

## State-of-the-art of Fly Ash Engineering Property I

Yu Zhou<sup>1\*</sup>, Xiyu Wang<sup>2</sup>, Junqi Liang<sup>1</sup>

1. Shanghai Sunking Project Management Co., Ltd

2. College of Civil Engineering, Tongji University

E-mail: Zhouy@sunkingpm.com.cn

**Abstract:** Crucial properties of Fly ash such as Classification criteria, Grain size distribution, Specific gravity, Compaction behavior, Permeability, Consolidation test, and Direct Shear Tests are discussed in this paper. More details and features about fly ash in Unconfined Compression, Self-hardening, Unconsolidated Undrained Triaxial Compression Test, Drained triaxial tests, and CIU triaxial tests, will be presented in the next paper. Large amount of data shows that geotechnical properties of fly ash are correlated with chemical composition. Most fly ash can be classified as sandy silt to silty sand or fine sand, and the specific gravity of fly ash depends on fineness, loss on ignition (LOI), mineralogy, and iron content. Moreover, the residual carbon content controls the compaction characteristics, even though other factors like gradation, iron content, morphology, etc. are also important. Class C fly ash is less permeable but shows a higher consolidation pressure resistance than class F fly ash.

**Keywords:** Fly ash; Engineering property; Chemical content.

### 1. Introduction

Fly ash has been successfully used as structure fill and seepage cutoff for a long history. The specific gravity is lower leading to lower unit weights resulting in lower earth pressures. Many laboratory results show that fly ash is a freely draining material with angle of internal friction of more than 30 degrees. However, geotechnical properties are correlated with chemical composition of fly ash. Factors like lime content (CaO), iron content (Fe<sub>2</sub>O<sub>3</sub>), loss on ignition, morphology, and mineralogy govern the geotechnical properties of fly ashes. Fly ash can be permeable or impermeable, and show various strength under different conditions. In this paper, basic geotechnical properties are discussed. Sorts of tests and affecting factors like water content, chemical composition, etc. are presented.

Generally speaking, fly ash are classified as Class F and Class C. The burning of harder, older anthracite and bituminous coal typically produces Class F fly ash. This fly ash is pozzolanic in nature, and contains less than 20% lime (CaO). However, class C fly ash are produced from the burning of younger lignite or subbituminous coal, in addition to having pozzolanic properties, and also has some self-cementing properties. In the presence of water, Class C fly ash will harden and gain strength over time. Class C fly ash generally contains more than 20% lime (CaO).

Moreover, based on the grain-size distribution, they can be classified as sandy silt to silty sand. The variation of unconfined compressive strength with moisture content is similar to that of very fine sand. The predominant frictional behaviour of compacted fly ash prior to cementation or in the absence of pozzolanic activity implies that the shear strengths is comparable to a silt or a loosely compacted fine sand.

According to Pandian, N. S. (2004), fly ash, pond ash and bottom ash are also classified by engineering property, as it is shown in Table 1.

**Table 1 Classification of fly ash, pond ash and bottom ash**

	Place of origin	Classification
Fly ash	Rae Bareli, Korba, Neyveli	ML
Pond ash	Raichur, Rae Bareli, Korba, Neyveli	SM
Bottom ash	Rae Bareli	SM
	Korba, Neyveli	SP-SM

In addition, based on the characteristics of self-hardening, fly ash can also be classified into three groups (Pandian, N. S. 2004). Details are shown in the self-hardening section.

## 2. Grain size distribution

Fly ash is a material of fine texture, comprising a mixture of amorphous, semi-crystalline and crystalline particles. The differences in particle size distribution, morphology, and surface characteristics of fly ash control its behaviour and its affinity to water and subsequent reactivity. Sieve analysis reveals that fly ash resembles a fine-grained soil, mainly silt. Based on the grain-size distribution, they can be classified as sandy silt to silty sand. The pond ashes consist of silt-size fraction with some sand-size fraction. The bottom ashes are coarser particles consisting predominantly of sand-size fraction with some silt-size fraction.

### 2.1 Method of Hydrometer and coulter counter

Different methods for different fly ash. Laser particle and XR sedimentation or electrolyte resistivity (coulter counter) method for high calcium fly ash, and hydrometer method low calcium fly ash.

According to Das, S. K. and Yudhbir (2005), different methods result in different answers. Two methods are used for Parichha, Panki and Neyveli fly ash. It may be noted that for Parichha and Panki the difference between two methods is rather small, whereas in case of Neyveli fly ash, the hydrometer method underestimates the  $< 45 \mu\text{m}$  fraction, which contains reactive minerals and glassy phase. The low calcium fly ashes contain very small amount of lime so they do not undergo any chemical change on hydration. High calcium fly ash undergoes significant chemical changes as reactive minerals and free limes react with water. Therefore, for low calcium fly ash, the hydrometer method can be used, but either grain counting by laser particle and XR sedimentation or electrolyte resistivity (coulter counter) method should be used for grain size distribution of high calcium fly ash. It may also be mentioned that, for fly ash, fineness by air permeability is misleading due to the presence of carbon content.

### 2.2. Typical grain size distribution

Distribution of typical and statistics grain size are listed in Fig. 1. Bounds for fly ash, pond ash and bottom ash are shown in Fig. 1. Even though the grain size distribution curve gathered from different these may be contradictory in some extent, they reflect a probable clue and a reference for general fly ash, pound ash and bottom ash.

## 3. Specific gravity

According to Pandian, N. S. (2004), the specific gravity generally lies between 1.46 and 2.66. The specific gravity of fly ash may also vary from 1.3 to 4.8 (Joshi and Lahiti 1997). The specific gravity of fly ash depends upon fineness, loss on ignition (LOI), mineralogy, and iron content. Data for more than 150 fly ashes collected from different sources along with present study did not show good correlation between  $G$  values with any of the above parameters individually.

1) The reason for a low specific gravity could either be due to the presence of large number of hollow cenospheres from which the entrapped air cannot be removed, or the variation in the chemical composition, in particular iron content, or both (Pandian, N. S. 2004). Das, S. K. and Yudhbir (2005) also get the same conclusion. The specific gravity of high calcium fly ash is more than low calcium fly ash and it is comparable to that of soil. This can be due to absence of cenospheres and presence of small amount of plerospheres.

2) High calcium fly ash have a high value of specific gravity. When the particles are crushed, they show a higher specific gravity compared to the uncrushed portion of the same material. But for high calcium fly ash increase in  $G$  value on grinding was not expected, as LOI was also very low.

Crushing is primary operation which is performed with a large size particle while grinding is performed after crushing. In crushing attrition force is applied while in grinding compression force is applied.

3) For iron content  $>10\%$ ,  $G$  value is directly proportional to iron content.

4) For a lime content  $\text{CaO} > 15\%$ ,  $G$  value is more irrespective of iron content and loss on ignition.

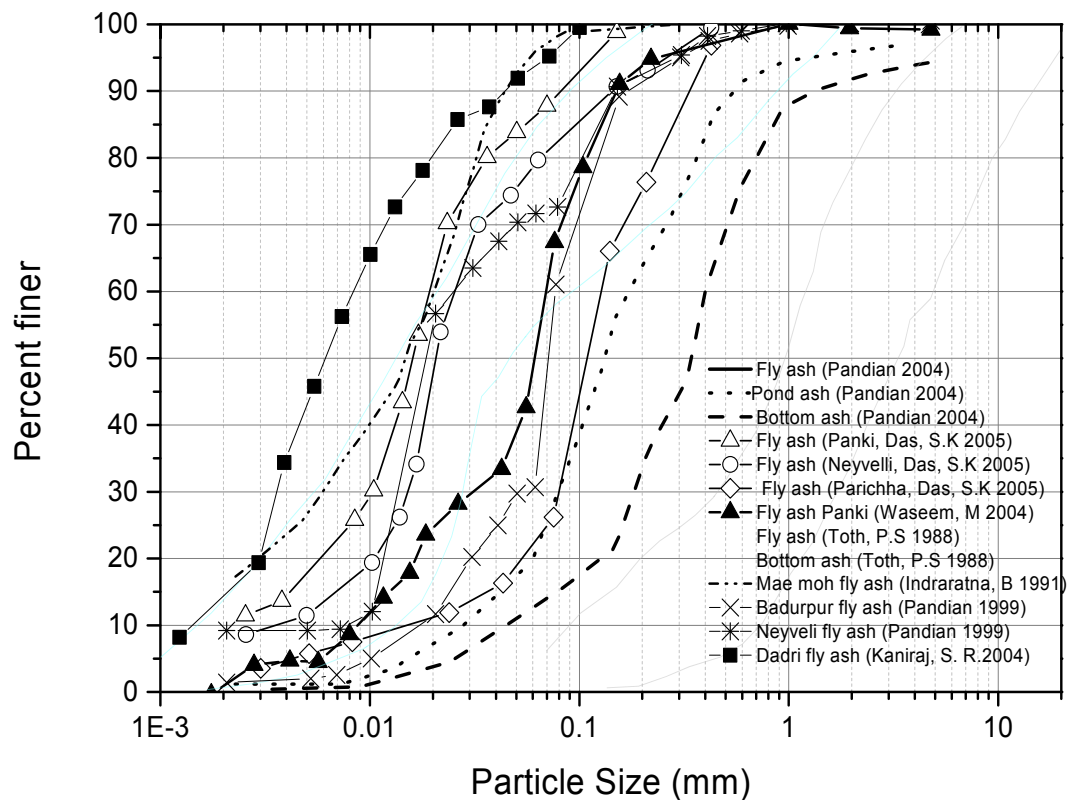


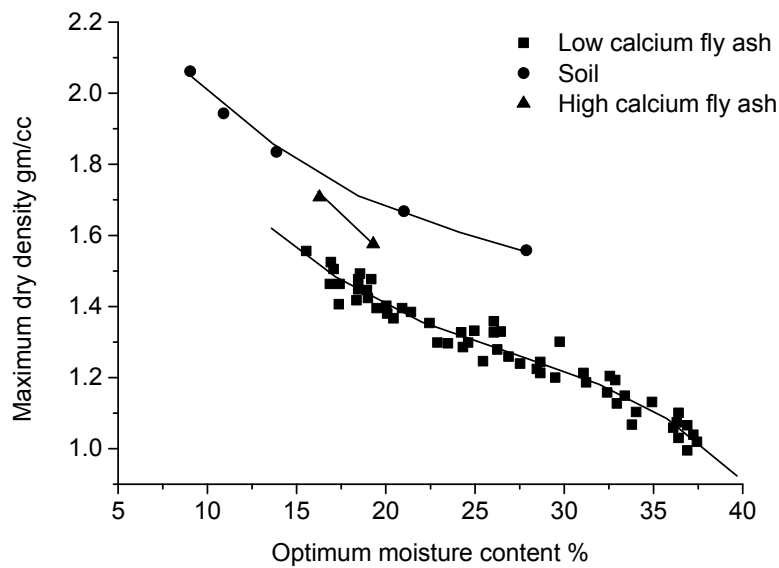
Fig. 1 Typical grain size distribution

#### 4. Compaction behavior

There are many factors like gradation, carbon content, iron content, and fineness etc., which control compaction characteristics of fly ashes. It is well known that MDD is inversely and OMC is directly proportional to organic content for fly ash. However, according to Pandian, N. S. (2004), the residual carbon content seems to be the controlling factor for compaction characteristics of fly ash though other factors like gradation, iron content, morphology, etc. are also important.

##### 4.1 General features

A review of the light compaction characteristics of 25 other class F Indian fly ashes shows that the values of  $G$ , MDD, and OMC are in the ranges of 1.85–2.35, 9.3–14.9 kN/m<sup>3</sup>, and 44.7–17.5%, respectively. According to Das, S. K. and Yudhbir (2005), harvard miniature compaction test for Parichha, Panki, and Neyveli fly ash showed higher density and lower optimum moisture content for high calcium fly ash compared to low calcium fly ash. The broad range of moisture content in Parichha shows little effect of water on low calcium high carbon fly ash, whereas for high calcium fly ash it is in a narrow range because of reaction of lime. The data are shown in Fig.2.



**Fig.2 Variation of MDD with optimum moisture content**

#### 4.2 Variation of dry density with moisture content

The work of Indraratna, B (1991) focus on the compaction characteristics of both fresh and aged Mae Moh fly ash, in comparison with a well graded lateritic fill. In Fig.3, the maximum dry density and the optimum moisture content for compacted fresh fly ash are 17.2 kN/m<sup>3</sup> and 12.0%, respectively. In contrast with fresh fly ash, aged fly ash collected from a disposal dump does not produce the same compacted densities, particularly as the water content is decreased below the optimum level. This difference in dry densities is perhaps attributed to slight cementation of aged fly ash that has been exposed at the site for several weeks prior to collection. Internal cementation of a material reduces its effective void ratio, hence its compaction characteristics.

Compaction curves (Fig. 3) also indicate that for a large variation in moisture content, only a relatively small change in dry density is obtained for fresh fly ash in comparison with the natural fill. Therefore, fly ash can be easily handled with conventional equipment because of its light weight and compacted over a relatively wide range of moisture contents (9-13%). This property certainly reveals that the moisture content in fly ash can be conveniently controlled in the field, if it is utilized as an embankment fill. Furthermore, because of the silty non-cohesive nature of fly ash, it can be compacted efficiently with rubber-tired rollers during construction.

Influence of lime and gypsum are discussed by Mishra, M. K. (2006). As it is shown in the figure below, the moisture content and dry density relationships vary between 28% to 31% and 1.32 to 1.39, respectively. The addition of gypsum reduces the density of the composite as compared to that of without gypsum.

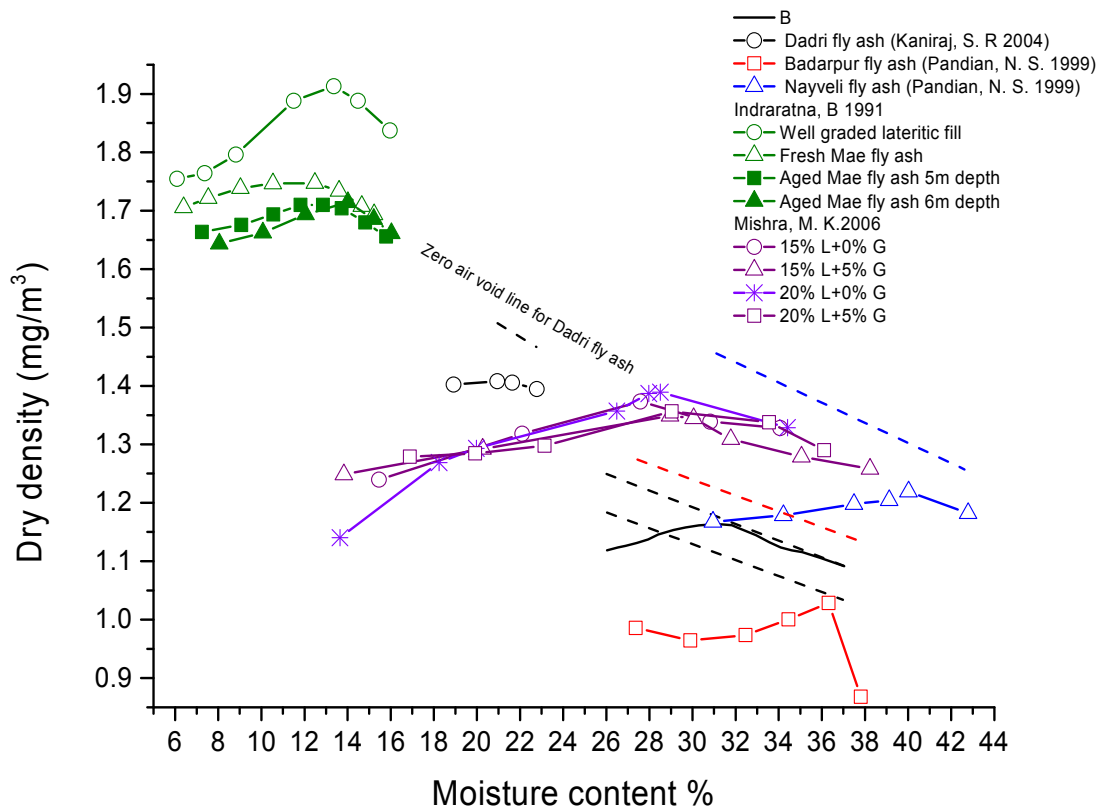


Fig.3 Variation of dry density with moisture content

**4.3 Correlation between OMC and MDD**

The correlation between maximum dry density MDD and optimum moisture content OMC of fly ashes has been described with linear (Raymond 1961), logarithmic (Kaniraj and Havanagi 2001) and polynomial (Kaniraj and Havanagi 2001; Sridharan 2002) relationships.

The Fig.3 above shows the compaction curve for the Dadri fly ash. The maximum dry unit weight (MDD) and optimum moisture content (OMC) of the Dadri fly ash were 13.8 kN/m<sup>3</sup> and 21%, respectively. The specific gravity, G, of fly ashes is smaller than that of normal soils. Because of the lower specific gravity and the porous nature of the particles, fly ashes have a lower MDD and a higher OMC than normal soils. Based on the analysis of 57 fly ashes from different countries, Kaniraj and Havanagi (2001) have suggested an empirical correlation between MDD, OMC, and specific gravity, G, as

$$MDD = 25.234G^{0.488}OMC^{-0.336} \text{ kN/m}^3$$

The equation indicates that, as the specific gravity of the fly ash increases, its MDD also increases. However, the MDD and OMC are inversely correlated. Kaniraj and Havanagi (2001) have also suggested a procedure to make a preliminary estimate of the MDD and OMC from the specific gravity to facilitate the planning of the compaction test. The tests results of Dadri fly ash, however, show that the MDD is more than the estimated upper limit and the OMC is less than the estimated lower limit. This suggests that the surface structure of the spherical particles may be smooth rather than porous, which might facilitate the densification of the Dadri fly ash at a relatively low water content.

## 5. Permeability

A comparison of data on the permeability of some Canadian ashes shows that class C fly ash tends to be less permeable than class F fly ash (Joshi and Nagaraj 1987; Toth et al. 1988). The cementations nature of class C fly ash has been reported by several studies (EPRI 1986; McLaren and DiGioia 1987). Inter granular cementation would result in a permeability range that is generally lower than that of class F fly ash of the same gradation. The coefficient of permeability is between  $10^{-6}$  and  $10^{-7}$  m/s for the fly ashes in the research of Porbaha, A. (2000). Chan et al. (1986) reported that the permeability of a Canadian fly ash, measured in situ, ranged from  $10^{-6}$  to  $10^{-9}$  m/s. The hydraulic conductivity of fly ash, measured in situ using rising-head and falling-head testing methods, ranges from  $10^{-4}$  to  $10^{-7}$  cm/s (Chan et al. 1986). Glogowski et al. (1992) reported the average value of  $k$  of eastern U.S. fly ashes as  $1.9 \times 10^{-5}$  cm/s, with standard deviation and coefficient of variation as  $2.8 \times 10^{-5}$  cm/s and 147%, respectively. The corresponding values for the western U.S. fly ashes are  $3.1 \times 10^{-5}$  cm/s,  $6 \times 10^{-5}$  cm/s, and 194%, respectively. Permeability values for bottom ash range from  $3.4 \times 10^{-3}$  to  $4.8 \times 10^{-3}$  cm/s (Chan 1983~). The values of  $k_{ave}$  vary from  $4.6 \times 10^{-6}$  to  $6 \times 10^{-6}$  cm/s, which are typically in the range of the coefficient of permeability of non-plastic silts. The compacted fly ash deposits, therefore, would be moderately permeable.

### 5.1 Consolidation time- permeability $k$

Based on the research of Porbaha, A (2000), Fig. 4 indicates that the coefficient of permeability  $k$  is almost unchanged for the Matsushima ash, whereas it slightly decreases with time in the case of the Hekinan ash, which has a higher calcium content. The figure shows that the rate of reduction in  $k$  due to time is more pronounced at higher stress level.

The compression index  $C_c$ , representing the slope of  $e$ -log  $p$  (void ratio versus the consolidation pressure), is quite small for both the ashes compared to that of clayey soil. This implies that the change in void ratio is not considerable as the consolidation pressure increases. The  $C_c$  values from this study are within the range of 0.036–0.078, whereas GIA (1985) reported the range to be between 0.05 and 0.37 for some Canadian ashes.

The examination of the microstructure using the SEM reveals the formation of needlelike substances for the Hekinan ash, which may contribute to the reduction of permeability with time.

Joshi and Nagaraj (1987) report that the initial permeability of compacted fly ash from Alberta varies from  $5 \times 10^{-4}$  to  $6 \times 10^{-6}$  cm/s depending on its gradation and that the permeability significantly decreases with time. The long-term permeability of compacted fly ash would depend not only on its gradation but also on the compaction energy imparted, type of minerals, unburned carbon content, and pozzolanic nature. Mae Moh fly ash (Indraratna 1991) compacted at the optimum moisture content produces very low initial permeability, in the range of  $10^{-6}$ – $10^{-7}$  cm/s, determined from the falling head apparatus. Subsequent tests conducted on the same compacted samples after 2 weeks have produced permeability coefficients of less than  $10^{-7}$  cm/s.

The above findings imply that fly ash may also be considered as an additive for effective seepage cutoffs in earth structures, e.g., impervious blankets and cores. However, the use of excessive amounts of fly ash may cause enhanced brittleness of cutoffs, thereby making them strain incompatible with adjoining material zones. This feature will be discussed in self-hardening section. It has been shown elsewhere (Indraratna et al. 1991) that a small proportion of fly ash (5%) can be used as an effective blending agent to stabilize highly dispersive or erodible soils. In this respect, it is anticipated that blending of natural soils with fly ash may enable the construction of non-erosive, impervious embankment structures.

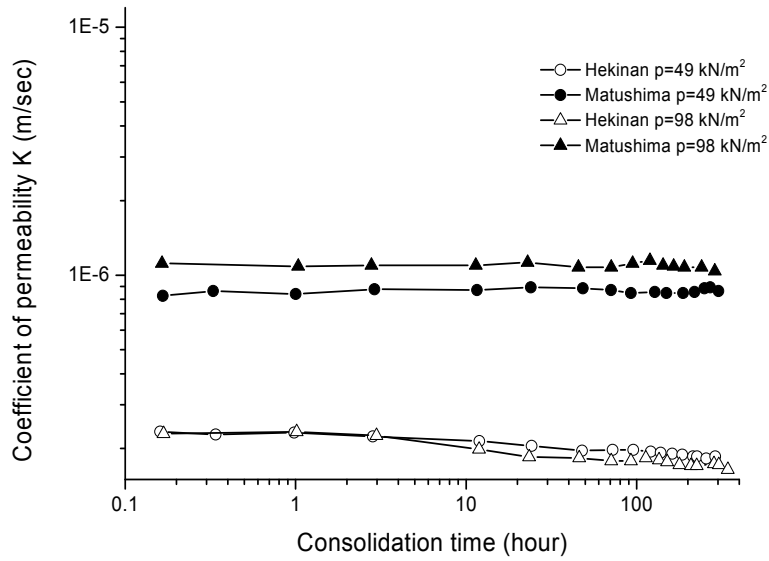


Fig.4 Variation of coefficient of permeability versus Consolidation time

5.2 Consolidation pressure- permeability k

Fig. 5 compares the coefficient of permeability k with respect to consolidation pressure. A large variation in k values suggests that the indirect back-calculation of k from the consolidation test may be misleading. Therefore, the coefficient of permeability should be measured directly, rather than back calculated from the standard consolidation tests.

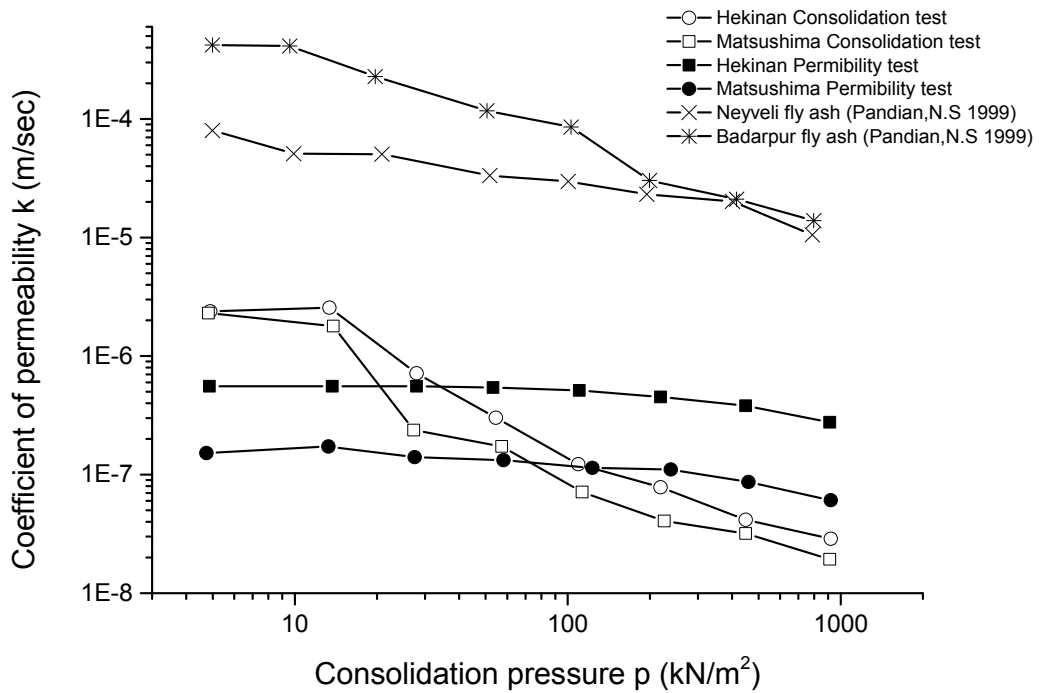


Fig. 5 Variation of coefficient of permeability versus Consolidation pressure

Similar results are obtained by Pandian, N. S (1999). They found that the permeability values of Neyveli fly ash decrease primarily due to the loss of interconnectivity of pores due to formation in the voids owing to the presence of free lime. For Badarpur fly ash, the permeability values decrease due to reduction of voids with increasing consolidation pressure. At higher consolidation pressures, both Neyveli fly ash and Badarpur fly ash have almost the same permeability values. This is because the effective pore volume available for water flow due to formation in the Neyveli fly ash is comparable to the effective pore volume available for flow of water in Badarpur fly ash (in spite of void reduction because of consolidation).

Pandian, N. S (1999) proposed that the permeability values calculated from the D10 size can be used in the absence of laboratory permeability data for both Neyveli and Badarpur fly ashes, as these values are seen to be of the same order as the coefficient of permeability values of Neyveli fly ash and Badarpur fly ash obtained from permeability tests in the laboratory.

### 5.3 Permeability with various moisture contents

Tests on the effect of the moisture content to the fly ash permeability are conducted by Lal, B. R. R., & Mandal, J. N. (2012). Fig. 6 shows the relation between average coefficients of permeability ( $k_{ave}$ ) values with different moisture contents for various vertical stresses. Fig. 7 shows the variation in the values of average coefficient of permeability ( $k_{ave}$ ) values with logarithmic values of vertical stresses for various moisture contents.

According to Lal, B. R. R., & Mandal, J. N. (2012), the increasing of moisture content results in a decrease in permeability of fly ash when compacted on the dry side of the optimum moisture content; where as a slight increase in permeability is observed when compacted on wet side of optimum. At higher values of vertical stress for all the values of moisture contents the permeability value is almost remains same.

The permeability values reduced with increase in vertical stress all the moisture content values. The fly ash samples when compacted on the dry of optimum gives relatively higher values of permeability than those of compacted on the wet side of optimum.

The tested fly ash is Koradi fly ash, and its permeability values is in the range of  $1.42 \times 10^{-7}$  to  $6.31 \times 10^{-8}$  /sec. These values of coefficient of permeability were in the same range as those of non- plastic silts. As compacted fly ash has higher values of permeability when it is compacted to dry side of optimum, it is suggested to compact the fly ash in dry side of optimum when used s back fill material in retaining wall.

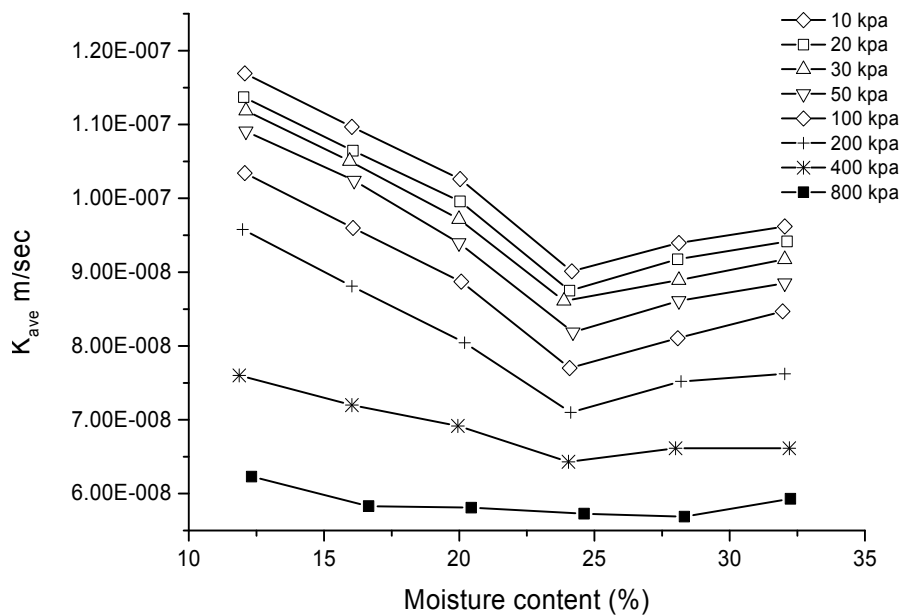
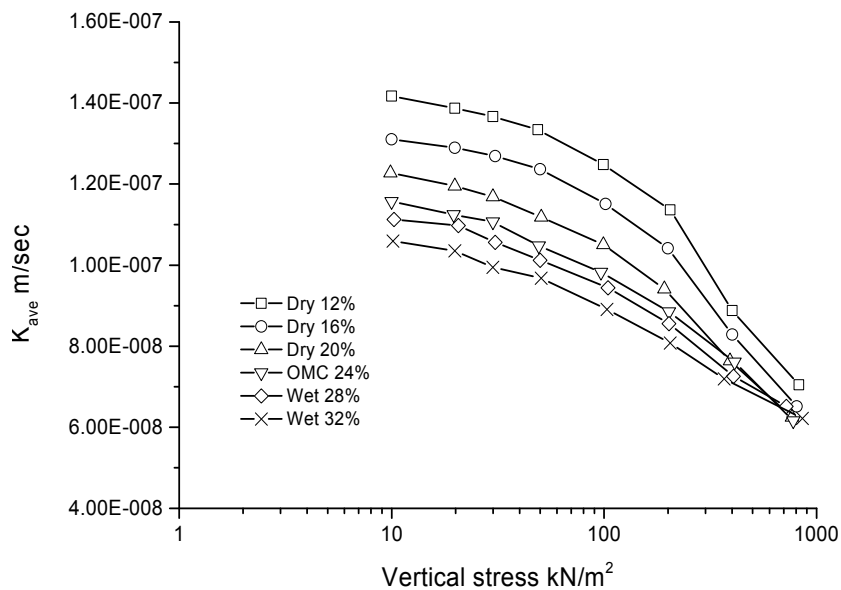


Fig. 6 Variation of average coefficient of permeability ( $k_{ave}$ ) versus various moisture contents





**Fig. 7 Variation of  $k_{ave}$  with vertical stress for different moisture content values**

#### 5.4 Effects of lime and gypsum

Hydraulic conductivity of fly ash with different content of lime and gypsum are tested by Ghosh, A., & Subbarao, C. (1998). The fly ash comes from Kolaghat Thermal Power Station KTPS. The influence of water content, curing time, percentage of lime and gypsum are shown in the Fig. 8 below.

Addition of lime to fly ash reduces hydraulic conductivity. Gypsum, in the presence of lime, helps to decrease hydraulic conductivity even further. It makes the matrix more stable and enhances the pozzolanic reaction. Hydraulic conductivity of the stabilized material reduces with an increase in moulding water content, and the reduction in hydraulic conductivity is less on the wet side of optimum. For all mixes of fly ash and lime or fly ash lime and gypsum, there is a reduction in hydraulic conductivity with an increase in the curing period. Stabilized compacted low lime fly ash mixed with 10% lime and 1% gypsum and cured for 28 days could produce an impermeable layer useful for base layers or waste containment liners with permeability on the order of  $8 \times 10^{-8}$  cm/s from fly ash with the permeability  $4.5 \times 10^{-5}$  cm/s.

Based on the features of fly ash-lime-gypsum mixes, a moulding water content in the range of OMC and OMC+5% can be specified for field control of fill moisture content. This moulding water content on the wet side of optimum has the advantage of low hydraulic conductivity, reduced leaching, marginal variations of hydraulic conductivity and obviously better workability. Fly ash stabilized with lime and gypsum can be considered for structural fill in road base and embankments and for use in impermeable barriers, such as covers and liner and cutoff trench wall, minimizing the potential for ground water contamination.

## 6. Consolidation test

It is expected that the quick termination of consolidation in fly ash makes it similar to the behavior of granular materials. For the fly ash from the Rajghat thermal power station in New Delhi, Kaniraj and Havanagi (1999) determined the values of  $C_c$  and  $C_r$  to be 0.072 and 0.017, respectively. For eight other class F Indian fly ashes, Pandian (1999) has reported the  $C_c$  to vary from 0.103 to 0.219. The average and standard deviation of this range were 0.148 and 0.039, respectively. In all the preceding cases, the fly ash specimens were prepared at their respective MDD, OMC state and saturated prior to the consolidation test.

Consolidation test for Koradi fly ash under various moisture content are conducted by Lal, B. R. R., & Mandal, J. N. (2012). The average value of compression index (Cc) is 0.078 when the effective stress is less than 100 kPa and 0.092 when effective stress is more than 100 kPa. The average value of compression index (Cr) determined from the unloading part of the curve was 0.014. The value of Cc obtained was low; hence fly ash can be used as back fill material in reinforced retaining walls as the deformations due to loadings will be less when it was properly compacted. Fig. 10 shows the  $e - \log \sigma_v$  curve.

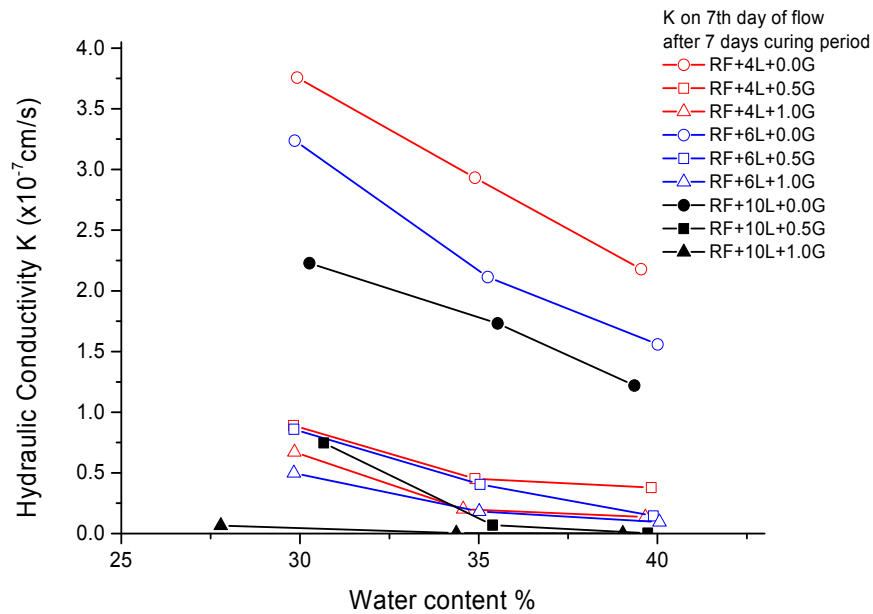


Fig. 8 Relationship between Water content and hydraulic conductivity with different content of lime and gypsum

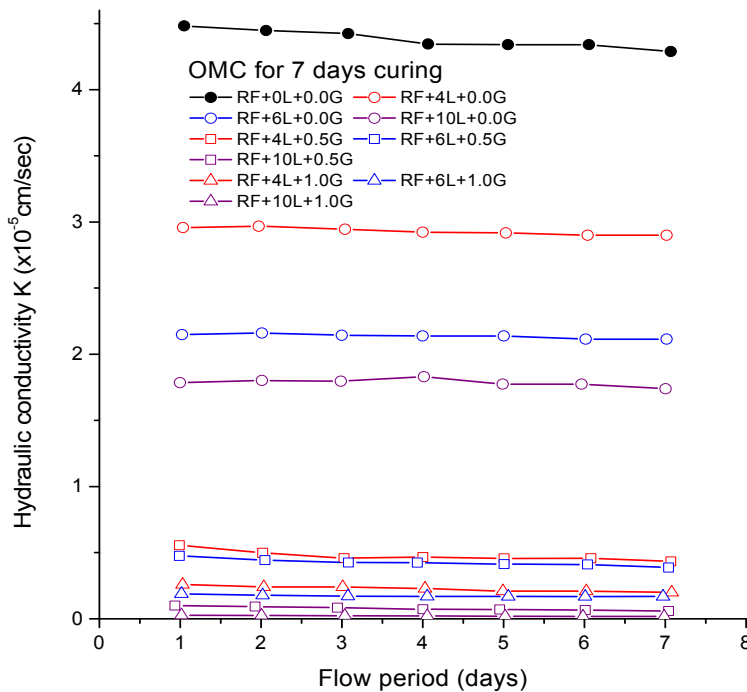
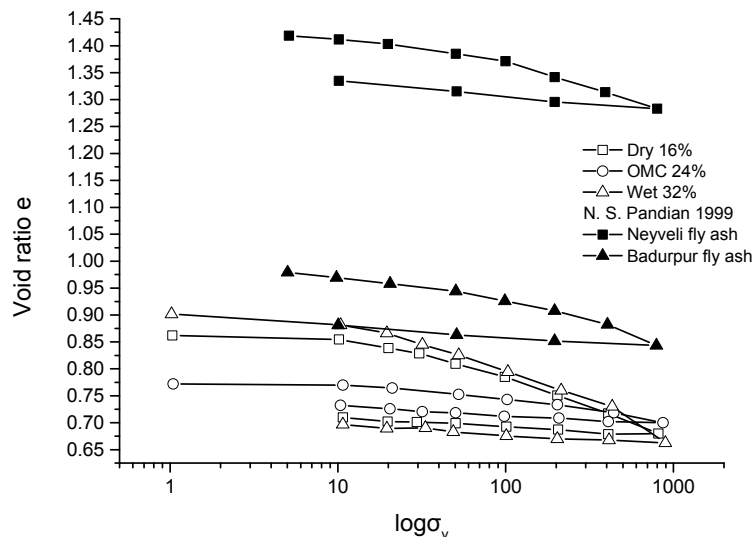


Fig. 9 Hydraulic conductivity versus flow period under OMC for different content of lime and gypsum

The data from Pandian, N. S (1999) are also added into the figure below. It can be observed from the figure that the Neyveli fly ash resists the consolidation pressure at a higher void ratio than does the Badarpur fly ash. This is because of higher strength developed in the Neyveli fly ash due to the presence of free lime, which causes bonding between fly ash particles.



**Fig. 10 e –  $\log \sigma_v$**

As the consolidation fly ash occur very fast, it is not possible to calculate the value of coefficient of consolidation  $C_v$  through the conventional methods. The value of  $C_v$  is back calculated by using the coefficient of permeability values, Porbaha et al. (2000). The  $C_v$  values are calculated using the equation below.

$$C_v = \frac{K}{m_v \gamma_w}$$

Where  $k$  is coefficient of permeability,  $m_v$  is volume compressibility coefficient and  $\gamma_w$  is unit weight of water. The figure below shows the variation of  $C_v$  with effective vertical stress for various moisture content used to prepare the compacted fly ash.

Fig. 11 shows the variation of  $C_v$  with  $s_8$  for Dadri fly ash. The values of  $C_v$  vary from  $8 \times 10^{-6}$  to  $2 \times 10^{-4}$  m<sup>2</sup>/s during loading. In fact, Porbaha et al. (2000) have recommended, the coefficient of permeability of fly ashes should be determined directly from permeability tests. Further, the coefficient of consolidation should not be determined by the log-time, square-root-time, or other methods. Instead it should be calculated from the equation above.

## 7. Direct Shear Tests

Several Direct Shear Tests are conducted in the experiments of Porbaha, A., Pradhan, T. B. S., & Yamane, N. (2000). The result of direct shear tests for the two types of fly ashes, Hekinan and Matsushima fly ash, are shown in Fig.17 below.

### 7.1 Consolidation time- shear strength

The increase in consolidation time increased the shear strength of both fly ashes. The shear stresses of both ashes increase up to a well-defined ultimate state and then gradually fall back, leading to softening at post peak states. For the Hekinan ash the normal stress starts to increase when the consolidation time is 1,390 min (1 day), whereas for the Matsushima ash the increase in strength is observed when the consolidation time is 4,320 min (3 days). This implies that the rate of increase of strength is slower for the case of Matsushima ash, which has a smaller free lime content.

In conclusion, an increase in consolidation time from 10 min to 3 days increased the shear strength of both fly ashes studied here. However, the rate of increase was different depending on the pozzolanic reactions taking place for the two ashes, each having a different Ca content.

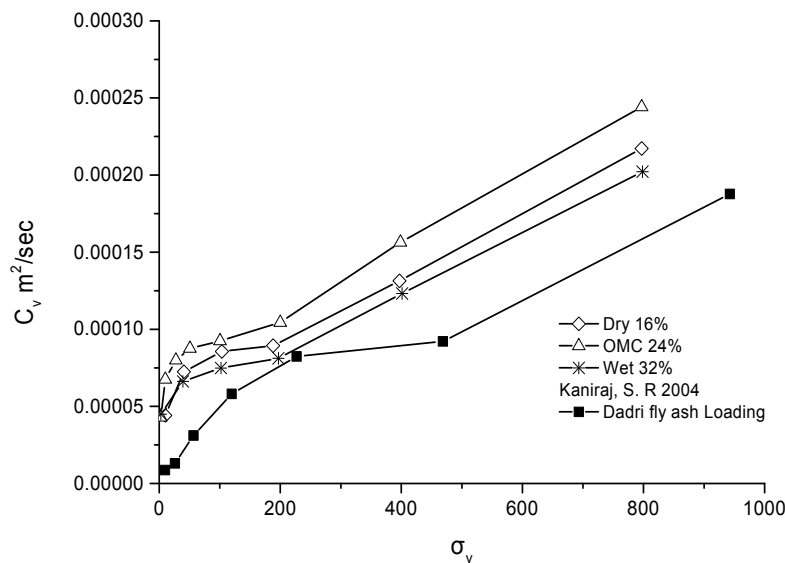


Fig. 11 Variation of  $C_v$  with effective vertical stress  $\sigma_v$

### 7.2 Transitional period between softening to hardening

At early stages of consolidation the shear strength of fly ash is low. However, as time passes the dilatancy occurring due to self-tightening, resulting from the pozzolanic reaction, leads to an increase in the shearing resistance of both ashes. The transitional period between softening and hardening is 720–1,390 min (0.5 to about 1 day) for the Hekinan ash, however, it increases from 1,440 to 4,320 min (1 to 3 days) for the Matsushima ash. This trend is reasonable because the pozzolanic reaction takes place faster for the case of the Hekinan ash, which contains a higher calcium content.

### 7.3 Consolidation time and settlement

At early stages of consolidation, immediate settling takes place in less than the first minute of the test, suggesting that the behavior of fly ash is similar to that of granular materials. However, as time passes the hardening process continues without any additional settling. In other words, the unit weight of fly ash remains constant, while the strength is increased due to the pozzolanic reaction, which leads self-hardening.

### 7.4 Cohesion, friction angle and moisture contents

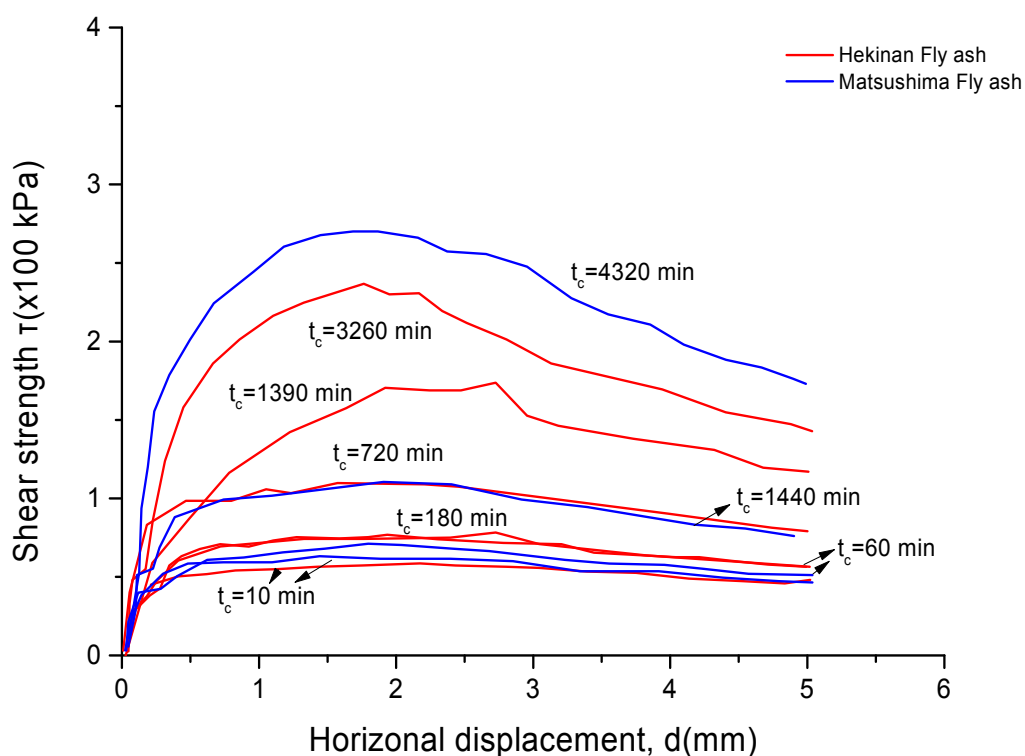
Being cohesionless, non-plastic materials, shear strength of dry fly ash is mainly due to frictional component except in the compacted unsaturated state where apparent cohesion is also present. The apparent cohesion value

is almost reduces to zero upon saturation. Fig.14 from Lal, B. R. R (2012) shows the variation of apparent cohesion with various moisture content values. The apparent cohesion value is increased with increase with moisture content and reached highest value at optimum moisture content of fly ash. Thereafter the apparent cohesion values are decreased with increase in moisture content.

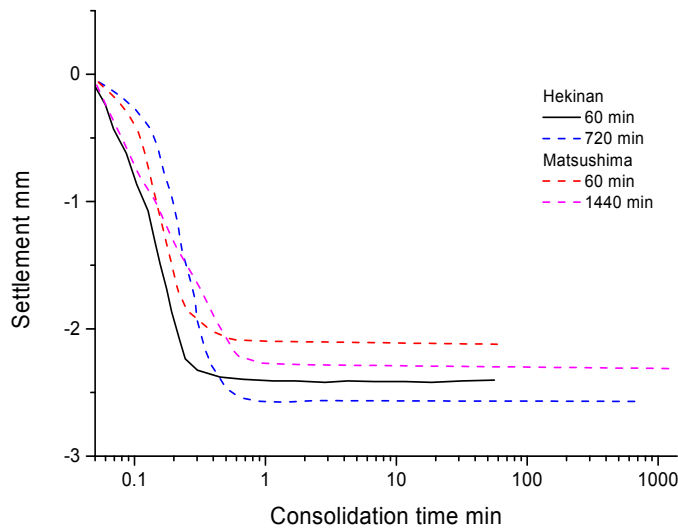
There is not much variation in value of angle of internal friction is observed due to change in the moisture content in fly ash sample. The angle of internal friction value is in the range of  $26.8^\circ$  to  $32.3^\circ$ . Fig.14 shows the variation of angle of internal friction of fly ash with various moisture contents. The samples compacted dry of optimum exhibited relatively high shear strength than those compacted wet of optimum. These tests results can be utilized to select amount of water to be added while compacting the fly ash, when it is used as back fill material in reinforced walls.

In this case, the shear strength of the fly ash is mainly governed by the angle of internal friction except under compacted unsaturated state. In compacted unsaturated state the apparent cohesion will also contribute to the shear strength of fly ash. The apparent cohesion value is increased with increase with moisture content and reached the highest value at optimum moisture content of fly ash. Thereafter the apparent cohesion values are decreased with increase in moisture content. There is not much variation is seen in the value of angle of internal friction of fly ash. A maximum value is recorded when the fly ash compacted to dry of optimum at 12%.

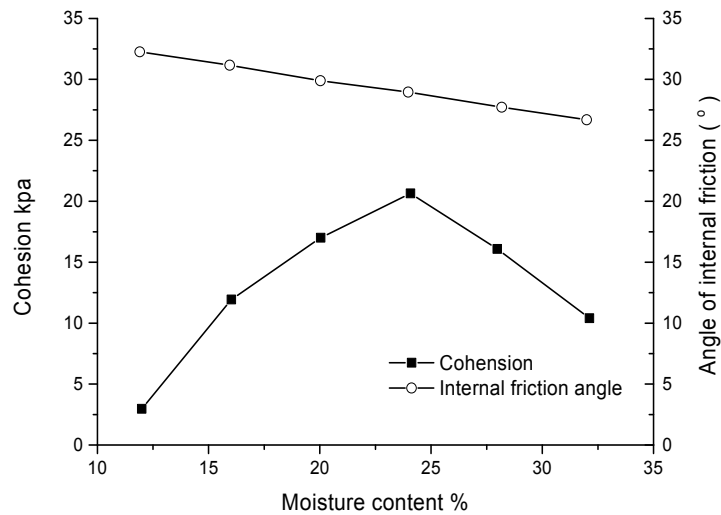
Other typical shear strength values are shown in Table 3 for reference. In most case, cohesion is ignored for conservative.



**Fig.12 Shear Stress versus Displacement**



**Fig.13 Consolidation time versus settlement**



**Fig. 14 Variation of apparent cohesion, friction angle with various moisture content**

**Table 3 Typical shear strength**

Ash type	Cohesion	Friction angle	Comments
Kanawha River fly ash	0	34	Consolidated undrained triaxial Pienpucta 1977
Kanawha River fly ash	0	37	Average void ratio 1.68 Seals <i>et al.</i> 1972
Fort Martin, unit 2 bottom ash	0	40	Average void ratio 1.41
Mitchell, bottom ash	0	42.5	Average void ratio 1.08
Nanticoke, fly ash	0	35	
Kolkata Ghosh, A (2005)	32 kN/m <sup>2</sup>	36	

Mae moh fly ash	0	26	CIU triaxial tests on saturated fly ash specimens
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## 8. Conclusions and recommendation

### 8.1 Summary

Geotechnical properties are correlated with chemical composition of fly ash. Factors like lime content (CaO), iron content (Fe<sub>2</sub>O<sub>3</sub>), loss on ignition, morphology, and mineralogy govern the geotechnical properties of fly ashes (Sarat Kumar Das, 2005). Following are the summaries for all the aspects discussed above.

1) Laser particle and XR sedimentation or electrolyte resistivity (coulter counter) method for high calcium fly ash, and hydrometer method low calcium fly ash. Most fly ash can be classified as sandy silt to silty sand or fine sand.

2) The specific gravity of fly ash depends on fineness, loss on ignition (LOI), mineralogy, and iron content. No good correlation between  $G$  values with any of the above parameters individually.

a) High calcium fly ash have a high value of specific gravity than low calcium fly ash.

b) For high calcium fly ash, when crushed, the specific gravity increase. But grinding will not increase the specific gravity, as LOI was also very low.

c) For iron content >10%,  $G$  value is directly proportional to iron content.

d) For a lime content CaO>15%,  $G$  value is more irrespective of iron content and loss on ignition.

3) Fly ashes which are non-plastic in nature. Typically, the liquid limit water content for fly ash is 26% to 51%, for pond ashes 22% to 64%, and 45 to 104% for bottom ashes. "Equilibrium water content under  $K_0$  stress method" is proven to be effective in testing the liquid limit of class F fly ash.

4) The residual carbon content controls the compaction characteristics, even though other factors like gradation, iron content, morphology, etc. are also important.

a) High calcium fly ash has a higher density and lower optimum moisture content than low calcium fly ash.

b) High calcium fly ash has a narrow range of OMC, as the reaction of lime.

c) Aged fly ash do not produce the same compacted densities as the fresh fly ash, particularly as the water content is below the OMC.

d) The addition of gypsum reduces the density.

e) Because of the lower specific gravity and the porous nature of the particles, fly ashes have a lower MDD and a higher OMC than normal soils.

f) Equitation for MDD-OMC relationship is not that accurate, but may be helpful.

$$\text{MDD} = 25.234G^{0.488}\text{OMC}^{-0.336} \text{ kN/m}^3$$

5) Class C fly ash is less permeable than class F fly ash.

a) As consolidation increase,  $k$  is almost unchanged for low calcium fly ash, whereas it slightly decreases with time in the case of higher calcium fly ash.

b) Back-calculation of  $k$  from the consolidation test is misleading. As the consolidation occurs very fast, it is not possible to calculate the value of coefficient of consolidation  $C_v$ . Therefore, the coefficient of permeability should be measured directly, rather than back calculated from the standard consolidation tests. We can use  $k$  to back calculate  $C_v$ .

c) As the consolidation pressure increase, the permeability of class C and F fly ash decrease. At high consolidation pressure, their permeability tends to be similar.

d) On the dry side of the OMC, the increasing of moisture content decrease the permeability of fly ash; however, on the wet side of OMC, the increasing water content help to increase permeability. All in all, the consolidation pressure is dominate. When the consolidation pressure is high enough, their permeability is similar, no matter what the water content is.

e) Addition of lime to fly ash reduces hydraulic conductivity. Gypsum, in the presence of lime, helps to decrease hydraulic conductivity even futher.

6) Class C fly ash resists the consolidation pressure at a higher void ratio than does class F fly ash. The compression index  $C_c$  is quite small for both the ashes. The change in void ratio is not considerable as the consolidation pressure increases.

## 8.2 Recommendation for application

As a foundation material, fly ash has a lesser bearing capacity than silt; fly ash exerts lesser lateral thrust on retaining walls than silts; and embankments on soft soils have a higher factor of safety and settle less when they are made of fly ash than of silt.

1) The compacted fly ash can be moderately permeable, if compacted at dry side of OMC. In this case, it cannot be used in seepage cutoff. However, in embankments and retaining walls the fly ash would perform better than clay, because it possesses better drainage characteristics. Furthermore, as the shear and tensile strengths of a pozzolanic fly ash increase with time, the internal stability of fly ash embankments should improve considerably.

2) Because of the silty non-cohesive nature of fly ash, it can be compacted efficiently with rubber-tired rollers during construction.

3) Fly ash can be used as an additive for effective seepage cutoffs in earth structures. However, excessive amounts of fly ash may cause brittleness of cutoffs. Blending of natural soils with a small proportion of fly ash may enable the construction of a stable (non-erosive), impervious core in rock fill dams.

4) The post peak behavior of some fly ash shows brittle rupture, which implies cracking in the embankments made of fly ash.

5) Fly ash stabilized with lime and gypsum are applicable for structural fill, embankments and impermeable barriers.

6) Compaction of fly ash at low moisture contents or at natural moisture content cannot obtain acceptable strength. However, things are different when compacted at OMC. The uniaxial compressive strength of hardened fly ash is comparable with some soft rocks after 2-3 weeks of curing, with an elastic modulus in the order of 3-5 MPa.

7) If compacted surfaces are left uncovered, the air drying would reduce strength very significantly.

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