Feasibility Study of Static Liquefaction Susceptibility of Pond Ash Treated with Bentonite

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Abstract.

Static liquefaction is often considered as the most catastrophic mechanism due to the fact that static liquefaction failures occur without warning. Pond ash, a by-product from coal fired power plants is dumped into ash ponds, which possess a risk of liquefaction due to cyclic or static loading. In this present study, the effects of confining pressure and bentonite content on the static liquefaction of pond ash have been explored. The materials were tested at their compacted maximum dry densities and optimum moisture contents. Strain controlled static consolidated undrained triaxial tests have been carried out on pond ash-bentonite samples (0-15% @5% increment of bentonite) at varying confining pressures (50, 100 and 150 kPa), at 0.8 mm/min rate of loading. Firstly, the pond ash sample mixed with bentonite showed a better friction angle and high cohesion. Secondly. heavy compacted pond ash samples are less susceptible to static liquefaction. Thirdly, the excess pore water builds up at a faster rate for the pond ash sample as compared to the pond ash bentonite mixture. Finally, it may be concluded that bentonite content increases the static liquefaction resistance of pond ash.

Keywords: Static liquefaction, Pond Ash, Bentonite.

1. Introduction

Liquefaction is a process in which a mass of loose, wet, non-cohesive soil loses a lot of its strength when it is loaded without draining, resulting in economic, social, and environmental destruction. The liquefaction vulnerability of fine-grained soil was talked about. It was shown that low plasticity silt is a type of fine-grained soil that is likely to liquefy (Chegenizadeh et al., 2018). Liquefaction is a natural disaster caused by loss of strength and stiffness during seismic events, typically affecting sandy soils (Keramatikerman et al., 2017). The abrupt increase in pore pressure during undrained shearing reduces effective stress, which diminishes shearing strength. Static liquefaction is regarded as the most catastrophic mechanism since static liquefaction failures are frequently sudden and occur without warning (Sadrekarimi, 2013). When static liquefaction occurs, the soil loses its ability to support geotechnical applications such as slopes, embankments, earth dams, mine tailing impoundments and building foundations. Recently, static liquefaction has gained considerable attention from researchers because of its most destructive consequences.

Pond ash is a byproduct of thermal power plant coal combustion (Vijayasri et al., 2016). It's sometimes referred to as ash pond residue or coal ash. Each year in India, roughly 225 million tonnes of ash are produced, but only 175 million tonnes are used (Mohanty & Patra, 2016). Bottom and fly ash that is no longer needed is mixed with a lot of water and dumped in ash ponds. These ash ponds have already taken up 65,000 acres of important land in India and many millions of acres around the world (Mohanty & Patra, 2015). Pond Ash is a man-made material, and its particle size ranges from fine sand to silt that might lead to liquefaction of the ash embankments (Jakka et al., 2010). Pond ash liquefaction can cause instability and slope collapses inside the ash pond. When subjected to cyclic or static loading, such as earthquakes or quick changes in water levels, the excess pore water pressure generated during liquefaction can drastically reduce the effective stress within the ash, leading the material to lose shear strength. This can cause slope instability, embankment collapses, and possibly the complete collapse of the ash pond. So, susceptibility analysis with a focus on the risk of liquefaction is very important. The rapid loss of stability in the ash pond embankments can cause ground settlement, differential settlement, or lateral spreading, which can put buildings and their foundations at risk.

Significant research has been done on compacted pond ash- bentonite composite in the past decade. Due to the low permeability ($k<10^{-9}$ m/s) of natural clays, highly expansive soils such as bentonites can be mixed with pond ash to build hydraulic barriers (Rout and Singh, 2020). Bentonites are made up of montmorillonite minerals and are highly plastic in nature. Pond-ash bentonite mixture might be less susceptible to static liquefaction due to the increase in plasticity and cohesion.

1.1 Concept of Static Liquefaction

Static liquefaction is a process in which a loose, wet, and non-cohesive mass of soil loses a considerable amount of strength due to soil particle rearrangement when subjected to undrained monotonic loading. The undrained condition arises when the rate of pore water dissipation is slower than the rate of filling and the soil content has much less permeability. In the laboratory, an undrained condition is created by closing the drainage valve and preventing drainage from the soil sample. Extensive research is necessary to understand the liquefaction behavior of naturally occurring soil deposits under monotonic and dynamic loading situations (Gujrati et al., 2023). Static liquefaction occurs in contractive soils that are subjected to monotonic loading trigger (Ng et al., 2022) and are almost or completely saturated, such as sands, silts, and sensitive clays. Raising embankment height, over steeping, toe erosion, construction loading, heavy rain, and reservoir filling are examples of undrained monotonic loading that can cause static liquefaction. When volumetrically contracting sand is deposited in an undrained state, soil instability results (Lade & Yamamuro, 1997). This can be performed by testing higher density soils at high confining pressures or very loose soils at low and high confining pressures. In porous, cohesion less soils, strain softening causes pre-failure instability, which leads to static liquefaction. Instability refers to the occurrence of significant, swift, and chaotic displacement of a soil mass, which takes place within the limits of effective stress failure (Hussain and Sachan, 2019). In the recent past, several failures have been attributed to static liquefaction. Notably, the catastrophic collapse of the Merriespruit gold mine tailing dams in Virginia, South Africa, in February 1994 serves as a poignant example. This incident resulted in the release of approximately 600,000 cubic meters of waste tailings, spreading over a distance exceeding 2000 meters (Davies et al., 2002). Tragically, it claimed the lives of 17 individuals, demolished 280 houses, and left a trail of destruction in its wake. Similarly, the failure of the Calaveras Dam in California in March 1918, which traveled approximately 200 meters, can also be attributed to liquefaction flow failure caused by the over steepening of the Merriespruit dam, brought about by monotonic loadings.

2. Materials and Methodology

The key materials mentioned in this study are pond ash and bentonite. The experimental approaches for describing these materials are also investigated. The main waste product and residue produced by coal burning is ash. To make it ecologically friendly, the created ash is disposed of in ponds by mixing it with water and specific chemicals. These ponds are referred to as ash ponds. Thick Slurry Disposal is the method used to get rid of coal ash. It uses a chemical treatment that makes the ash slurry quickly solidify as soon as it is dumped at the spot. The Pond ash used in this present geotechnical investigation has been collected from the ash pond of the Rourkela steel plant, Odisha. Bentonite is a type of clayey material composed primarily of montmorillonite, a soft phyllosilicate mineral formed from volcanic ash. Montmorillonite has a layered structure with a high specific surface area and a negative charge on its surfaces, allowing it to absorb and hold water molecules. The bentonite used in this present study was collected from local market and it is sodium-based bentonite.

2.1 Material Characterization

In order to investigate the physical and geotechnical properties of pond ash and bentonite materials various tests like X-ray diffraction, specific gravity, particle size distribution, Atterberg's limits, standard proctor, modified proctor and UU triaxial tests have been carried out. Here two XRD tests were performed for two parent materials (Pond Ash and Bentonite). The mineral composition of pond ash (Quartz, Hematite, Calcite) and Bentonite (Quartz, Montmorillonite, Halite, Calcite, Eskolite) are shown in Figure 1.

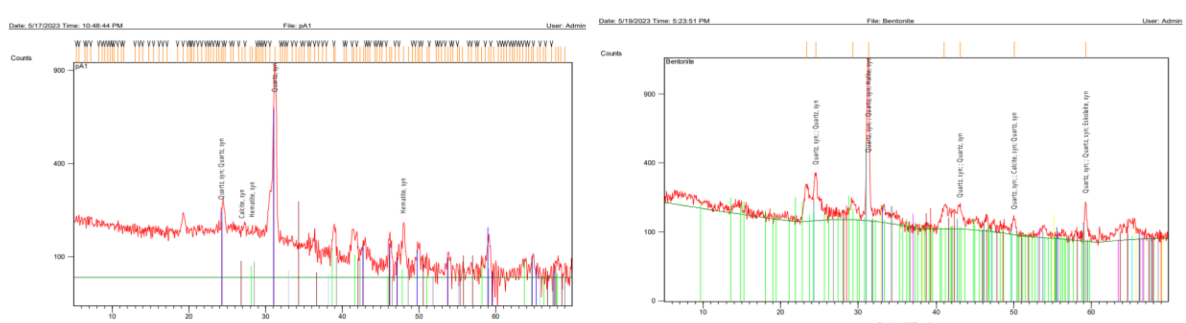
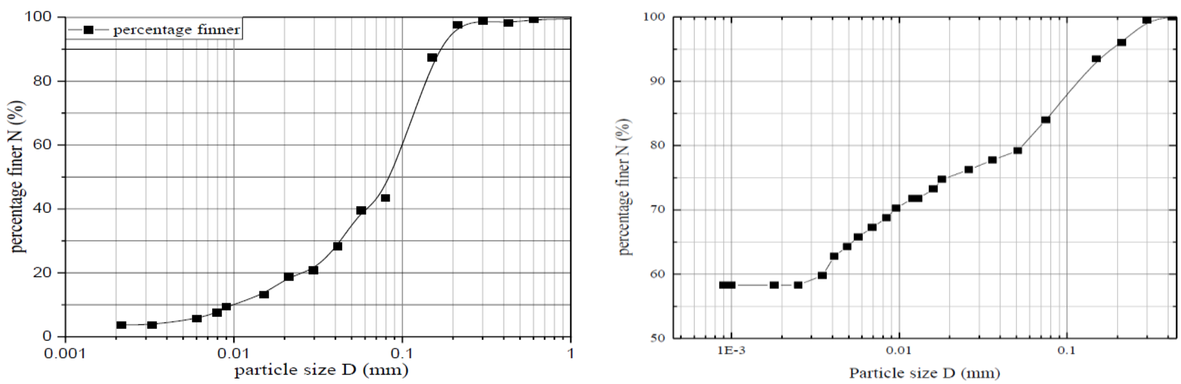


Figure 1: XRD test of pond ash (in left) and bentonite (in right)

According to the grain size analysis of pond ash, the pond ash components are well graded within the range of possible particle sizes. The majority of the particles in pond ash range in size from silt to fine sand (49% silt, 31% fine sand and 19% clay). More than half of the soil particles present in bentonite are clay type particles (58.2% clay, 25.8% silt and 16% fine sand). Figure 2 shows the particle distribution curves for pond ash and bentonite. Index and geotechnical properties for both materials (pond ash & bentonite) are depicted in Table 1.



(a) *(b)*

Figure 2: Particle size distribution curve of (a) pond ash, (b) bentonite

Table 1: Index and geotechnical properies of pond ash and bentonite

Materials	Specific Gravity	Liquid Limit (%)	Plastic Limit (%)	Shrinkage Limit (%)	Plasticity Index
Pond Ash	2.15	48	0	0	0
Bentonite	2.74	264	51	10.21	213

2.2 Methodology Adopted

Specific gravity, Atterberg's limit, grain size distribution tests have been carried out to identify the index and geotechnical properties of pond ash and bentonite as per *IS 2720: 1980 Part 3, IS 2720-5 (1985) and IS: 2720 (Part IV)* respectively. Compaction tests are performed to identify the best water content to mix with soil in order to produce the highest soil density for the least amount of compaction effort. In this study, compaction tests (both standard proctor and modified proctor) are done on Pond ash and Pond ash-bentonite mixes with various bentonite content (5%, 10% and 15% by weight.) as per *IS: 2720 (Part VII) - 1980, Reaffirmed 1987*. Light compaction approach achieves a compaction effort or energy of 592 kJ/m^3 and heavy compaction method achieves 2700 kJ/m^3 of work or energy to compact which is 4.5 times that of in the light compaction test. Unconsolidated undrained triaxial tests have been performed to determine the shear strength parameters (c and ϕ) of pond ash and pond ash-bentonite mixtures. Strain controlled static consolidated undrained triaxial tests were carried out to identify the static liquefaction susceptibility of pond ash and pond ash bentonite mixtures (5%, 10% and 15% bentonite contents) for light compacted and heavy compacted samples in three different confining pressures i.e. 50 kPa, 100 kPa and 150 kPa.

2.2.1 Experimental Test Setup

Both tests are done for pond ash and pond ash-bentonite mixture in an automated cyclic triaxial system (as shown in Figure 3). In this system, Triaxial Cell has been designed to test different sizes of samples at various pressure ratings ranging from 0.5 – 10 kg/cm^2. It is provided with an internal load cell of 1000 kg. The transfer rod passing through linear bearing is strong enough to transfer the force of 1000 kg from the actuator to the test sample. A load of 1000 kg is sufficient to test majority of the samples both in saturated or unsaturated condition. There are four ports provided in the base one each for – confining pressure, back pressure, top drainage and pore water pressure.

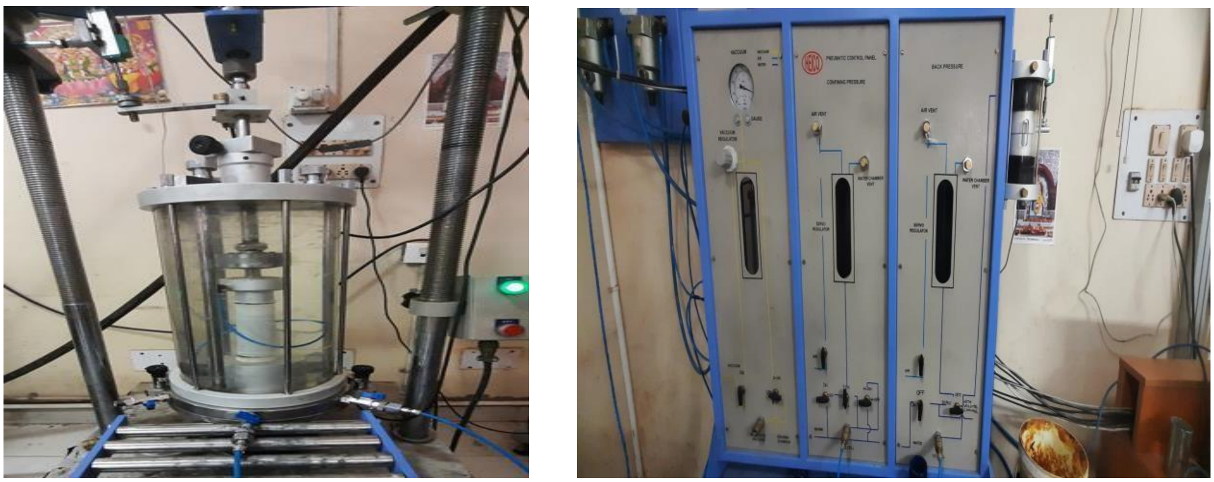


Figure 3: Triaxial Cell and Pneumatic Control Panel

Pneumatic control panel is the part of cyclic triaxial set for creating confining and back pressure, this is done for determining the compressive strength of a saturated soil specimen in the triaxial equipment under constant confining pressure circumstances. Control panel has four independent circuits- Vacuum for de-airing and for fixing of the sample, confining pressure, back pressure and volume change.

2.2.2 Preparation of Sample

The 38 mm dia. and 76 mm height samples were prepared using a moist tamping specimen preparation procedure. Specimens are produced in accordance with the requirements for conducting triaxial tests on compacted specimens appropriate to MDD and OMC. The required amount of moist soil corresponding to the specimen size to be tested is taken and compacted in layers (3-5 layers) in the constant volume mould to obtain the specimen for triaxial test.

2.2.3 Saturation of Sample

The sample was soaked by applying both back pressure and limiting pressure at the same time. During the process of preparing the material, care was taken to make sure that the effective stress never exceeds 20 kPa. Percentage of saturation of sample was obtained by calculating the skempton's parameter B and minimum value of 0.95 was obtained for all the tests.

$$B = \frac{\Delta u}{\Delta \sigma 3} \tag{1}$$

Where, $\triangle u$= change in pore water pressure and $\triangle \sigma_3$= change in confining pressure.

2.2.4 Consolidation

Once the saturation part of the test is over, bring the axial load piston into contact with the specimen cap and record the number on the deformation indicator to three significant digits. Keep the highest back pressure the same while raising the pressure in the chamber until the difference between the pressure in the chamber and the back pressure is equal to the effective consolidation pressure. Plot the changes in volume and warping against the logarithm or square root of the amount of time that has passed. When the volume change graph shows that the volume isn't changing, the consolidation should stop.

2.2.5 Shearing

While pushing the axial load piston downward against the specimen cap, the chamber pressure must be maintained. Shear prohibits specimen drainage in case of CU test. The specimen receives a constant or gradual axial load. This load causes specimen shear stress. Axial load, displacement, and pore water pressure are measured during shearing. Axial load and displacement measurements determine soil stress-strain and shear strength. Pore water pressure measurements assess shearing-induced excess pore pressure development and dissipation.

3. Results and Discussion

3.1 Geotechnical properties of pond ash and pond ash- bentonite mixtures

Pond ash and bentonite are combined with various bentonite concentration, i.e., 5%, 10%, 15%, and 20% by weight, and their geotechnical properties are evaluated.

3.1.1 Consistency limits

Several experiments, including liquid limit, plastic limit, and shrinkage limit tests, were performed to assess the influence of increasing bentonite concentration on the consistency limits of pond ash and bentonite mixes. The results of these tests are shown below (Table 2), and it is shown that how the consistency limits change as the bentonite level goes up.

Table 2: Consistency limits for different pond ash and bentonite mixtures

PA:B	Liquid Limit (*LL*)%	Plastic Limit *(PL)*%	Plasticity Index *(PI=LL-PL)* %
80:20	61.23	33.2	28.03
85:15	56	30.85	25.15
90:10	47	27.68	19.32
95:5	42.56	18.46	24.1
100:0	40.23	0	55.24

Figure 4 depicts how the liquid limit varies with increasing bentonite percentage in pond ash-bentonite mixes. The figure clearly shows that adding bentonite to pond ash raises the liquid limit.

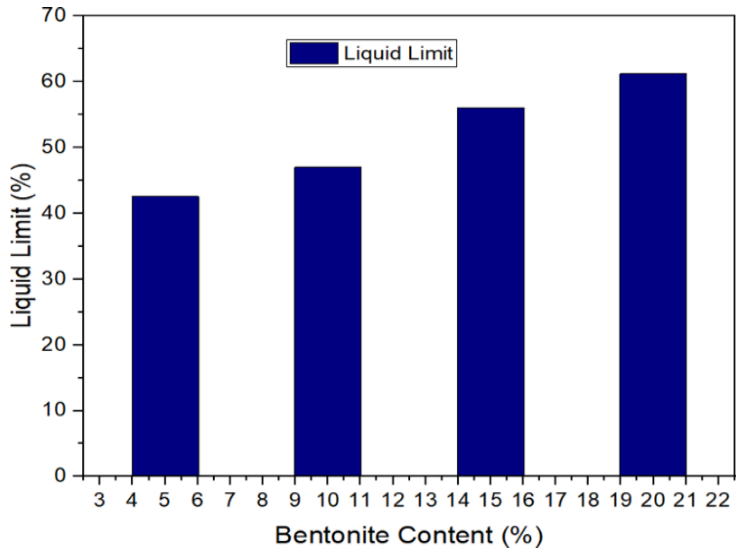


Figure 4 : Variation of liquid limit with bentonite content

The addition of bentonite to pond ash results in an increase in plasticity index, as observed in Fig. 5. Bentonite, being highly plastic, imparts plasticity to the pond ash-bentonite mixture, with higher bentonite content leading to increased plasticity.

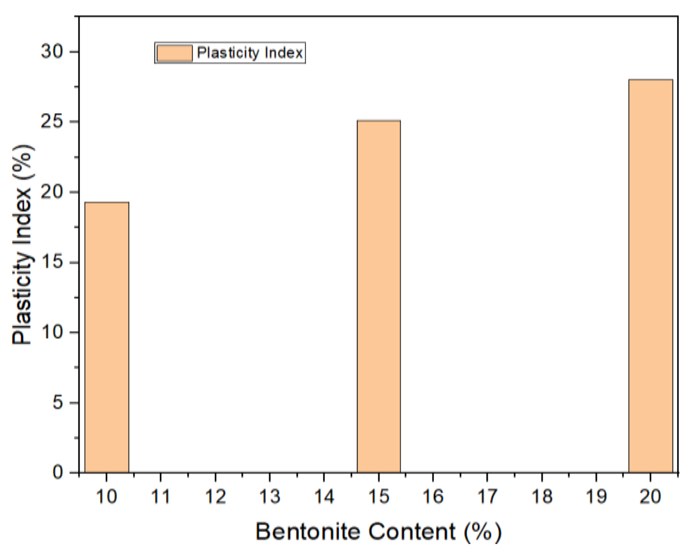


Figure 5: Variation of plasticity index with bentonite content

3.1.2 Compaction and Shear Strength Parameter Characteristics

Experiments with light compaction and heavy compaction were done on different mixtures of pond ash and bentonite with 5%, 10%, and 15% by weight of bentonite. The data were analyzed to evaluate the effect of different compaction techniques on the static liquefaction of the pond ash and bentonite mixes indicated above.

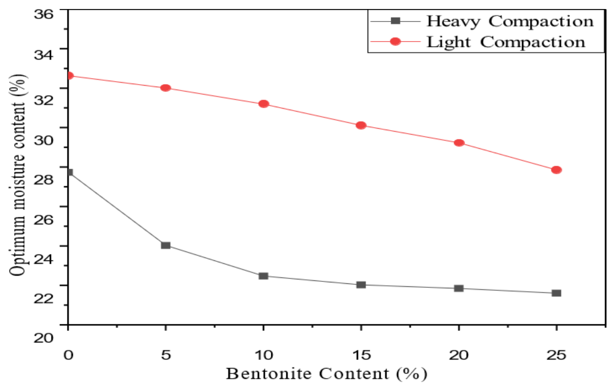


Figure 6: Variation of optimum moisture content with bentonite content

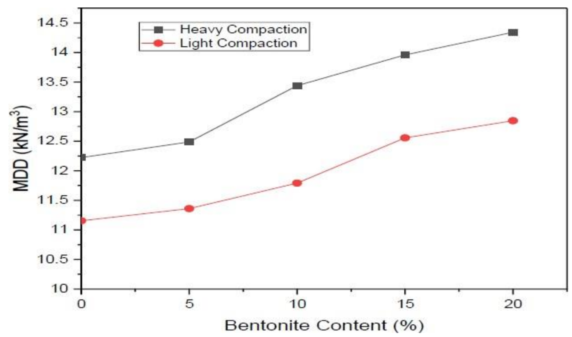


Figure 7: Variation of maximum dry density with bentonite content

Bentonite has a high-water absorption capacity, and as its content increases in the mixture, it absorbs moisture from the surrounding environment and the mixture itself. This leads to a reduction in the amount of free water available within the mixture, resulting in a lower optimum moisture content (as shown in Figure 6). As the bentonite increases, the cohesive and fine-grained nature of bentonite particles enhances the binding and interlocking of soil particles. This results in a denser arrangement of particles and reduced porosity, which causes the MDD to go up (as shown in Figure 7).

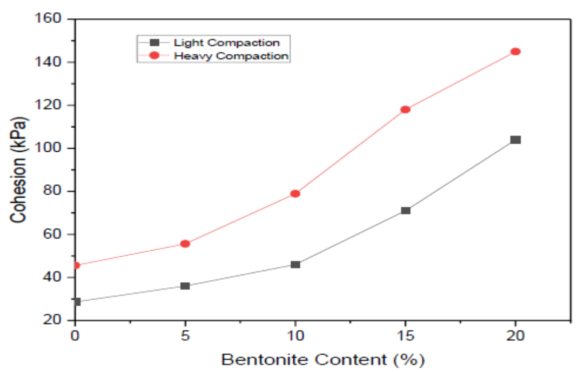


Figure 8: Variation of cohesion with bentonite content

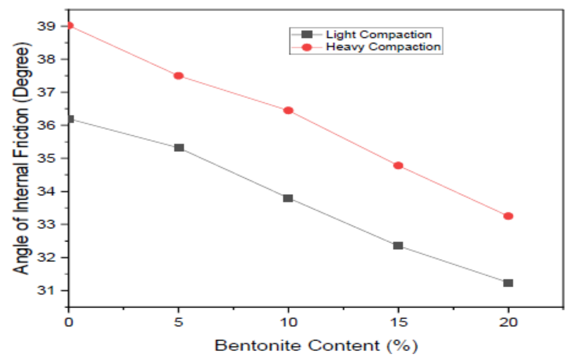
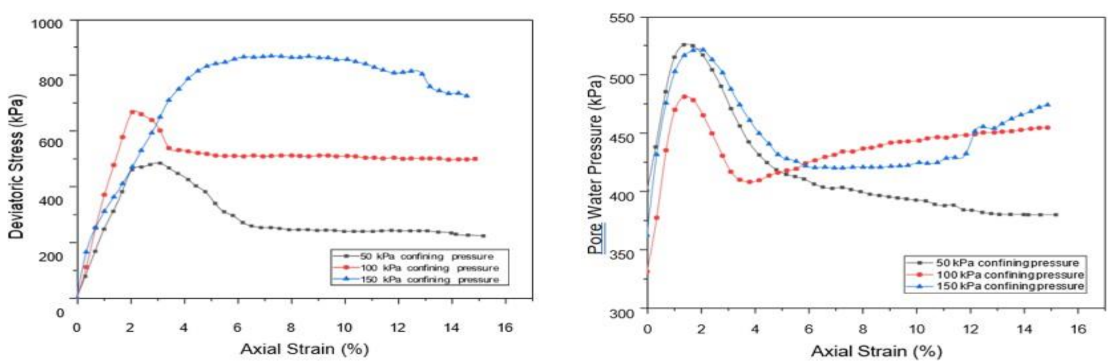


Figure 9: Variation of angle of internal friction with bentonite content

The cohesive and swelling characteristics of bentonite account for the rise in cohesiveness with increasing bentonite concentration in a pond ash-bentonite combination. The expanding bentonite particles create cohesive forces, which contribute to the increase in cohesiveness as observed in Figure 8. The addition of bentonite transforms the behavior of pond ash from more granular and friction-dependent to more cohesive and plastic. This change shifts the material's shear strength characteristics from frictional resistance to cohesion, resulting in a lower internal friction angle (as shown in Figure 9.

3.2 Consolidated Undrained Triaxial Test Results on pond ash and pond ash- bentonite mixtures at varying confining pressures

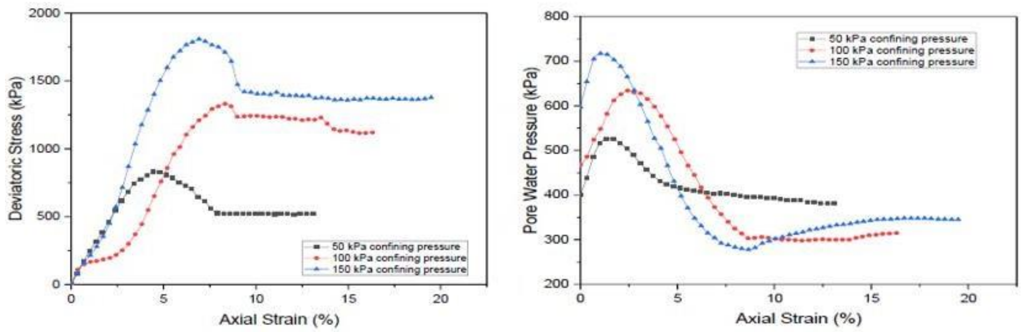
The specimens were saturated by the application of back pressure. Back pressure is applied through the bottom of the specimen. Confining pressure and back pressures were applied simultaneously. Initial effective confining pressure of 50 kPa, 100 kPa and 150 kPa were chosen. Liquefaction is characterized by a rapid reduction in deviator stress that occurs after the peak point in the stress-strain curve and continues until reaching the criteria (σ_3= 0 or σ_1- σ_3 = 0) (Sabbar et al., 2017)



(a) (b)

Figure 10: (a) Deviatoric stress vs axial strain curve and (b) pore water pressure vs axial strain curve (in right) for light compacted pond ash samples at varying confining pressures

During shearing, the sample was observed to manifest contractive behaviour at all confining pressures. Peak deviator stress varies from 486 to 868 kPa with axial strain ranging from 3.09 to 7.25 % across the measured range of confining pressure (50, 100 and 150 kPa). Additionally, it has been seen that as confining pressure goes up, the amount of contracting and pore water pressure goes up.



(a) (b)

Figure 11: (a) Deviatoric stress vs axial strain curve and (b) pore water pressure vs axial strain curve for heavy compacted pond ash samples at varying confining pressures

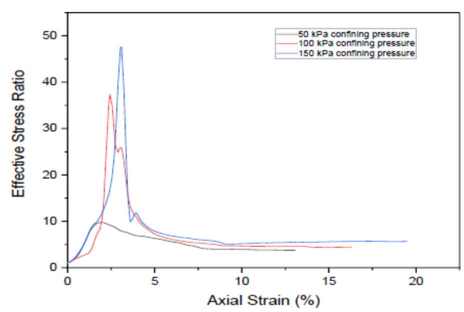


Figure 12: Effective stress ratio vs axial strain for heavy compacted pond ash samples

Peak deviatoric stress varies between 760 kPa and 1760 kPa, with axial strain ranging from 4.8% to 7%, for confining pressures of 50, 100, and 150 kPa (as observed in Figure 11). Due to the incapacity of water to rapidly dissipate, excess pore pressure begins to build up as the soil undergoes shearing. The accumulation of excessive pore water pressure is caused by the compaction and rearrangement of soil particles, which forces water from the void spaces into the pore spaces. As shearing proceeds, soil particles progressively reorient and compact, thereby reducing void spaces. This compaction reduces the soil sample's volume and, as a result, the available pore space. Consequently, the excess pore pressure begins to decrease, eventually reaching a maximum and transitioning to a constant state. As the effective stress ratio increases with increasing confining pressure (as shown in Figure 12), so does the static liquefaction resistance. For all confining pressures, the undrained brittleness index value is extremely low. Thus, a sample of densely compacted pond ash is less susceptible to static liquefaction at 50 kPa, 100 kPa, and 150 kPa effective confining pressure.

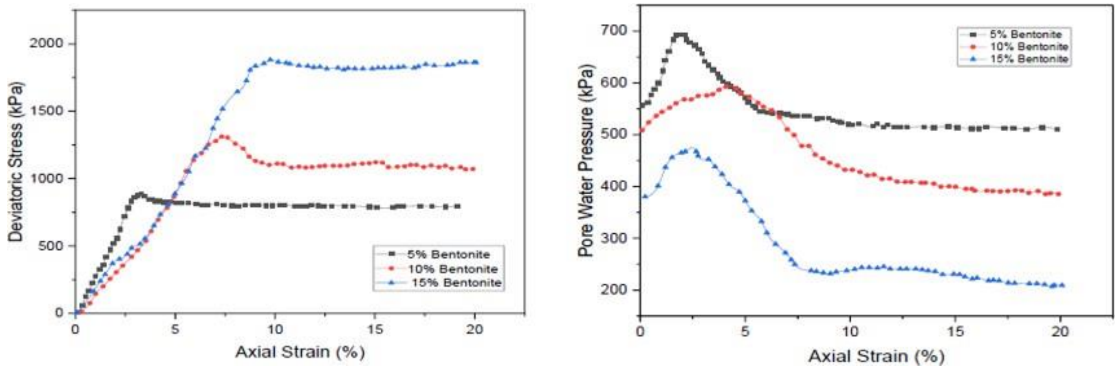


Figure 13: Variation of deviatoric stress vs axial strain (in left) and pore water pressure vs axial strain (in right) at different bentonite contents at 50 kPa confining pressure

It is observed that deviatoric stress increases with increase in bentonite content (as shown in Figure 13). Resistance to static liquefaction also increases with increase in bentonite content. After a threshold amount of strain, the pore water pressure dissipation rises with rising bentonite content, but the pore water pressure increment declines. Bentonite has a high capacity for cation exchange and a swelling effect due to its propensity to absorb water. Static liquefaction is less likely to occur if there is better drainage and dissipation of excess pore pressure during undrained loading situations, as enabled by this feature.

4. Conclusions

Feasibility studies of static liquefaction susceptibility of compacted pond ash and pond ash-bentonite mixture was investigated in this research work. Experiments were conducted to investigate the compaction characteristics and shear strength characteristics of pond ash-bentonite mixtures for the samples prepared at MDD and OMC obtained from two different compaction energies. The effect of bentonite content on static liquefaction and strength properties are investigated and the following conclusions were drawn:

- Effective stress ratio (considered range 10-48) increases with increase in initial effective confining pressure (considered range 50-150 kPa) which increases the static liquefaction resistance.
- Heavy compacted pond ash samples are not susceptible to static liquefaction but at low confining pressure (50 kPa), light compacted pond ash is susceptible to limited static liquefaction.
- Bentonite content up to 15% at the rate of 5%, increases the shear strength and strain hardening behavior of stress strain curve, implies that bentonite content increases the static liquefaction resistance.

So, it may be inferred that compacted pond ash and bentonite mixture can sustain static liquefaction.

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