Dynamic Properties of Fly Ash-Sand Mixtures

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Abstract. Large quantities of coal ashes are being generated by thermal power plants (coal-fired) all over the world. The coal ashes are proving to be potentially hazardous materials causing environmental pollution. Bulk utilization of fly ash requires a relatively good knowledge of the characteristics of fly ashes, their response and engineering behaviour. Various studies are available on the behaviour of fly ash without and with various additives, but a very few researchers focus on the behaviour of fly ash-sand mixtures. A series of resonant column tests have been carried out on fly ash, sand and fly ash-sand mixtures to investigate the influence of sand particles on the maximum dynamic shear modulus (G_{max}) and dynamic damping (D) of fly ash. Dynamic properties of fly ash-sand mixtures are found to be dependent upon the percentage of sand particles in the mix, confining pressure and shear strain. The maximum dynamic shear modulus of fly ash-sand mixtures is found to be more than the maximum dynamic shear modulus of fly ash. The damping ratio of sand is found to be more than the damping ratio of fly ash irrespective of the confining pressure.

Keywords: Fly ash, Resonant Column test, Dynamic shear modulus, Damping ratio

1 INTRODUCTION

In India, with more than 100 billion tons of coal reserve, coal-based thermal power generation occupies a predominant place in the energy sector. From these industries, fly ash is generated as a byproduct from the combustion of pulverized coal. Disposal of fly ash in a cost-effective and environment-friendly way is of importance. Some of its properties such as low unit weight, ease of compaction and pozzolanic nature are favourable for its use in embankment and road construction.

Numerous studies are available on the behaviour of fly ash as geomaterial. The studies mainly focus on the engineering (Kim et al., 2005: Prakash and Sridharan, 2009; Pal and Ghosh, 2014), physical (Martin et al., 1990; Sivapullaiah et al., 1995; Pandian et al., 1998; Prakash and Sridharan, 2009; Mir and Sridharan, 2013), and chemical (Komonweeraket et al., 2015) behaviour of fly ash without and with various additives such as clay, bottom ash, lime kiln dust (LKD), rice husk ash (RHA), cement, fiber and spent coffee grounds (CG).

Study on unprocessed, compacted fly ash ass structural fill was carried out by Martin et al. (1990). Compacted densities indicated low sensitivity to moisture content.

Determination of optimum lime content for Neyveli fly ash (NFA) and Vijaywada fly ash (VFA) samples were investigated by Sivapullaiah et al. (1995). Investigations have been carried out to study specific gravity (Pandian et al., 1998) of different types of fly ashes. Suitability of high volume fly ash mixtures as construction material (Kim et al., 2005) also has been studied. Compaction characteristics suggest that compacted dry unit weights are insensitive to moisture content variation (Prakash and Sridharan, 2009). Laboratory tests for determination of compaction and swell potential (Mir and Sridharan, 2013) and volume change characteristics (Pal and Ghosh, 2014) of fly ash-clay mixtures have been conducted by various researchers. Compressibility characteristics have been found to improve due to addition of fly ash to Black cotton soil (Mir and Sridharan, 2013). Effect of addition of various additives such as lime kiln dust (Kang et al., 2015), cement, fiber (Kumar and Gupta, 2016), spent coffee grounds (Arulrajah et al., 2016) have also been studied. Malik and Shah (2016) carried out plate load tests on compacted fills of fly ash (FA), fly ash (FA)-waste sludge (S), fly ash (FA)-cement (C) and fly ash (FA)-cement (C)-waste sludge (S) to determine their bearing capacity. A new correlation has been proposed by Chattaraj and Sengupta (2017) for predicting the value of G_{max} for the fly ash based on confining pressure and void ratio. Saride and Dutta (2016) conducted fixed-free type resonant column tests to determine the dynamic properties, including shear modulus (G) and damping ratio (D); and Poisson's ratio (ν) of untreated and fly ash treated expansive soils. Gorakhki and Bareither (2017) conducted unconfined compressive strength tests on synthetic and natural mine tailings amended with fly ash and cement to assess the effects of tailings solids content, tailings particle-size distribution, and binder type on UCS of binder amended mine tailings. Keatts et al. (2018) experimentally studied relationships between dry density, apparent contact angle, and water entry head for Ottawa sand (OS) and a Class-F coal fly ash (CFA).

Ottawa sand samples containing fines in the range of 5-20% showed considerable influence on peak friction angle and critical-state friction angle (Salgado et al., 2000; Carraro et al., 2009). Liquefaction susceptibility of sands containing non-plastic fines (Polito and Martin, 2001) and non-plastic silt (Carraro et al., 2003) have been studied. The cyclic resistance of the mixture is controlled by the relative density of samples (Polito and Martin, 2001). Thevanayagam et al. (2002) studied the stress-strain response of different granular mixes. Initial shear modulus of sand-clay mixtures, of fluvial and marine origin, increase with the decrease in fines content (Yamada et al., 2008a). Normalized shear modulus and damping ratio of sand-clay mixtures are independent of confining pressure, irrespective of fines content and plasticity (Yamada et al., 2008b). Hazirbaba and Rathje (2009) investigated the effect of fines content on excess pore water pressure generation in sands and silty sands (Monterey #0/30). Hydraulic conductivity of sands is reduced by more than 3% due to the addition of bentonite slurries (Castelbaum and Shackelford, 2009). Degree of saturation should be considered while estimating hydraulic conductivity of sand-silt mixtures (Bandini and Sathiskumar, 2009). Introduction of non-plastic fines in sandy soils causes greater geologic aging effects, which result in a higher liquefaction resistance (Kokusho et al., 2012). Anagnostopoulos and Papaliangas (2012) investigated the effect of epoxy resin dilution on the physical and mechanical properties of sand and resin mixes. Liquefaction resistance of clean sands mixed with varying fines content (Paydar and Ahmadi, 2016) and plasticity were studied (Park and Kim, 2013; Yee et al., 2014). Liquefaction resistance of sandy soils depends upon plasticity of fines (Park and Kim, 2013). Small-strain shear modulus (G_0) and cyclic liquefaction resistance ratio (CRR) decrease with different rates when fines in small amounts are added to the sand (Paydar and Ahmadi, 2016). Seismic compression of the sand-fines mixture depends upon the relative compaction of mixtures (Yee et al., 2014). Addition of fines also increases the compressibility of the sand-fines mixture (Rahman and Lo, 2014). Chen and Indraratna (2015a, 2015b) studied the cyclic and shear behaviour of sandy silt soil treated with Lignosulfonate (a by-product of timber industry). Goudarzy et al. (2017) conducted resonant column tests on Hostun sand and Hostun sand mixed with 5, 10, 20 and 30% non-plastic quartz powder. It was found that when void ratio (e) in Hardin's equation is replaced by equivalent granular void ratio (e^*), maximum shear modulus ($G_{\max}$) for Hostun sand is predicted more accurately.

Compressive strength of different cement stabilized fly ash-soil mixtures have been studied (Kaniraj and Havanagi, 1999). Kumar and Raju (2009) investigated the effect of proportion of fly ash, relative density of soil samples, and vertical overburden pressure on sand.

Studies are available on the static and dynamic behaviour of fly ash without and with various additives. But very few studies are available on the dynamic behaviour of fly ash-sand mixtures. Hence the primary objective of the present investigation is to study the dynamic behaviour of fly ash-sand mixtures of different proportions and assess their suitability as a construction material in geotechnical engineering applications.

2 TEST PROCEDURES

The different materials used in this study are fly ash and local river sand. The fly ash used in the investigation is collected from Kolaghat Thermal Power Station (KTPS), Mecheda, West Bengal. The river sand utilized in the study collected from Kangsabati River, West Bengal, India. Figure 1 represents the particle size distribution of fly ash and local river sand. According to the Unified Soil Classification System, the local River sand is classified as poorly graded sand (SP). It may be seen from the figure that the fly ash consists mainly of silt-sized particles. Figure 2 indicates the compaction curve for KTPS fly ash. It may be seen from the figure that the moisture density curve for the fly ash is relatively flat, indicating that dry density does not change significantly with the variation of moisture content. Similar results were also reported by Martin et al. (1990), and Ghosh and Subbarao (2007). This behaviour of fly ash ensures that minor variation in moisture content may not affect the field density significantly. Fly ash and River sand samples are mixed at various proportions and compaction tests are carried out. Figure 3 presents the compaction curves obtained at different optimum moisture content (OMC) and maximum dry density (MDD) for different mixes.

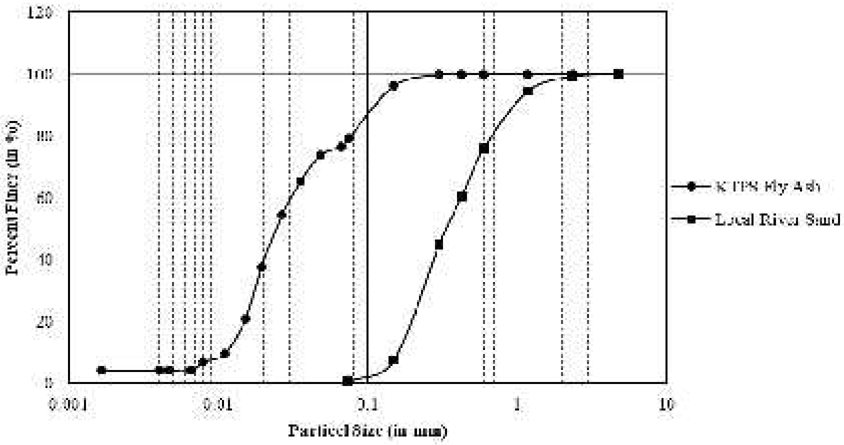

Fig. 1. Grain Size distribution curve for KTPS Fly ash and local River sand

The geotechnical properties of fly ash and local river sand are given in Table 1. The chemical composition is determined by using Axios XRF Spectrometer by PANalytical. The chemical compounds and their respective concentrations (%) are provided in Table 2. According to ASTM standard (ASTM C618-15), the fly ash is classified as Class F type.

Table 1. Geotechnical Properties of KTPS fly ash

Properties	KTPS Fly Ash	Local River Sand
Specific Gravity	2.15	2.67
Coefficient of Uniformity, C_u	2.5	2.78
Coefficient of Curvature, C_c	0.9	0.81
Effective Size, D_{10} (mm)	0.012	0.18
Maximum Dry Density (gm/ml)	1.19	-
Optimum Moisture Content (%)	28.4	-
Maximum dry unit weight,$(\gamma_d)_{max}$ (kN/m^3)	-	17.07
Minimum dry unit weight,$(\gamma_d)_{min}$ (kN/m^3)	-	14.22

2.1 Preparation of Samples

All the fly-ash samples are prepared in three layers by using static compaction technique. All the test samples are of 70 mm in diameter and 140 mm in length. In order to achieve the maximum dry density, the required amount of fly ash and water are taken, thoroughly mixed, and poured into the mould in three layers. The river sand samples are prepared by dry pluviation method at the relative density of 70%. The fly ash-sand mixture samples are also prepared at different ratios (90:10, 80:20, 70:30, 60:40 and 50:50) by static compaction method based on the MDD and OMC values obtained from compaction tests.

Table 2. Chemical Composition of Fly Ash

Chemical Compound	Concentration (%)
SiO_2	59.021
Al_2O_3	29.220
Fe_2O_3	6.177
CaO	0.679
MgO	0.679
Others	4.224

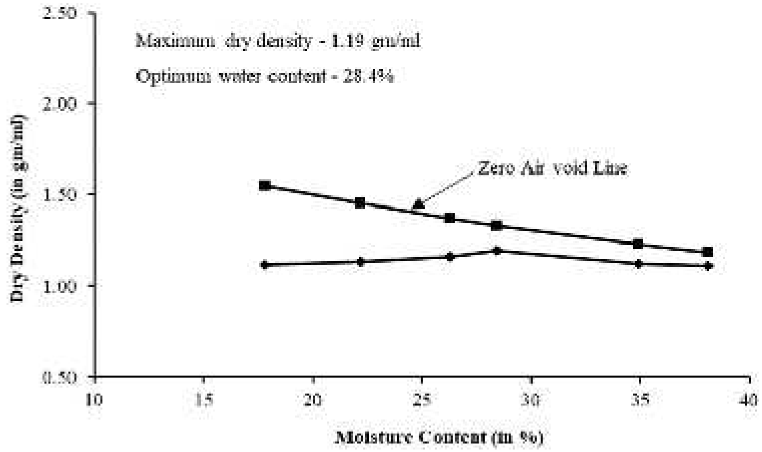

Fig. 2. Compaction curve for KTPS Fly ash

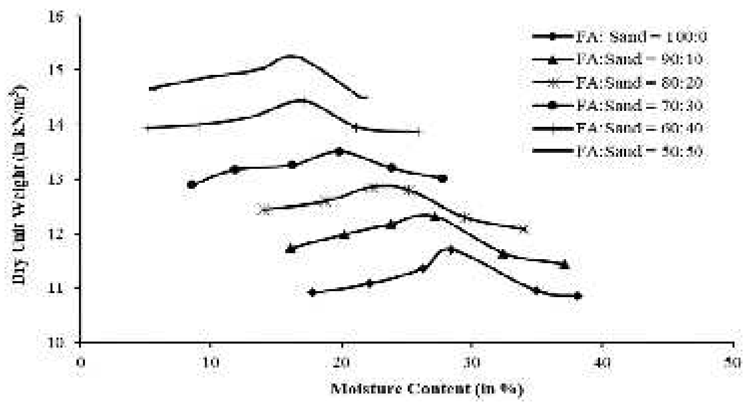

Fig. 3. Compaction curve for KTPS Fly ash and local River sand mixes

2.2 Resonant Column Test

Dynamic properties of soils play an important role when soils are subjected to cyclic loading. The resonant column apparatus employed in the present study is a fixed-free type resonant column device. The specimen is fixed to the pedestal at the bottom end and to the driving plate through the top cap at the other end. Figure 4 represents the resonant column unit after the installation of the specimen and arrangement of hardware around it.

The resonant column test is performed by applying a sinusoidal excitation via an electromagnetic drive system. Confining pressures of 50 kPa, 100 kPa, 200 kPa, and 300 kPa are applied with the value of shear strain varying in the range of 0.0005% ≤ γ ≤ 0.01%.

The shear wave velocity is calculated from the following equation (1),

$$V_s = \frac{2® fl}{} \qquad (1)$$

where,

V_s = shear wave velocity (in m/s); f = natural frequency of sample found from resonant column test (in Hz); and l = length of sample (in m).

is found from the basic equation of fixed-free resonant column given by equation (2) given below,

$$I/I_0 = \quad \tan(\quad) \qquad (2)$$

where,

I = mass polar moment of inertia of cylindrical soil sample = $m d^2/8$ (mass in *kg* and diameter in *m*); and I_0 = mass polar moment of inertia of drive system (found out experimentally from calibration of the system).

Shear Modulus (G) is then found out using the following relationship,

$$G = °V_s^2 \qquad (3)$$

where ρ = density of soil specimen.

The viscous damping ratio is measured in the resonant column test from the shape of the free vibration decay curve. The logarithmic decrement (¢) is calculated by taking logarithm of the ratio of amplitudes of successive cycles.

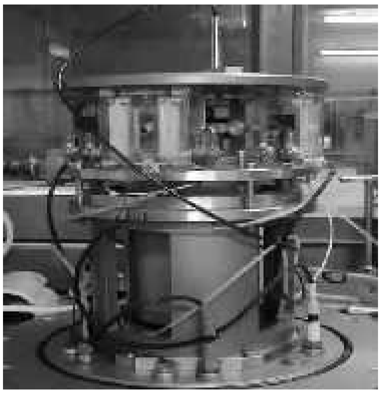

Fig. 4. Resonant Column Unit

Then damping ratio is calculated using equation (4) given below:

$$D = \sqrt{\frac{¢^{2}}{4®^{2} + ¢^{2}}} \tag{4}$$

3 TEST RESULTS AND DISCUSSION

3.1 Variation of Shear modulus with shear strain

Figure 5 (a) shows the effect of confining pressure on the variation of shear modulus with strain for local River sand at 70% relative density. It was observed that shear modulus value increased with increase in the confining pressure, and there was no significant change below the strain level of 0.001%. Hence shear modulus measured at strain level of 0.001% was considered as maximum shear modulus (G_{max}). Shear modulus was found to decrease with an increase in shear strain at a given confining pressure. In Fig. 5(b) variation of shear modulus with strain for KTPS fly ash is shown. It may be seen that at constant confining pressure, shear modulus degraded with increase in shear strain. For fly ash, the reference strain was found to be 0.001%. Figures 6(a) to 6(e) show the interrelation between shear modulus and shear strain for mixtures of fly ash and river sand at 50:50, 60:40, 70:30, 80:20 and 90:10 ratios, respectively. It may be observed that similar behaviour to that of river sand and KTPS fly ash was observed. Shear modulus values were found to decrease with shear strain at constant confining pressure. Reference strain for maximum shear modulus of fly ash-river sand mixtures was determined to be 0.001%.

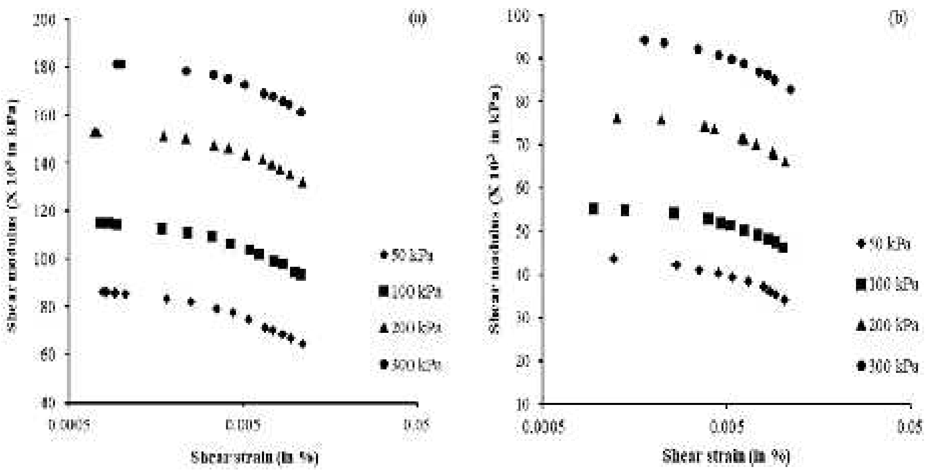

Fig. 5. Variation of Shear modulus with strain at different confining pressures for (a) river sand at relative density of 70% and (b) KTPS fly ash at maximum dry density

3.2 Variation of maximum shear wave velocity and maximum shear modulus with shear strain

Figures 7(a) and 7(b) represent the comparison of maximum shear wave velocity and maximum shear modulus (G_{max}), for river sand, fly ash and fly ash-river sand mixtures at different confining pressures, respectively. It was observed that with the increase in confining pressure, value of shear wave velocity increased. It was studied that with increase in confining pressure, the value of maximum shear modulus increased for river sand, fly ash and fly ash-sand mixtures. At confining pressure of 50 kPa, the mixture ratio of 50:50 (fly ash : sand) showed an increase in the value of G_{max} by 51.97% than that of fly ash only. It was observed that with the increase in percentage of sand particles, in the fly ash-sand mixture, the values of maximum shear modulus increased as compared to that of fly ash only. This behaviour can be due to an improvement in the frictional strength of mixtures due to sand particles. Similarly, for the same mixture ratio (50:50), the increase in the value of G_{max} was observed to be 66.11%, at confining pressure of 300 kPa than G_{max} of fly ash only. It was further observed that the rate of increase in the maximum shear modulus value reduced as confining pressure was increased beyond 200 kPa for river sand, fly ash, and mixtures of different ratios. This behaviour can be attributed to the fact that with an increase in confining pressure samples get stiffer due to the reduction of void ratio, which increases the shear modulus. At 200 kPa, the samples achieve maximum reduction of void ratio possible and a further increase in confining pressure does not contribute significantly to the rate of increase in maximum shear modulus values.

It may be also noted that at 50-300 kPa of confining pressure the G_{max} values of fly ash, at OMC and MDD, are 47% - 52% of the value of river sand at relative density of 70%. It may be noted that at same confining pressure, the G_{max} value of fly ash was 59% - 65% of the values of fly ash-river sand mixture ratio of 50:50. It was also further observed that the G_{max} value of fly ash-river sand mixture of 50:50 ratio was 77% - 86% of the values of river sand at relative density of 70%.

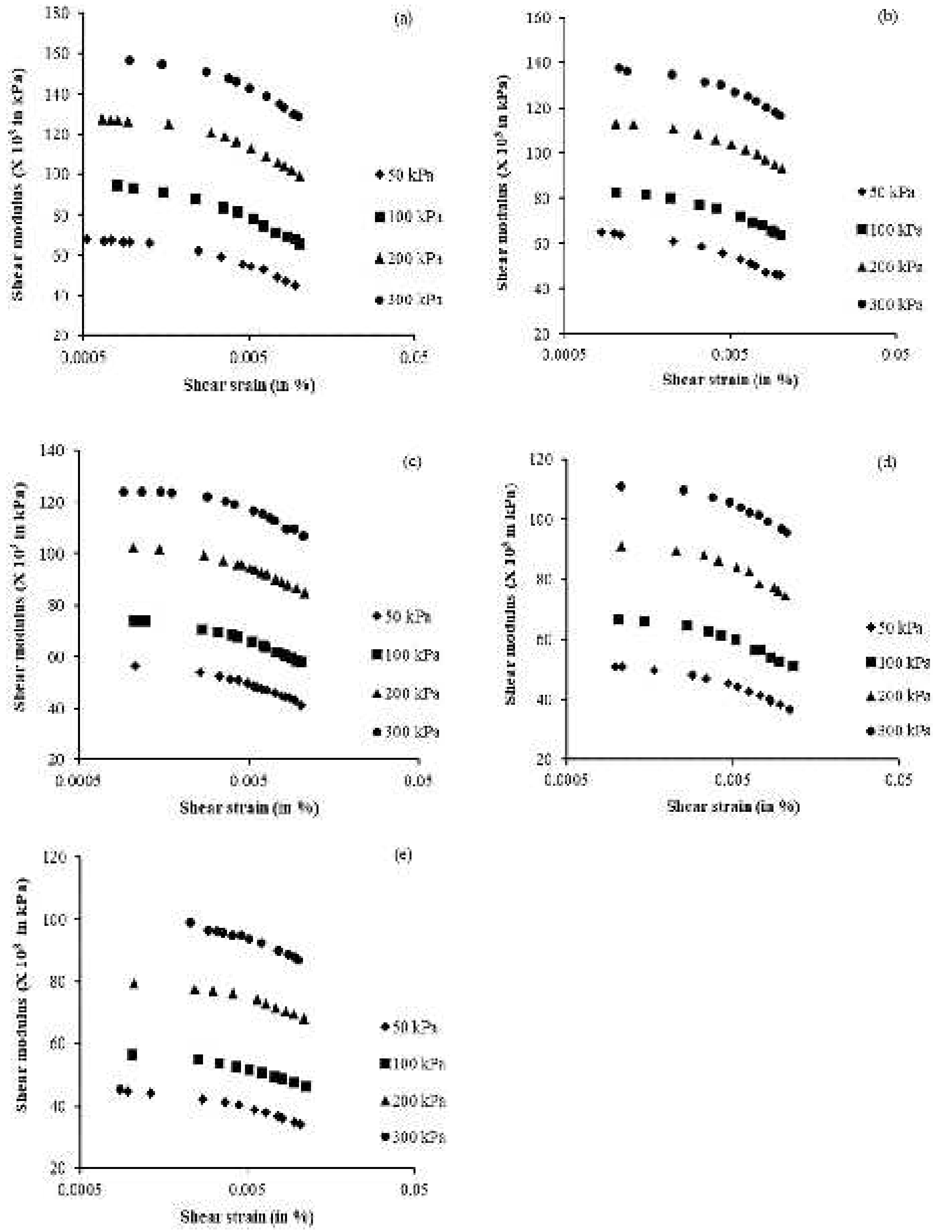

Fig. 6. Variation of Shear modulus with strain at different confining pressures for Fly ash-River sand mixtures at (a) 50:50, (b) 60:40, (c) 70:30, (d) 80:20 and (e) 90:10 ratios

3.3 Variation of damping ratio and modulus degradation (G/G_{max}) with shear strain

Figures 8(a) and 8(b) represent the comparison of damping ratio values, at different shear strain, for river sand, fly ash and fly ash-river sand mixtures for confining pressures of 50 kPa and 300 kPa respectively. Damping value depends upon the confining pressure and shear strain. It was observed that with an increase in shear strain, damping ratio increases at the same confining pressure. Damping ratio was found to be less than 4% and 3% for river sand and fly ash respectively at 50 kPa.

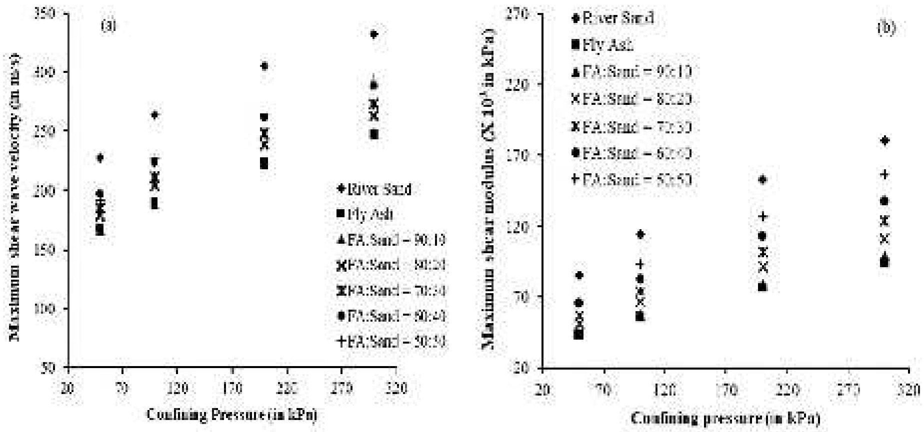

Fig. 7. Comparison of (a) maximum shear wave velocity and (b) maximum shear modulus values of river sand, fly ash and fly ash-river sand mixtures with confining pressure

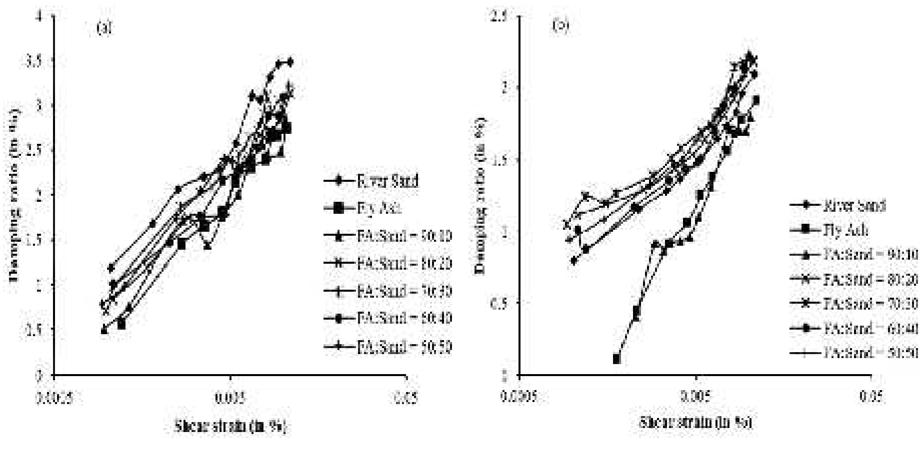

Fig. 8. Comparison of damping ratio values of river sand, fly ash and fly ash-river sand mixtures with shear strain at (a) 50 kPa and (b) 300 kPa confining pressure

For the different ratios of mixtures of fly ash and river sand, damping ratio was found to be less than 3.5% at 50 kPa. It was observed that the damping ratio of sand was higher than the damping ratio of fly ash at 50 kPa. It may be noted that, from Figs. 8(a) and 8(b), damping at 50 kPa was found to be more than at 300 kPa for river sand, fly ash and mixture ratios of fly ash- river sand. It is because of increase in stiffness, at a given shear strain level, due to the increase in confining pressure. It was also observed that at 300 kPa confining pressure and 0.01% strain, damping ratio of fly ash was about 91% of the damping ratio of sand. At confining pressure of 50 kPa and 0.01% strain, the damping ratio of fly ash was almost 79% of damping ratio of sand. This behaviour may be attributed to the fact that stiffness of sand reduces faster than that of fly ash as confining pressure reduces. Similar behaviour was also reported by Chattaraj and Sengupta (2017). At 50 - 300 kPa confining pressure and 0.01% strain, the damping ratio of the fly ash was found to be 85% - 86% of the value of fly ash-river sand mixture of 50:50 ratio.

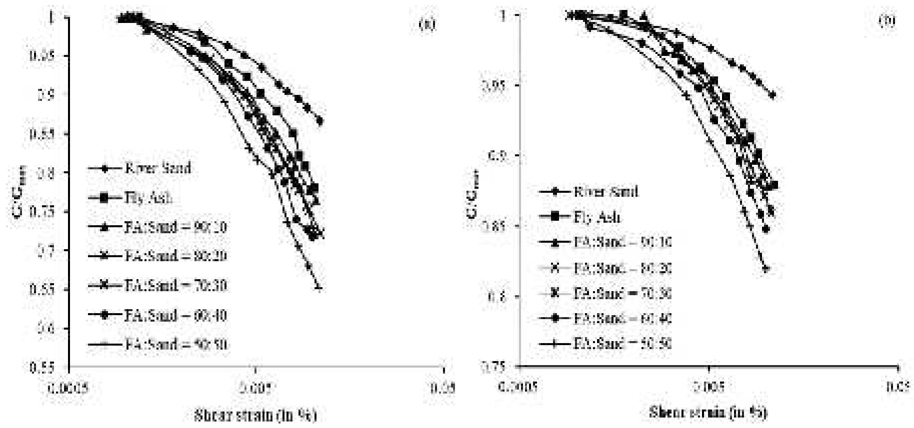

Fig. 9. Comparison of modulus degradation (G/G_{max}) of river sand, fly ash and fly ash-river sand mixtures with shear strain at (a) 50 kPa and (b) 300 kPa confining pressure

Figures 9(a) and 9(b) represent the variation of G/G_{max} with shear strain for river sand, fly ash and fly ash-river sand mixtures at confining pressure of 50 kPa and 300 kPa respectively. It was observed that in case of river sand at confining pressure of 50 kPa shear modulus degraded by 25%. However, it degrades by 11% at 300 kPa confining pressure. In case of fly ash, compacted at OMC and MDD, shear degradation was found to be 22% and 12% at 50 kPa and 300 kPa confining pressure, respectively. In case of fly ash-river sand mixture ratio of 50:50, at 50 kPa confining pressure, shear degradation was found to be 35% and at 300 kPa the degradation was found to be 18%. At higher confining pressures, the modulus degradation was found to be less.

3.4 Comparison of experimental data with other studies

The present experimental values of the maximum shear modulus of River sand and fly ash are compared with the empirical relationships suggested by Chattaraj and Sengupta (2017). Equation (5) and Equation (6) represent the relation for estimation of G_{max} in case of sand and fly ash respectively,

$$G_{\max} = \frac{611.58 \times (P_a)^{0.532} \times (\pm_0)^{0.468}}{(0.3 + 0.7e^2)} \quad (5)$$

$$G_{\max} = \frac{463.98 \times (P_a)^{0.545} \times (\pm_0)^{0.455}}{(0.3 + 0.7e^2)} \quad (6)$$

where, P_a= atmospheric pressure; $\pm_0$ = confining pressure (kPa); and e = void ratio

Figures 10(a) and 10(b) represent the variation of predicted value with experimental values for both sand and fly ash, respectively. It was observed that experimental values are quite in agreement with the predicted values of river sand and fly ash respectively.

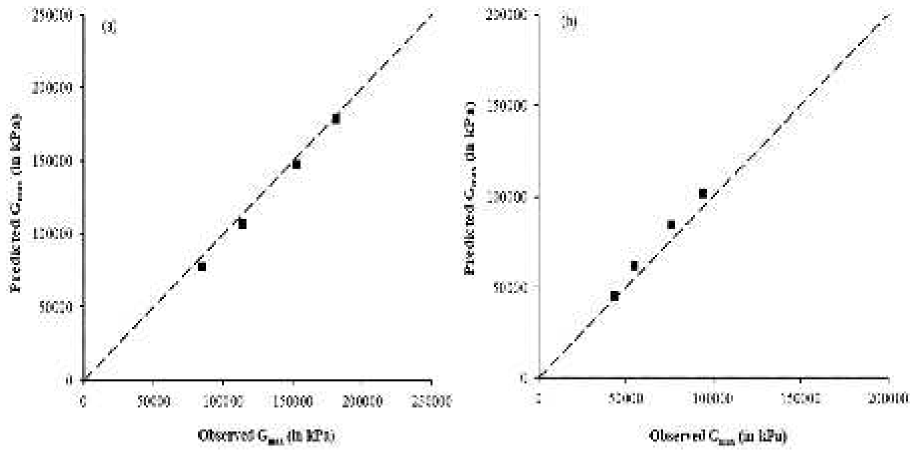

Fig. 10. Comparison of observed values of G_{max} with predicted values of G_{max} for (a) river sand and (b) fly ash at different confining pressures

4 CONCLUSIONS

In the present paper, the dynamic properties of local river sand, fly ash and fly ash-river sand mixtures have been studied. Dynamic behaviour of fly ash and river sand have been reviewed and compared. It is observed that confining pressure has a significant influence on the rate of change of G/G_{max} (modulus degradation) for fly ash, river sand, and fly ash-river sand mixtures. It is observed that the damping ratio of sand is always greater than the damping ratio of fly ash at all confining pressures. It is found that with increase in percentage of sand particles, in the fly ash-river mixture, the value of maximum shear modulus increases. The fly ash-river sand mixture of 50:50 ratio exhibits the highest value of shear modulus as compared to fly ash and other mixtures of fly ash-river sand. This behaviour may be because of the fact that there is an improvement in the frictional strength of mixtures due to sand particles. It is also further observed that the G_{max} value of fly ash-river sand mixture, of 50:50 ratio, is 77% - 86% of the values of river sand at a relative density of 70% for 50-300 kPa of confining pressure. It is also noted that at 300 kPa confining pressure and 0.01% strain, damping ratio of fly ash is about 91% of the damping ratio of sand. At 50 kPa confining pressure and 0.01% strain, the damping ratio of fly ash is almost 79% of damping ratio of sand. This behaviour may be attributed to the fact that stiffness of sand reduces faster than that of fly ash as the confining pressure reduces. At 50 kPa – 300 kPa confining pressure and 0.01% strain, the damping ratio of the fly ash is found to be 85% - 86% of the value of fly ash-river sand mixture at ratio of 50:50.

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