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# Shear Strength and Dilatancy Behaviour of Steel Slag

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***Abstract:*** **--A series of direct shear tests was conducted at normal stress of 50,100, 200, 300 and 400 kPa in order to study the peak friction angle, dilation angle and critical state friction angle of the angular steel slag. The different relative densities at which tests were conducted are 20%, 50%, and 80% respectively, with corresponding unit weights are 17.75 kN/m3, 18.15 kN/m3and 18.57 kN/m3respectively. Most of the direct shear tests were conducted to shear strain in excess of 40% to achieve the critical state. All the tests are conducted at constant strain of 0.05 mm/min. The stress-strain response was observed and recorded, and the shear strength and dilatancy parameters were obtained for each relative density and normal stresses. Also in the present work, a correlation between peak friction angle, dilatancy angle and critical state friction angle was obtained for steel slag. It was observed that as the normal stress increases, both frictional angle and dilatancy angle was found to decrease. Also as noted 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.**

**Index Terms: — Strength, Dilatancy, Relative density, Peak friction angle, Critical state, Correlations, Steel Slag.**

## I. INTRODUCTION

Dilatancy is one of the important characteristic feature of granular materials, defined as the change in volume induced by shear deformation. However, the development of dilatancy behavior depends on the grain size and shape of the particles. Even though the strength of both fine and coarse-grained soils are governed by the dilatany, only for coarse-grained soils dilatancy has an effect on the formation of shear plane, thus possess a major role in controlling the geometry of failure mechanisms. Due to this fact, dilatant behavior of coarse-grained soils draws much attention from the academia. 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 soils particularly, granular particles are usually portrayed by the peak friction angle φp and the critical state friction angle φcv. In the present study, an attempt is made to evaluate the strength and dilatancy parameters of Steel slag and to establish a correlation between peak friction angle, dilatancy angle and critical state friction angle for steel slag.

## II. LITERATURE REVIEW

Many researchers have studied the shear strength and dilatancy characteristics of various types of granular materials. Reynolds(1885) made the earliest observations to evaluate the volume change behavior during shearing processes. Reynolds showed that dense sands exhibit volume expansion and loose sands exhibit contraction during the shear deformation. The role of volume change behavior during shearing especially dilatancy was recognized by Taylor (1948). He performed direct shear tests on dense sand specimens and inferred the

work at peak shear stress state and showed that the energy input is dissipated by the friction using the expression

$$\frac{\tau peak}{\sigma 1} = tan\varphi p = \mu + \left(\frac{dy}{dx}\right) \text{..................................(1)}$$

Thus, the peak shear stress ratio, or the mobilized peak friction angle (φp) consists of both interlocking (dy/dx) and sliding friction between grains (μ). This equation which relates stress to dilation is called the stress – dilatancy rule, and it is an important relationship in characterizing the plastic deformation of soils. Bolton (1986) studied the concepts of friction and dilatancy angles in relation to the

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Vol 4, Issue 2, February 2019

strength of the soil. The shear strength and dilatancy of 17 sand types at various densities and normal stresses were collected. Axisymmetric and plane-strain tests were conducted and the variations of shear stress and volumetric strains with respect to axial strains were obtained from these tests. A new term 'relative density index' was defined in terms of relative density and effective stress level. Bolton 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:

φp = φcv + 0.8ψp.........................................................(2)

φp = φcv + 5 IR for plane strain condition ......................(3)

φp = φcv + 3 IR for triaxial condition.............................(4)

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(σv))-R.......................................................(5)

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 a series of direct shear tests on Bangalore sand. Kumar et al. (2007) provided the following empirical relations.

φp = φcv + 0.932ψp........................................................(6)

φp = φcv + 3.5 IR for plane strain cndition...................(7)

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 behavioural features such as relative density and stress level.

## III. MATERIALS AND METHODS

### A. Materials Description

Materials used in this experiment was Steel slag obtained from JSW Steel Plant, Torangallu, Bellary.

The Steel slag was found to comprise of generally sub-angular grains as can be seen from Photo plate 1. and microscopic picture of a portion of the sample (Fig.1). The Scanning Electron Microscope images of Steel slag are taken from NITK, Surathkal. As per the Indian Standard for classification of soils (IS 1498-1970, reaffirmed 2002), Steel slag was found to be well graded.

***Photo plate 1. Steel Slag Sample***

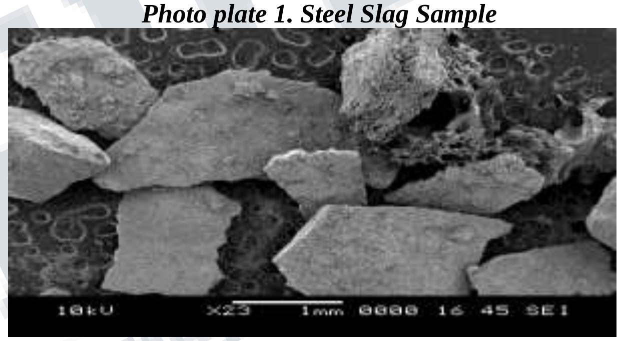


***Fig. 1. Microscopic View of a Portion of Steel Slag Sample***

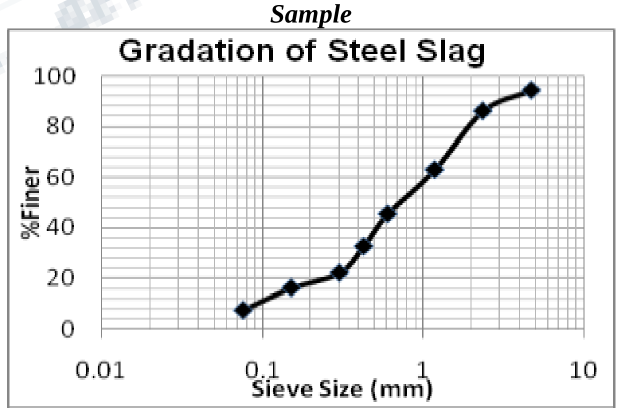


***Fig. 2. Gradation Curve***

***Table 1 Properties of Steel Slag***

| Parameter | | Values |
|---|---|---|
| Coefficient of Uniformity, Cu | | 11.96 |
| Coefficient of Curvature, Cc | | 1.58 |
| Specific gravity, G | | 3.125 |
| % Uncompacted Voids | | 41.48% |
| Relative Density, $I_d$% | 20% | 17.75 KN/m$^3$ |
| | 50% | 18.15 KN/m$^3$ |
| | 80% | 18.57 KN/m$^3$ |

### *B. Direct Shear Tests*

A number of direct shear tests were conducted on chosen dry Steel slag at three different values of unit weight viz. 17.75kN/m$^3$, 18.15kN/m$^3$ and 18.57kN/m$^3$; the corresponding relative densities of these samples were

IFERP
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Vol 4, Issue 2, February 2019

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

### A. Presentation of test results with graphs

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 Figures 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:

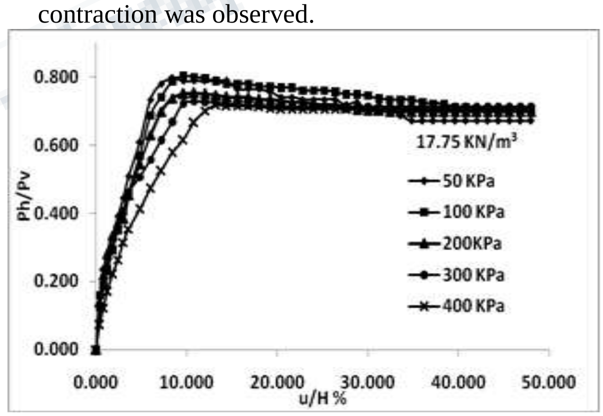
$\varphi = \tan^{-1}(Ph/Pv)$............................................................ (8)

$\psi = \tan^{-1}(\delta v/\delta u)$............................................................ (9)

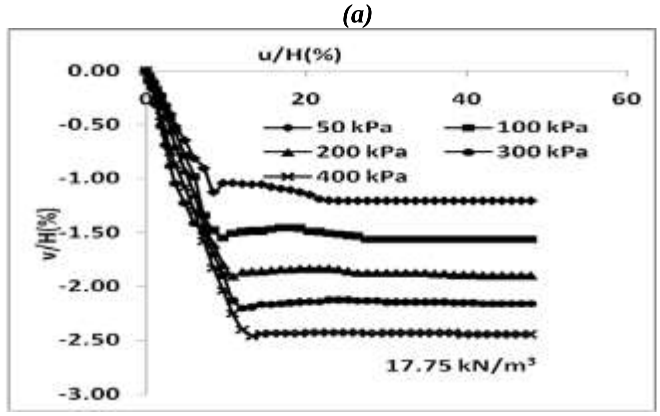
φp and ψp are the peak values of φ and ψ respectively. Variations of φp and ψp with variations of normal stress (σv) is illustrated in fig. 7 for the Steel Slag.

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 sand 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 sand 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. The effect of σv on the changes in the values of φp and ψp was seen to be more significant in the case of coarse sand and medium sand than fine sand. Also, it is observed that upon shearing fine sand at loose and medium dense states dilatancy (increase in volume during shear was not observed) in which case contraction was observed.



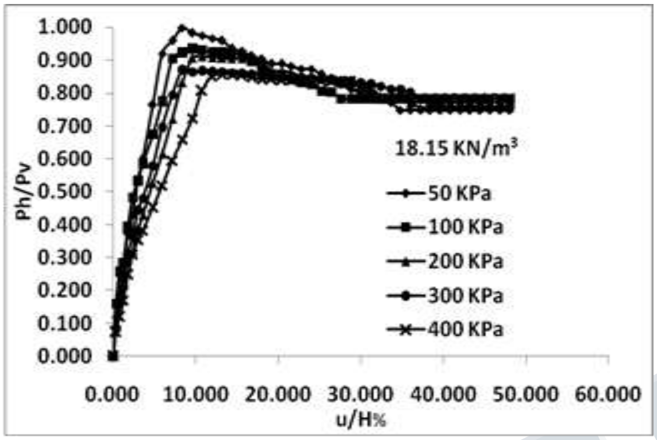

*(a)*



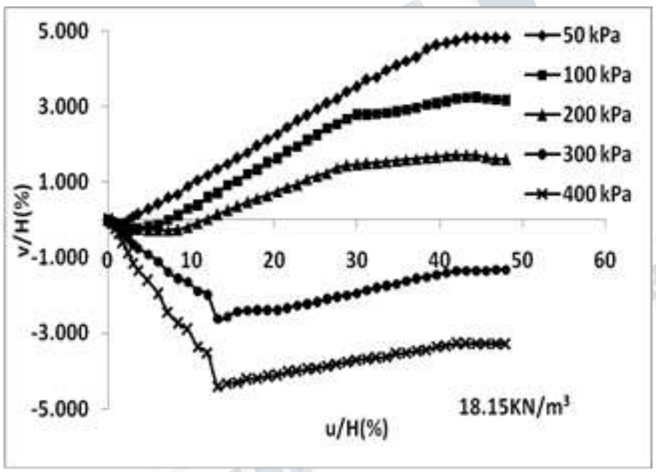

*(b)*

***Fig.3 For ϒ= 17.75 kN/m³ Steel Slag, the observed variation of (a) Ph/Pv with u/H, and (b) v/H with u/H***

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 4, Issue 2, February 2019

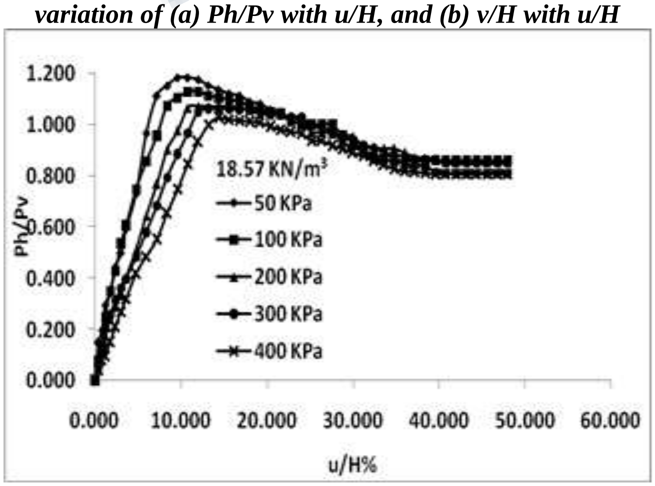



*(a)*

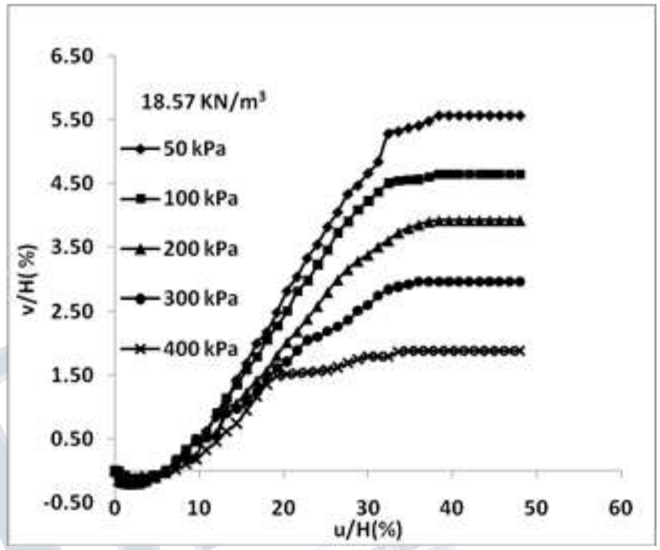



*(b)*

***Fig.4 For ϒ= 18.15 kN/m3 Steel Slag, the observed variation of (a) Ph/Pv with u/H, and (b) v/H with u/H***




*(a)*




*(b)*

***Fig.5 For ϒ= 18.57 kN/m3 Steel Slag, the observed variation of (a) Ph/Pv with u/H, and (b) v/H with u/H***

**B. Correlation Between $\varphi_p$ and $\psi_p$**

A linear relationship is established between peak friction angle and peak dilation angle as shown in Fig.6 the critical state friction angle ($\varphi_{cv}$) 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 $\varphi_p$ and $\psi_p$ can be best described by the following expression:

$\varphi_p = \varphi_{cv} + 0.96\ \psi_p$ ......................................................... (10)

It is very well known from figure 7 that the value of $\varphi_{cv}$ for the chosen Steel Slag sample is found to be equal to 36.32°.

As shown in Fig.6, the strength-dilatancy equation can be well predicted by Eq. (10) with a coefficient of correlation i.e. $R^2$=0.974 from the regression analysis. Hence, from the regression of $\varphi_p$ on $\psi_{p,}$ it is observed that both the $\varphi_p$ and $\psi_p$ values are strongly positively correlated.

IFERP
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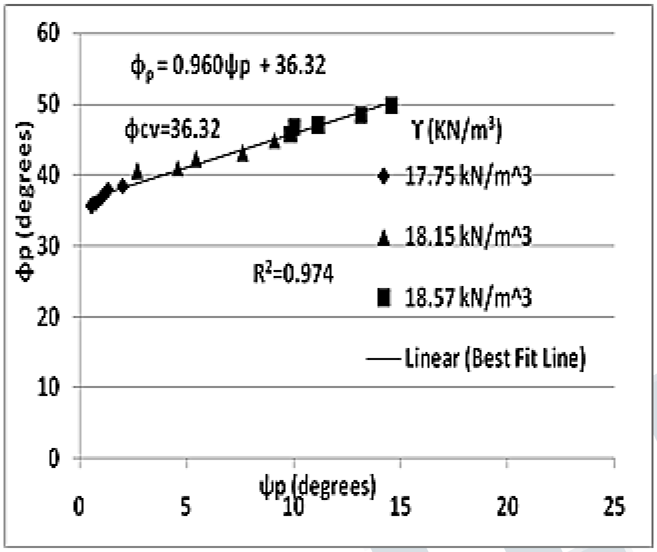


***Fig.6 Established relationship between peak friction angle (φp) and maximum dilation angle (ψp)***

It can be observed from Fig.6. that, the value of $\varphi_{cv}$ for the chosen Steel slag sample was found to be equal to $36.32^o$(i.e., τ/σv=0.735). It can also be noticed from Figure 3a, 4a, and 5a., that the value of τ/σv at a very large value of u/H (35-40%) remains very close to 0.735 indicating the achievement of the same critical state in all tests.

***C. Correlation between $\varphi_p$ and $\sigma_v$***

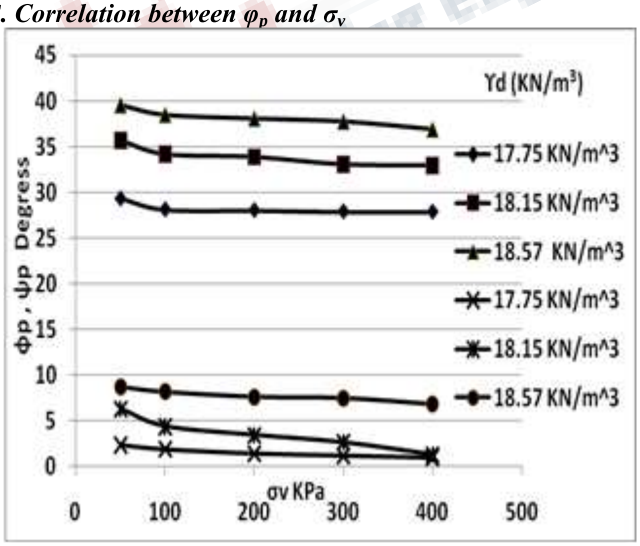


***Fig.7 The variation of $\varphi_p$ and ψp with $\sigma_v$ for Steel Slag***

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 (11) for plane strain case and according to Kumar et. al. equation (12) obtained, where IR (dilatancy index) is defined by Equation (13) with Q = 10 and R = 1.

$$\varphi_p = \varphi_{cv} + 5\ IR \quad (11)$$

$$\varphi_p = \varphi_{cv} + 3.5\ IR \quad (12)$$

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

$$IR = DR(Q - \ln(\sigma v)) - R \quad (13)$$

$\sigma_v$ expressed in kPa, DR in decimal.

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

$$\varphi_p = \varphi_{cv} + 3.534\ IR \quad (14)$$

where, IR =DR(Q-ln(σv))-R

σv expressed in kPa, DR in decimal.

Experimentally measured values of $\varphi_p$ were plotted against those estimated using (i) Bolton's recommendation (Equation 11), (ii) Kumar's recommendation (Equation 12), (iii) present correlation (Equation 14), and (iv) Salgado et al. (2000) recommendation and the corresponding comparison from four different correlations is shown in Figure 8 for all the data points.

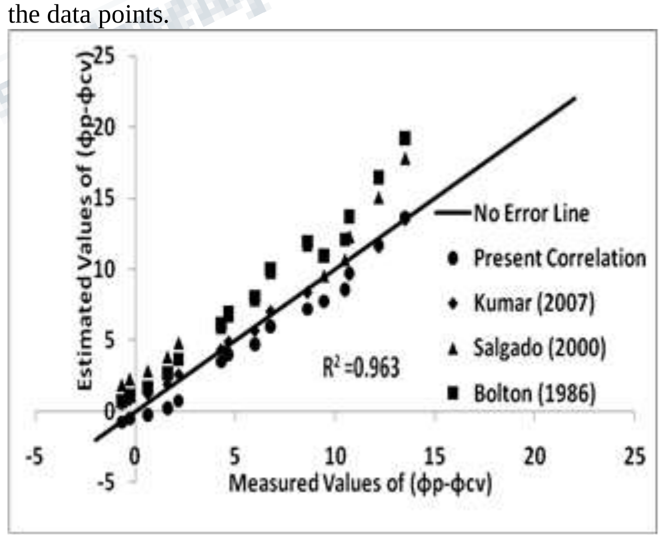


***Fig 8 The prediction of (φp-φcv) by different formulae against measured values of (φp-φcv) for all the tests***

It can be noted that the estimated values of $\varphi_p$ 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 (14) 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 0.963. 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.

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 4, Issue 2, February 2019

## V. CONCLUSION

Based on a number of shear tests on Steel Slag, at different density states and stress levels, an empirical relationship correlating $\varphi_p$, $\varphi_{cv}$ and IR similar to that recommended by Bolton (1986), Kumar et al. (2007), has been suggested. Using this relationship from the knowledge of relative density (Dr) and critical state friction angle ($\varphi_{cv}$), the value of peak friction angle can be determined for any required effective stress level (σv). Further, an expression correlating $\psi_p$ with $\varphi_{cv}$ and $\varphi_p$ has also been provided for the Steel Slag on the basis of which the value of $\varphi_p$ 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 a decrease in σv leads to an increase in the values of $\varphi_p$ and $\psi_p$. The value of φcv is found to be 36.32$^o$ for the Steel Slag. It is well illustrated from the present experimental work that critical state friction angle (φcv) is independent of stress level and density.

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