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STRENGTH AND DILATANCY CHARACTERISTICS OF POND ASH

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ABSTRACT: This paper focuses on the peak friction angle, dilation angle and critical state friction angle of the pond ash. The pond ash sample collected from the ash pond of Udupi Thermal Power Plant, Nandikur, Udupi district, was subjected to shearing at normal stress of 50,100, 200, 300 and 400 kPa at constant strain rate of 0.05 mm/min. The different relative densities at which tests were conducted are 20%, 50%, and 80% respectively, with corresponding unit weights are 6.25 kN/m^3, 6.79 kN/m^3 and 7.43 kN/m^3 respectively. Most of the shear tests were conducted to shear strain in excess of 40% to achieve the critical state. The stress-strain response was observed and recorded. For each relative density and normal stresses, shear strength and dilatancy parameters were obtained. Also in the present work, a correlation between peak friction angle, dilatancy angle and critical state friction angle was obtained for pond ash. It was observed that as the normal stress increases, both frictional angle and dilatancy angle was found to decrease. It was also noted that increase in density increases friction and dilatancy angle. The present data were also compared with those of established correlations by Bolton (1986) and Kumar et.al (2007) and found to compare well.

Keywords - Dilatancy, Relative density, Peak friction angle, Critical state, Pond ash

I. INTRODUCTION

In India thermal power is the one of the major source of energy and produces nearly 75 percent for total energy production. The production of coal ash from all the existing thermal power plants is more than about 100 million tonnes per year. When the coal is burnt in thermal power plants to heat the water for preparing the steam, a waste product from the boilers is obtained from the wet disposal of flyash. This fly ash gets mixed with bottom ash and disposed off in large pond or dykes as slurry. It is also termed as ponded fly ash, which contains relatively coarser particles.

The pond ash is actually a mixture of fly ash and bottom ash which is dark grey in color, granular and porous material. The main difference between pond ash and fly ash is its particle size. The pond ash is coarser and less pozzolonic and is therefore not accepted as pozzolona. The dissolvable alkalis present in the pond ash are washed with water. Some of the main constituents of pond ash are metal oxides, Sulphur, silica and aluminum materials with less pozzolonic properties than fly ash. These ashes produced can cause environmental risks, i.e. air pollution, surface water and groundwater pollution, if disposed of unscientifically, and therefore its safe disposal is essential.

The storage of pond ash requires a vast area of land and the disposal of ash is problematic and creates environmental risks. In the low-lying areas, pond ash has been used as structural fills for the development of residential and industrial sites to mitigate these problems. Soil mixed with pond ash canal is used in different applications like for the construction of embankment, under foundation or as a fill material etc.

Major geotechnical aspects like stability - bearing capacity of shallow and deep foundations, slope stability, the penetration resistance etc. depends on the soil strength. The strength characteristics of particularly, granular particles are usually influenced by the peak friction angle (φp) and the critical state friction angle (φcv). Dilation plays a key role in every soil-structure response under any loading conditions especially in soils denser than critical state. Existing stress-dilatancy theories (Rowe, 1962; Bolton, 1986) include dilatancy as a gross parameter without the explicit consideration of the grain geometry. Although, dilatancy influences almost all aspects of the behaviour of granular materials, ranging from shear strength to stress- strain behaviour, there is no practical method for estimating the dilatancy angle based on the in situ soil properties, although the variables that influence dilatant behaviour are well-known.

The current paper presents an experimental study on the shear behaviour of granular Pond ash. The experimental program consists of conducting a series of direct shear tests on the Pond ash sample of varying sizes and inter-particle friction conditions, performed under three ranges of relative densities namely, loose, medium-dense and dense. The variation in mobilized peak friction angle, peak shear strain, dilatancy angle, critical shear strain, critical state angle are studied under increased normal stresses by changing the relative density of the Pond ash. Test data are interpreted in terms of the stress- dilatancy relationship and shear strength parameters. The purpose is to find a relation between the grain-size characteristics of Pond ash and the shearing resistance. Experimental results are analysed in terms of the frictional and dilatant contributions to the strength of Pond ash as a function of its relative density and are compared with dilatancy theories and empirical equations established in literature.

II. LITERATURE REVIEW

Many researchers have studied the shear strength and dilatancy characteristics of various types of granular materials. Their research findings are discussed below;

Zeng and Wang (2019) conducted a total of 48 direct shear tests were carried out to research the evolution of shear and dilatancy of stored wheat in silos. It was revealed that strength of wheat in bulk attributes to the combination of frictional and dilatant during shearing, in particular attributing to its elliptic shape. An increase in relative density enhanced the peak friction angle as well as the dilation.The relationships between relative density, peak friction angle, and dilatancy anglewere presented based on the tests data and Bolton's theory. Then an advanced model was developed to evaluate the peak shear behavior of wheat stored in silos considering the dilatancy of the stored wheat.

Harehdasht et. al (2018) have examined the potential influence of particle size and grading on the shear strength–dilation relation of granular materials from the results of 276 symmetrical direct shear tests. The applicability of physical symmetrical direct shear tests to interpret the plane strain frictional shearing resistance of granular materials was widely discussed using the DEM computer code SiGran. Sixteen different grain-size distribution curves of three different materials namely, Peribonka sand, Eastmain sand, basalt beads and sands with rounded particles were tested at different normal pressures (50, 200 and 400 kPa) and initial relative densities (50% and 90 %). It is demonstrated that while the contribution of dilatancy to the shear strength is not influenced by the variation in the coefficient of uniformity Cu in the investigated range, it is significantly decreases with increasing mean particle size D50. The coefficients of Bolton's equations have been, therefore, adjusted to account for D50. A comparison of the predictions by the proposed empirical formulas with φps and ψ data from literatures shows that accounting for the grain size yields more authentic results.

Kandasami et. al., (2017) studied the effect of particle morphology (grain shape) on the mechanical response of granular materials. Two model systems with extreme differences in morphology were selected (spherical glass ballotini and angular sand) for the experimental programme. A series of hollow cylinder torsion tests were conducted under monotonic drained conditions on specimens reconstituted to the same relative density. Tests were conducted under different intermediate principal stress ratio (b) on both the model materials. The glass ballotini showed increased dilation at the outset of the test, however, at large strains, the particle rearrangement in the sand and the increased interlocking leads to higher strength at the critical state. The effect of individual particle morphology was manifested in both the increased friction angle and a larger sized failure locus in stress space with increase in angularity. The stresses developed in these two model materials were also accompanied by intriguing volume change behaviour. The glass ballotini despite a lower strength presented a predominantly dilative response immaterial of the 'b' value, while the angular sand showed increased strength at large strains with contractive response.

Fang- Wei et. al. (2016) performed several drained triaxial tests on Silica sand No.5 under 3 MPa confining pressure to produce the pre-crushed sands in simulating the pressure shear process on soil to result in particle breakage, and then the pre-crushed sands were re-sheared in series of drained triaxial test to investigate the mobilized strengths of the pre-crushed sands in detecting the influence of particle breakage. It was found that, by deteriorating strain-stress behaviour, partcile breakage resulted in change of stress- dilatancy behaviour in translation and rotation of the relation of the dilatancy factor and the effective principal stress ratio. For a given initial void ratio, particle breakage resulted in impairment of dilatancy behavior of soil to be more contractive in deterioration of the mobilized dilatancy angle and reduction of void ratio. However, particle breakage resulted in increase of the mobilized basic frictional angle especially before failure. In addition, the influence of the particle breakage on the mobilized strengths was revealed to be influenced by the shear stress- strain state.

Mashiria et. al (2015) investigated the shear strength and dilatancy behaviour of Sand-tyre chip (STCh) mixtures. A series of monotonic triaxial tests were carried out on sand mixed with various proportions of tyre chips. It was found that tyre chips significantly influenced the shear strength and the dilatancy behaviour of STCh mixtures. The effects of confinement and relative density on the shear strength, dilatancy and initial tangent modulus of the STCh mixtures were also investigated. Moreover, a dilatancy model for STCh mixtures was proposed and validated with the experimental results.

Raju and Khan (2014) have conducted a series of direct shear tests on dry sand having different relative densities (i.e.,20%, 50%, & 80%) subjecting them to different constant values of vertical normal stress ranging from 50kPa to 400kPa. It was found from the present results with an increase in effective normal stress the peak frictional angle and dilation angle was found to decrease. Also, it was found that with an increase in density lead to an increase in peak friction angle and dilation angle. Also, it was found that the as the grain size of sand decreases from coarse to fine there is a substantial reduction in peak frictional angle, critical state friction angle, and dilation angle. In the study, critical state friction angle was found out for the three different types of graded sand. It was found that φcv for coarse sand was 35.34°, φcv for medium sand was 27.07° and φcv for fine sand was 24.08°.

Kumar et. al. (2007) have performed a number of direct shear tests on Bangalore (quartz) sand by varying the magnitude of normal stress in between 50 kPa and 800 kPa. Four different relative densities (i.e 28.5 %, 55.6 %, 79.6 %, and 90.6 %) of sands were employed. All the tests were continued up to a substantial value of the horizontal displacement so that the critical state was achieved in all the tests. The values of φp and ψp were determined in all the tests for different combinations of σv and Rd (Relative Density). All the test results were compared with the recommendations of Bolton (1986) and Salgado et al. (2000). The suggested expressions are found to match well with the test results. The testing has clearly indicated that a decrease in σv leads to an increase in the values of φp and ψp which necessitates the need of employing secant values of φp rather than using tangent φp, with some small value of an apparent cohesion, as is normally followed in practice to avoid complications in performing the analysis.

Salgado et. al. (2000) have extensively studied the properties of clean sands pertaining to shear strength and stiffness. A series of laboratory tests were performed on samples of Ottawa sand with fines content in the range of 5–20% by weight. Most of the triaxial tests were conducted to axial strains in excess of 30%. It was observed that the small-strain stiffness at a given relative density and confining stress level decreases dramatically with the addition of even small percentages of silt. It was observed that the addition of even small percentages of silt to clean sand considerably increases both the peak friction angle at a given initial relative density and the critical-state friction angle. This study suggested that silty sands with non-floating fabric in the 5–20% silt content range are more dilatant than clean sands; dilatancy appears to peak at around 5% silt content, but even at 20% silt content it remains above that of clean sand. It was observed that, although small-strain stiffness drops, peak and critical-state strengths increase with increasing fines content.

Bolton (1986) reviewed a large number of triaxial and plane strain test results and proposed a much simpler relationship among φp, φcv and ψp; where ψp is the angle of dilatancy which indirectly quantifies the rate of dilation. Bolton provided the following simplified expressions:

$\varphi p=\varphi cv+0.8\psi p$..(1)

$\varphi p=\varphi cv+5$ IR for plain strain condition..........(2)

$\varphi p=\varphi cv+3$ IR for triaxial condition.................(3)

The quantity IR is dilatancy index and its magnitude is related to the relative density (DR) and the effective stress (σv) by the relationship

$IR=DR(Q-\ln(\sigma v))-R$.....................................(4)

σv expressed in kPa, DR in decimal and Q and R are constants. According to Bolton(1986) observations R=1 and Q=10 was obtained. Later Salgado et al.(2000) took values as Q=9 and R=0.49 from their experiments. Kumar et al. (2007) examined further the correlations between φp, φcv, ψp and IR by conducting series of direct shear tests on Bangalore sand. Kumar et al. (2007) provided the following empirical relations

$\varphi p=\varphi cv+0.932\ \psi p$..(5)

$\varphi p=\varphi cv+3.5$ IR for plain strain condition....(6)

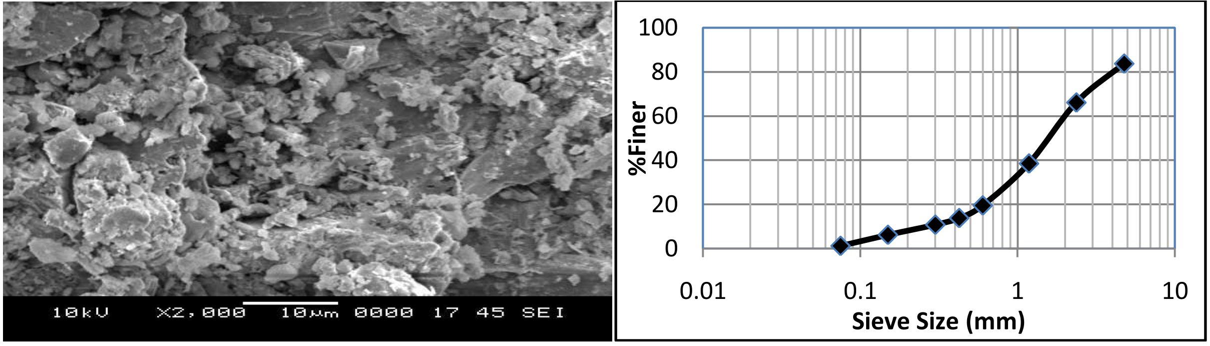
Rowe (1962) proposed stress dilatancy theory, which is based on the energy principle and represented by granular material with a regular packing of sphere or cylinders. The stress dilatancy model proposed by him does not take into account the important behavioral features such as relative density and stress level.

Strength-Dilatancy relationships of almost 17 types of sands were extensively studied by Bolton and other researchers.

In this present paper, an attempt has been made to establish correlation between strength and Dilatancy for the Pond ash. The scarcity of natural building materials has necessitated the use of alternative materials. Pond ash is used in most applications that require fine aggregate and is particularly suitable for structural light weight fills and embankments, road base layers, hot mix asphalt and flowable fill.

III. MATERIALS AND METHODS

Pond ash used in this study was collected from the ash pond of Udupi Thermal Power Plant, Nandikur, Udupi district. The samples were mixed thoroughly to bring homogeneity and dried at an oven temperature of 105–110 ^{0}C to avoid the presence of moisture. Then the ash was sieved through a 4.75 mm sieve to separate out foreign and vegetative matter and was stored in airtight containers for subsequent use. The surface morphology of pond ash was studied by using Scanning Electron Microscope equipped with an energy dispersive X-ray detector. Micrographs were taken at accelerating voltages of 10 kV for the best possible resolution. Fig. 1(a) shows the surface morphology of pond ash. The physical properties of the pond ash sample were determined and are presented in Table 1. The grain size distribution curve of the pond ash used is given in Fig. 1(b).



(a) (b)

FIGURE 1.(a) Scanning electron micrograph (SEM) of Pond ash (b) Grain size distribution curve of Pond ash.

TABLE 1. Properties of Pond ash

Parameter		**Pond Ash**
D_{10} (mm)		0.3
D_{30} (mm)		0.9
D_{60} (mm)		2
Coefficient of Uniformity, Cu		6.67
Coefficient of Curvature, Cc		1.35
Specific gravity, G		1.96
% Uncompacted voids		69.13
Relative Density, I_d%	20%	6.25 KN/m^3
	50%	6.79 KN/m^3
	80%	7.43 KN/m^3

As per the Indian Standard for classification of soils (IS 1498-1970, reaffirmed 2002), Pond ash was found to be well graded.

A number of direct shear tests were conducted on chosen dry Pond ash at three different values of unit weight viz. 6.25 kN/m^3, 6.79 kN/m^3 and 7.43 kN/m^3; the corresponding relative densities of these samples were found to be 20 %, 50 % and 80 % respectively. The size of the shear box was 60 mm x 60 mm and the sample height was kept equal to 25 mm for all the tests. All the samples were sheared at a uniform relative horizontal movement of 0.05 mm/minute between the upper and lower box. The vertical effective normal stress on all specimens was varied in between 50 kPa and 400 kPa. The samples of a given density were prepared by either raining the material from a constant height of fall (for loose to medium dense) or with the tamping technique using a fixed number of blows (for dense to very dense). All the tests were continued up to u/H = 40%; where H is the initial height of the sample and u is the horizontal displacement at any time.

IV. RESULTS AND DISCUSSION

For all the tests, the variation of the horizontal (shear) force (Ph) and the corresponding change (v) in the vertical height of the sample with an increase in the horizontal displacement (u) was continuously monitored at a regular time interval; volumetric strain simply becomes equal to v/H. The corresponding test results are shown in Fig. 3-5 in terms of (i) the variation of Ph/Pv with u/H, and (ii) the variation of v/H with u/H; where Pv is the magnitude of the vertical force. From these plots the values of friction angles (φ) and dilatancy angles (ψ) were determined using the following expressions:

$$\varphi = \tan^{-1}\left(\frac{\mathrm{Ph}}{\mathrm{Pv}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

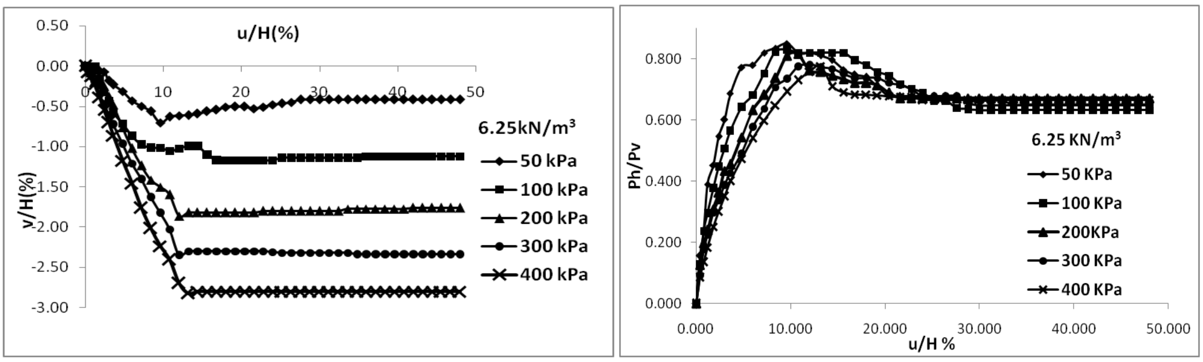
$$\psi = \tan^{-1}\left(\frac{\delta v}{\delta u}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

φp and ψp are the peak values of φ and ψ respectively. A variation of φp and ψp with variations of normal stress (σv) is illustrated in Fig. 7 for the Pond ash.

Following observations were drawn from Fig. 3-5 and Fig. 7:

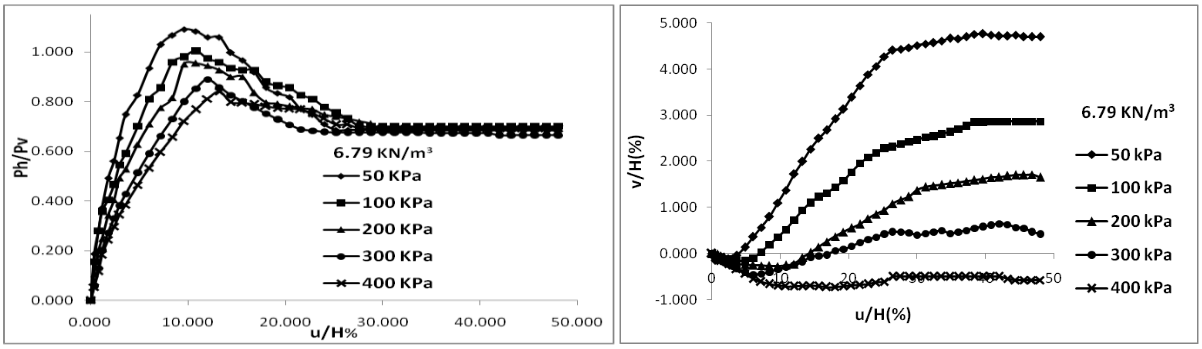
1. It is found that the peak values of friction angle and dilation angle invariably occur almost at the same value of the horizontal displacement.
2. The magnitude of the (u/H) corresponding to φp increases with increase in σv. Also the magnitude of shear strain corresponding to ψp increases with increase in σv.

3. An increase in the relative density of the material causes a marginal decrease in the value of the shear strain associated with φp and ψp.
4. For a given relative density of the material, the behavior of the material at low stress level always remains typically that of a dense pond ash which indicates a well defined peak corresponding to φp and then followed by a decrease in the shear stress which ultimately leads to the critical state of the material at very high values of shear strain; in such cases the material initially shows a decrease in volume followed by an increase in volume.
5. At low values of σv, the rate of dilation becomes maximum corresponding to φp and subsequently, the value of dilatancy angle again decreases and finally becomes equal to zero in the critical state. On the contrary at very high values of σv, the behavior of the material remains similar to that of loose pond ash where the shear stress increases continuously to yield the critical state at very high values of horizontal displacement. In such cases, the material experiences a continuous decrease in volume until reaching the critical state.
6. The values of φp and ψp decreases with an increase in the value of σv.



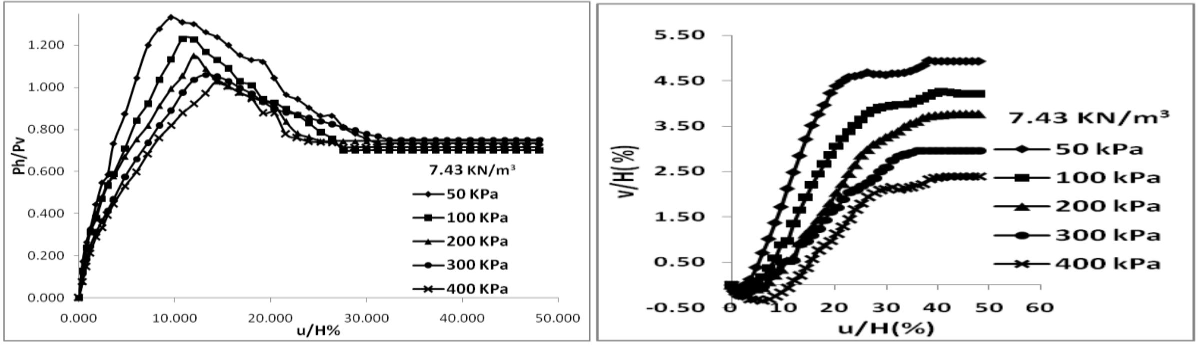
(a) (b)

FIGURE 3. For ϒ= 6.25kN/m^3 Pond ash, the observed variation of (a) Ph/Pv with u/H, and (b) v/H with u/H



(a) (b)

FIGURE 4. For ϒ= 6.79 kN/m^3 Pond ash, the observed variation of (a) Ph/Pv with u/H, and (b) v/H with u/H



(a) (b)

FIGURE 5. For ϒ= 7.43 kN/m^3 Pond ash, the observed variation of (a) Ph/Pv with u/H, and (b) v/H with u/H

A linear relationship is established between peak friction angle and peak dilation angle as shown in Fig.6 the critical state friction angle (φ_{cv}) is determined by the intercept made corresponding to zero dilation state. It is a unique parameter, which remains independent of density, stress level and type of test conducted. It depends only on the grain size and mineral comprising the granular material. For different chosen values of σv and relative density (DR) of the material, the obtained values of φp were plotted against the corresponding values of ψp.

All the data points are indicated in Fig. 6, it can be noted that the relationship between φ_p and ψ_p can be best described by the following expression:

$$\varphi p = \varphi cv + 0.869\,\psi p \text{..(9)}$$

It is very well known from Fig. 7 that the value of φ_{cv} for the chosen Pond ash sample is found to be equal to 38.11^o.

As shown in Fig. 6, the strength-dilatancy equation can be well predicted by Eq. (9) with a coefficient of correlation i.e. $R^2=0.981$ from the regression analysis. Hence, from the regression of φ_p on $\psi_{p,}$ it is observed that both the φ_p and ψ_p values are strongly positively correlated.

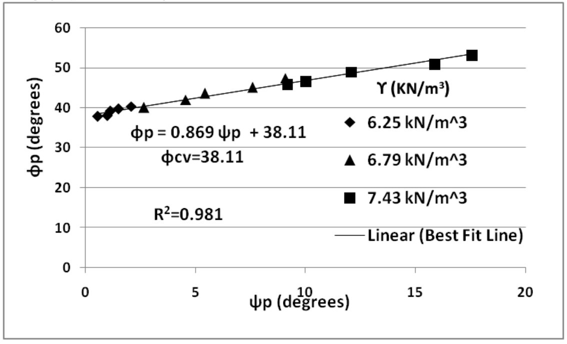


FIGURE 6. Established relationship between peak friction angle (φp) and maximum dilation angle (ψp)

It can be observed from Fig. 6. that, the value of φ_{cv} for the chosen Pond ash sample was found to be equal to 38.11^o(i.e., $\tau/\sigma v=0.784$). It can also be noticed from Fig. 3a, 4a, and 5a., that the value of $\tau/\sigma v$ at a very large value of u/H (35-40%) remains very close to 0.784 indicating the achievement of the same critical state in all tests.

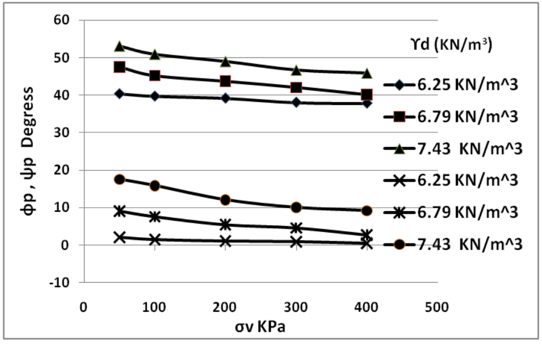


FIGURE 7. The variation of φ_p and ψp with σ_v for Pond ash

As seen from Fig. 7 that the value of φp reduces with an increase in the value of σv. According to Bolton's observations provided the following equation (10) for plane strain case and according to Kumar et. al. equation (11) obtained, where IR (dilatancy index) is defined by Equation (12) with Q = 10 and R = 1.

$$\varphi p = \varphi cv + 5\,IR \text{ ....(10)}$$

$$\varphi p = \varphi cv + 3.5\,IR \text{...(11)}$$

The quantity IR is dilatancy index and its magnitude is related to the relative density (DR) and the effective stress (σ_v) by the relationship

$$IR = DR(Q - \ln(\sigma v)) - R \text{.......................................(12)}$$

σ_v expressed in kPa, DR in decimal.

From the regression analysis, it is found that the following relationship holds quite good for the present data:

$$\varphi p = \varphi cv + 3.534\,IR \text{...(13)}$$

where, $IR = DR(Q-\ln(\sigma v))-R$

Experimentally measured values of φ_p were plotted against those estimated using (i) Bolton's recommendation (Equation 10), (ii) Kumar's recommendation (Equation 11), (iii) present correlation (Equation 13), and (iv) Salgado et al. (2000) recommendation and the corresponding comparison from four different correlations is shown in Fig. 8 for all the data points.

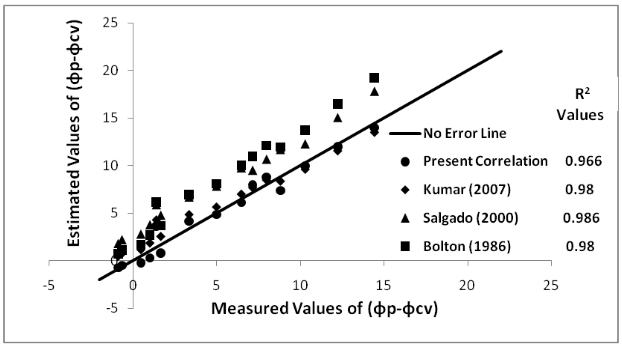


FIGURE 8. The prediction of (φp-φcv) by different formulae against measured values of (φp-φcv) for all the tests

It can be noted that the estimated values of φ_p from the recommendations of Bolton (1986) and Salgado et al. (2000) are found to be slightly higher than those actually measured. On the other hand, the estimation from Equation (13) seems to be better. Additionally, from the regression analysis, it is found that the value of Coefficient of correlation i.e R^2 equal to 0.966. From this, it can be interpreted that there exists a strong positive correlation between the estimated values (φp-φcv) and measured values of (φp-φcv) for the present data.

V. CONCLUSION

Based on a number of direct shear tests on Pond ash, at different density states and stress level, an empirical relationship correlating φ_p, φ_{cv} and IR similar to that recommended by Bolton (1986), Kumar et al. (2007) and Salgado (2000) has been suggested. Using this relationship from the knowledge of relative density (Dr) and critical state friction angle (φ_{cv}), the value of peak friction angle (φ_p) can be determined for any required effective stress level (σv). Further, an expression correlating ψ_p with φ_{cv} and φ_p has also been provided for Pond ash on the basis of which the value of φ_p can also be predicted. The suggested expressions are found to match well with the test results. Based on the test results, it can be concluded that decrease in σv leads to an increase in the values of φ_p and $\psi_{p.}$ It was also concluded from the test results that critical state friction angle (φcv) is independent of stress level and density.

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