction controlled apparatus required very long testing duration, trained personals and expensive machinery (Vanapalli et al., 1996; Nishimura et al., 2008; Vanapalli, 2009; Al-Mahbashi and Elkady, 2017). Due to these difficulties involved in unsaturated shear strength testing, Vanapalli et al. (1999) proposed a methodology to determine unsaturated shear strength parameter by assuming planer failure envelope. They recommended simplified procedure by using conventional shear strength tests (e.g. UC and CU) and matric suction measurements. Equation (2) is used in current study to determine the values of \(\phi^b\), which represents the contribution of matric suction towards undrained shear strength of unsaturated fly ash.

\[
tan\phi^b = \frac{\sigma_3}{2} \left( \cos \theta + \sin \theta \tan \phi \right) - \frac{\sigma_1}{2} \left( \tan \phi - \epsilon \right)
\]

Where, \(\sigma_f/2 = \) undrained shear strength.

3.1.1 Soil water characteristic curve

The soil water characteristic curve (SWCC) of uncrushed fly ash specimen, which determined through filter paper tests, is plotted in Fig. (1). SWCC is expressed as the relationship between degree of saturation \((S_r)\) and matric suction \((u_a-u_w)\). All the measured matric suction values are presented in Table 2. To generate the SWCC in the entire suction range, the mathematical fit (equation 3) given by Fredlund and Xing (1994) was used.

\[
\theta = \theta_s \ast \left[ \frac{1}{\left( \ln \left( 1 + \left( \frac{u_a - u_w}{a} \right) \right) \right) ^n} \right] ^m
\]

Where, \(\theta_s = \) volumetric water content at \(S_r=100\%\), \((u_a-u_w)_r = \) suction corresponding to the residual degree of saturation, \((a, n \& m) = \) fitting parameters determined based on experimental results.

The volumetric water content was converted to degree of saturation by using volume-mass relationships and SWCC was plotted. The experimental data and mathematical fit was found to be in good agreement. The air-entry value (AEV) and residual degree of saturation \((S_r)_r\) were estimated to be 10 kPa and 35%, respectively from Fig. (1). The residual suction \((u_a-u_w)_r\) value corresponding to \((S_r)_r = 35\%\) was obtained as 100 kPa. Based on these values, SWCC can be divided into three subzones as: boundary effect zone, transition zone and residual zone of unsaturation (Vanapalli et al., 1996; Vanapalli et al., 1998; Vanapalli et al., 2000). These zones are mentioned in Fig (1). The SWCC of uncrushed fly ash specimen was observed to be similar to that of cohesionless type soils.

![Soil water characteristic curve (SWCC) of type-F fly ash](Image)

3.1.2 Saturated and unsaturated shear strength parameters

The effective shear strength parameters, \(\phi^s\) and \(c^s\) were obtained from consolidated undrained (CU) triaxial compression tests and their values were obtained as 38 kPa and 37\(\text{°}\) respectively. The unconfined compressive strength (UCS) values obtained for different degrees of saturation are presented in Table 2. The variation of UCS with matric suction is plotted in Fig. (2), by assuming pore-air pressure as atmospheric and constant matric suction while shearing in UC test. This assumption was valid as the time required to perform UC test was low (high strain rate 1.25%/min). UC test is an unsaturated shear strength tests performed under zero minor principal stresses \((\sigma_2 = \sigma_3 = 0)\), wherein the particles are held together by matrix suction (Fredlund and Rahardjo, 1993; Vanapalli, 2009). Hence, the variation of UCS with matric suction represents actual unsaturated soil behaviour. The UCS of uncrushed fly ash specimen was observed to increase with matric suction until it reached the residual zone of unsaturation, after which it was observed to reduce. The contribution of matric suction to increase the unconfined compressive strength from 177 kPa to 244 kPa was prominently detected in the transition zone only \((S_r = 90\% \text{ to } 50\%)\). As SWCC curve started shifting after transition zone, the UCS decreased non-linearly from 244 kPa to 202 kPa. The similar response of unsaturated shear strength was observed by few researchers for non-cohesive materials (Donald, 1957) and fine grained materials under high suction ranges (Escario and Juca, 1989; Vanapalli and Fredlund, 2000; Vanapalli et al., 2000). The value of \(\phi^b\) is a function of matric suction and thus it is also the function of degree of saturation (Vanapalli, 2009). Hence, after taking this into account, equation (1) can be re-written as below (Vanapalli et al., 1996; Fredlund
et al., 1996; Vanapalli, 2009).

\[ \tau_f = \phi' + (c' - u_w) \tan \phi + (u_a - u_w)(S_r)^k \tan \phi \]  \hspace{1cm} (4)

Where, \( \kappa \) is the fitting parameter. The reason for the reduction in UCS in residual zone of unsaturation can be explained by differentiating the equation (4) by matric suction and can be written as follows,

\[ \tan \phi^b = \frac{d(\tau)}{d(u_a - u_w)} \]  \hspace{1cm} (5)

\[ \frac{\tan \phi^b}{\tan \phi} = \left[ (S_r)^k + (u_a - u_w) \left( \frac{d(S_r)^k}{d(\tau)} \right) (u_a - u_w) \right] \]  \hspace{1cm} (6)

Equation (6) indicates that at higher matric suction values close to the residual zone of unsaturation, \( S_r \) value is extremely small and value of \( \frac{d(S_r)^k}{d(\tau)} \) is negative. Thus the net summation of these two terms approach negative values of \( \tan \phi^b \). The net contribution of matric suction caused the reduction in the unsaturated shear strength of fly ash in the residual zone of unsaturation. This result is very important for the practicing engineers in the design of slopes because the factors of safety of unsaturated fly ash slopes increases till the residual suction value, after that it starts to decrease. This behaviour is contradicting the common perception regarding stability of unsaturated slopes. The unsaturated shear strength behaviour of fly ash was observed to be similar to that of non-cohesive types of soils, which desaturates relatively faster. Hence, when the suction value reached near to the residual suction, the water content could be relatively low and the transfer of suction to the soil particle contact points might not efficient enough. Thus, it might also reduce the shear strength of fly ash at higher range of suction values.

\[ c_{app} = c' + (u_a - u_w) \times \tan \phi^b \]  \hspace{1cm} (7)

The value of \( c_{app} \) is equal to \( c' \) at degree of saturation \( S_r = 100\% \). Values of calculated \( c_{app} \) is mentioned in Table 2. The \( c_{app} \) was found to be increased with the reduction in \( S_r \) value till 50\% degree of saturation and then decreased with further reduction in \( S_r \) values near to the residual zone of unsaturation. At lower degree of saturations (at higher matric suction values), the \( c_{app} \) was more influenced by the matric suction \( (u_a-u_w) \) values as compared to that of \( \phi^b \) values.

![Fig. 2. UCS variation with respect to matric suction](image)

The unsaturated shear strength parameter, \( \phi^b \) values were calculated by using equation (2) and presented in Table 2. The variation of \( \phi^b \) with matric suction is shown in Fig. (3). The value of \( \phi^b \) was found to be decreased non-linearly from 30.24° to 3.42° as matric suction increases from 10 kPa to 202 kPa and \( S_r \) decreases from 90\% to 30\%, respectively. The \( \phi^b \) value was observed close to the \( \phi' \) value (37°) at the AEV of fly ash. This indicated that the effect of unsaturation was not prominent in the boundary effect zone and material behaved similar to fully saturated condition. Apparent cohesion \( (C_{app}) \) due to matric suction can be defined by taking the summation of effective cohesion and strength contribution due to matric suction from equation (1) and can be presented as follows,

![Fig. 3. Unsaturated shear strength parameter (\( \phi^b \)) variation with respect to matric suction](image)

3.1.3 Stiffness variation with matric suction

The stiffness of the specimens was calculated by taking secant modulus at half of the peak axial stress from the stress-strain curves of UC tests. The stiffness of samples was found to increase continuously with the
increase in matric suction and its variation is presented in Fig. (4). The sudden reduction in stiffness at higher degree of saturation ($S_r = 90\%$) can be explained by schematic representation, as shown in Fig. (5). Uncrushed fly ash contains hollow cenospheres and solid plerospheres as shown SEM images (Fig. 6a-6b). At low water content, all the present water might remain in the form of meniscus water and not absorb inside the hollow cenosphere. However, at very high water content, water can absorb or imbibe inside the partially broken hollow cenosphere and make them water saturated (Fig. 5b). The shearing of samples at higher degree of saturation might have led to the breakage of these water filled cenospheres. The escaped water from cenospheres increased the amount of bulk water (Fig. 5c). This could have resulted in the sudden decrease in matric suction, which led to the reduction in stiffness of fly ash sample.

### 3.2 Effect of crushing on matric suction of type-F fly ash

The grain size distribution curves for various crushing cycles are presented in Fig. (7a). The curves were observed to shift towards the left and upward with each increment in crushing cycle. This indicated an increase in the percentage of fines in the fly ash samples as they went under successive crushing cycles. The detailed analysis of these curves in terms of particle breakage parameters are mentioned in Gupta and Sachan (2018). They concluded that the larger particle size range of type-F fly ash was more crushed during impact loading cycles. The compaction curves with different cycles of crushing are shown in Fig. (7b) and the values of MDD and OMC are mentioned in Table 3. The value of MDD increased from 1.16 g/cm$^3$ to 1.22 g/cm$^3$ and OMC decreased from 31\% to 27\% as the degree of crushing increased from S0 to S4.
specimens respectively. The effect of crushing was not observed very prominent in the compaction curve for the last two cycles of impact loading (S3 & S4). Cone penetration method was used to determine liquid limit (LL) of all the fly ash specimens and its value was found to decrease from 44% to 34% for samples S0 to S4 respectively. This behaviour could be compared with the OMC values obtained for different crushing cycles.

![Graph](image1)

Fig. 7. Effect of crushing on type-F fly ash: (a) Grain size distribution curves (b) Compaction curves

To understand the alteration at microscopic particle level, scanning electron microscope (SEM) images were obtained for S0 to S4 specimens subjected to different degree of crushing. The SEM images of uncrushed to highly crushed fly ash specimen are shown in Fig. (6). The uncrushed fly ash specimen contained spherical particles of hollow cenospheres or solid plerospheres. As the number of crushing cycle increases, the hollow cenosphere either broke into small fragmental pieces or compressed completely as observed from Fig. (6c-6d). Few larger fly ash particles were observed, which were filled with several small spherical particles (Fig. 6e-6f). These large particles could be ruptured plerospheres, as their outer covering got damaged during crushing cycles. Initial crushing cycles (S1 & S2) mainly crushed the hollow cenospheres whereas severe deformations of plerospheres were observed at higher crushing cycles (S3 & S4).

The fly ash particles became finer with successive crushing cycles and these crushed particles filled the inter particle void spaces during the compaction process of next cycle which led to the increase in MDD from S0 to S4. The uncrushed fly ash particles retained more water as some amount of water was occupied the void spaces inside hollow cenospheres (Gupta and Sachan, 2018). This could be the reason of higher OMC and LL values for uncrushed specimen (S0). At higher crushing cycles, decrease in OMC and LL could be due to the reduction in water retention capacity because of breakage of cenosphere and degradation of plerospheres.

Effect of crushing on matric suction evolution of type-F fly ash was evaluated by performing a series of in-contact filter paper tests. The value of matric suction ($u_w-u_o$) was found to decrease from 18 kPa to 9 kPa with increase in degree of crushing (S0 to S4). The reduction was found to be linear with respect to crushing cycle, as observed in Fig. (8). The reason for reduction could be explained by the alteration of void spaces within the specimen. The uncrushed specimen had void ratio of 0.84, whereas the void ratio increased to the value of 0.87 for highly crushed specimen prepared at same dry density of 1.16 g/cm³. The increase in void ratio could be attributed to the removal of internal air voids from the broken cenospheres as crushed hollow cenospheres required less volume. Due to increase in interparticle void spaces, the capillary suction reduced which could have led to decrease in matric suction values for successive crushing cycles.

![Graph](image2)

Fig. 8. Effect of crushing on matric suction of type-F fly ash

4 CONCLUSIONS

Experimental study was performed on the uncrushed type-F fly ash specimens to evaluate the effect of matric suction variation on the unsaturated shear strength behaviour. The crushing nature of fly ash particles and its influence on matric suction generation were also studied. An attempt was also made to correlate the macroscopic behaviour with the microscopic (particle level analysis using SEM images) behaviour. The
following major conclusions were derived from the current study:

- The shear strength of uncrushed type-F fly ash specimen was observed to increase with the increase in matric suction ($u - u_w$) in the boundary effect zone and transition zone of SWCC. It was further decreased non-linearly in the residual zone of unsaturation.
- The angle of internal friction with respect to matric suction ($\phi - u$) was observed to increase from $24^\circ$ to $32^\circ$ as degree of saturation ($S_i$) decreased from 90% to 30% for uncrushed fly ash specimens.
- Stiffness of uncrushed specimens increased with the increment in matric suction. The sudden reduction in the stiffness at higher $S_i$ value could be due to the breakage of water filled cenospheres.
- Hollow cenospheres and solid plerospheres crushed and deformed under the repeated crushing cycles which led to reduction in matric suction evolution with crushing cycles of type-F fly ash.

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