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Suitability of Bentonite Treatment for Liquefaction Mitigation of Pond Ash for Ash Dyke Construction

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ABSTRACT

Combustion of coal in thermal power plants results in the generation of large quantities of ash. The finer ash (< 45 microns) is utilized by cement industries. The remaining portion along with the bottom ash is transported to the ash pond (disposal site) in the form of slurry. This disposed pond ash being a waste material needs to be utilized in raising dykes around the ash pond. However, pond ash being highly prone to liquefaction may cause catastrophic failures if used without treatment. The present study investigates the efficiency of commercially available bentonite in the mitigation of the liquefaction issues of compacted pond ash for ash dyke construction. Bentonite was used in small dosages (0%, 2.5%, 5%, 7.5%, and 10%) to treat the pond ash. Strain-controlled cyclic simple shear (CSS) tests were performed to study the effect of bentonite treatment on liquefaction behavior and dynamic properties of compacted pond ash. The hysteresis response of bentonite-treated pond ash showed higher cyclic strength than the untreated pond ash. The untreated pond ash specimens showed cyclic liquefaction in only 12 loading cycles. However, the bentonite-treated specimens showed a delayed pore pressure evolution and higher liquefaction resistance. The average shear modulus increased and the cyclic degradation parameter decreased linearly with an increase in the percentage of bentonite. Considering the liquefaction, cyclic instability, and dynamic characteristics; it was concluded that the addition of bentonite in small percentages (between 5% to 10%) could provide significant liquefaction resistance and high stiffness to the compacted pond ash under cyclic loading conditions.

Keywords: Ash dyke, Liquefaction mitigation, Pond ash, Bentonite treatment, Cyclic simple shear

1 INTRODUCTION

Many countries largely depend on coal-fired thermal power plants to fulfill their electricity requirements. Combustion of coal in these thermal power plants results in the generation of huge quantities of ash (a waste material), which requires careful utilization or disposal. The finer portion of the generated coal ash (< 45 microns particle size) is utilized by cement industries. The remaining portion along with the bottom ash is mixed with sufficient amounts of water to prepare a slurry-like consistency. This prepared slurry is then transported in pipes to a disposal site known as “Ash Pond” located in the vicinity of the thermal power plant. The ash pond is surrounded by a ring embankment known as “Ash Dyke”. The main function of the ash dyke is to safely store the disposed coal ash. The height of the ash dyke is raised by making another dyke over the previously existing dyke to increase the capacity of the storage facility (Choudhary et al., 2009; Mohanty & Patra, 2016; Pant et al., 2019). Environmental protection agencies (EPA) of many countries are nowadays emphasizing the maximum utilization of the coal ash available in these disposal facilities, which is also termed as “Pond Ash”. However, pond ash, being a highly liquefiable material endangers the structural integrity of the ash dyke especially in earthquake-prone areas, if used without proper treatment (Dey & Gandhi, 2008; Jakka et al., 2010; Jakka et al., 2011; Mohanty & Patra, 2016). Further, pond ash, being a lightweight and cohesionless material is subjected to erosion and requires some added cohesiveness to remain stable during heavy winds or rainfall (Singh & Sharan, 2014; Bachus et al., 2019). Therefore, it is a common practice to use the disposed pond ash with some locally available cohesive soil to raise the dykes around the ash pond. However, the locally available soil may either enhance or mitigate the liquefaction issue of pond ash based on its characteristics. Additionally, this practice of using local soil with pond ash is subjected to the availability of good cohesive soil in the vicinity of the ash dyke construction site. In many situations, it may happen that good cohesive soil is not available in the nearby area, and transportation of good cohesive material from a large distance becomes a costly solution. Hence, there is a need to explore a generalized and cost-effective solution to this problem, so that, pond ash can be utilized in bulk amounts to construct ash dykes without the danger of liquefaction and cyclic instability.

The present study investigates the efficiency of commercially available bentonite in the mitigation of the liquefaction issues of compacted pond ash for ash dyke construction. Bentonite was used in small quantities (0%, 2.5%, 5%, 7.5%, and 10%) to treat the pond ash collected from the disposal site of the Gandhinagar thermal power plant. A comprehensive study of the effect of bentonite treatment on liquefaction behavior and dynamic properties of compacted pond ash specimens was accomplished by performing a series of strain-controlled cyclic simple shear (CSS) tests.

2 MATERIAL PROPERTIES AND EXPERIMENTAL PROGRAM

The pond ash was collected from the disposal site of Gandhinagar Thermal Power Plant, Gujarat, India. Pond ash had a very low specific gravity of 2.24 due to the presence of Cenospheres (hollow particles). The grain size distribution (GSD) curve of pond ash is shown in Figure 1. The geotechnical properties of the Pond ash are reported in Table 1. Commercially available Bentonite was used to treat the pond ash in dosages of 0%, 2.5%, 5%, 7.5%, and 10%. Table 2 reports the effect of bentonite addition on the compaction parameters of pond ash. The sample IDs given in Table 2 have been used throughout this study. The oven-dried bentonite and pond ash was first dry mixed followed by mixing the required amount of water as per the 95% of MDD and OMC of the respective bentonite content. The specimens were prepared in three layers in an aluminum ring of 70 mm diameter and 20 mm height using the moist tamping technique. After preparation, the specimens were extracted from the ring, shrink-wrapped, and kept for moisture equilibrium inside the desiccator for 24 hours. These specimens were further used to conduct a series of consolidated undrained, strain-controlled cyclic simple shear (CSS) tests as per ASTM D8296-19 at a frequency of 1 Hz, 0.5% shear strain amplitude, and 500 loading cycles. The input sinusoidal loading for CSS tests is shown in Figure 2. The saturation of the specimen was achieved by flushing 150 ml (approximately twice the specimen's volume) of water from the bottom of the specimen under a hydrostatic head of 1 m and a seating pressure of 12 kPa. The consolidation was done by applying a vertical stress of 100 kPa at a rate of 5 kPa per minute under K_0 loading conditions.

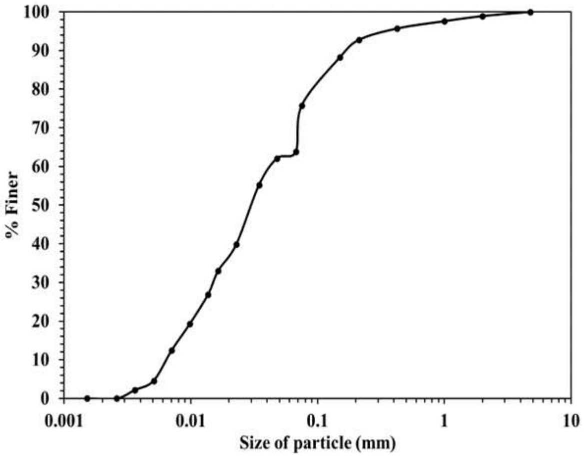

Figure 1. *Grain size distribution curve of the pond ash*

Table 1. *Geotechnical properties of the pond ash*

Properties	Values
Specific gravity (GS)	2.24
Liquid limit (LL)	32.5 %
Plastic limit (PL)	Non-plastic
Gravel (> 4.75 mm)	0.0 %
Sand (4.75-0.075 mm)	24.2 %

Silt (0.075-0.002 mm)	75.8 %
Clay (< 0.002 mm)	0.0 %

Table 2. *Effect of bentonite on compaction parameters of pond ash*

Sample ID	Bentonite content (%)	MDD (g/cc)	OMC (%)
B0	0.0	1.37	21.2
B2.5	2.5	1.40	21.0
B5	5.0	1.42	20.4
B7.5	7.5	1.44	20.5
B10	10.0	1.46	20.6

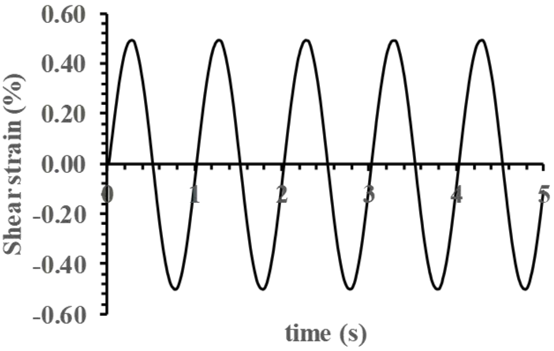

Figure 2. *Input loading for strain-controlled cyclic simple shear tests*

3 RESULTS AND DISCUSSION

3.1 Effect of bentonite treatment on hysteresis response and liquefaction resistance of compacted pond ash

Figure 3 shows the hysteresis loops of the first 5 cycles for specimens treated with different bentonite content. The area of the hysteresis loops rapidly decreased in the initial loading cycles and became almost stable afterward. The cyclic shear stress was found to be increased due to the addition of bentonite. The untreated pond ash specimen showed a maximum cyclic shear resistance of around 15 kPa which increased up to 26 kPa with the addition of 10% bentonite. The specimens treated with 7.5% and 10% bentonite content showed almost similar shear resistance behavior during cyclic loading.

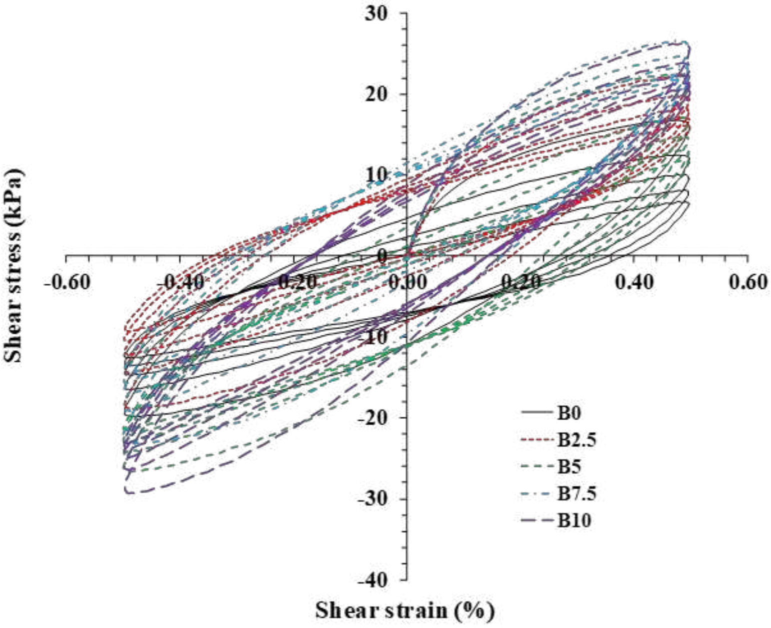

Figure 3. *Effect of bentonite treatment on hysteresis response of pond ash*

Figure 4 depicts the effect of bentonite treatment on excess pore water pressure evolution during cyclic loading in compacted pond ash specimens. The pore pressure was measured using the active height control method. In this method, the vertical stress was adjusted to keep the specimen height constant during the cyclic shearing. The reduction in the vertical stress to maintain a constant height of the specimen was assumed to be the equivalent pore water pressure generated within the specimen. Pore pressure was found to be increased with each loading cycle and reached an almost constant value after some number of cycles. Untreated pond ash showed the highest excess pore water pressure generation reaching almost equal to the applied vertical stress (100 kPa). A lesser pore pressure generation was observed in bentonite-treated specimens as compared to the untreated specimen during cyclic loading.

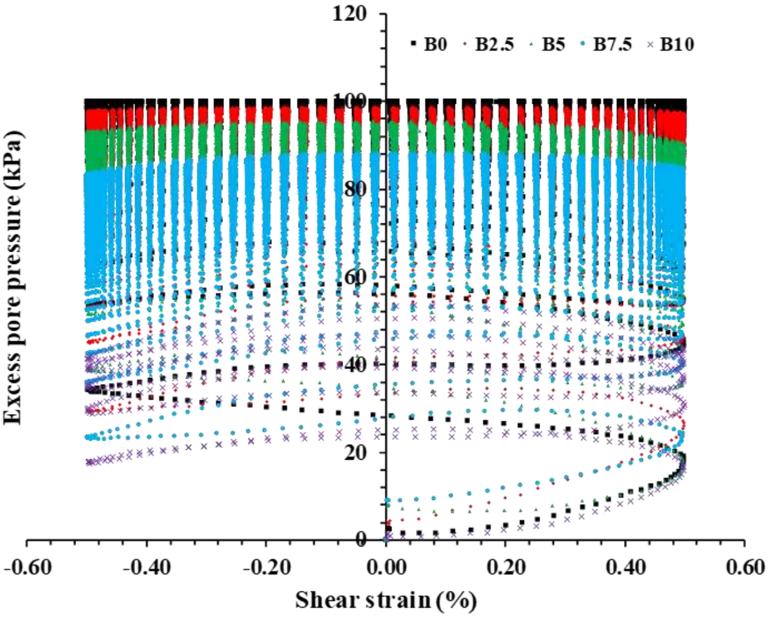

Figure 4. *Effect of bentonite treatment on excess pore water pressure evolution in pond ash*

Figure 5 shows the effect of bentonite addition on the equivalent pore pressure ratio in compacted pond ash specimens with the number of loading cycles. The equivalent pore pressure ratio (r_u) was calculated as the ratio of excess pore water pressure generated within the specimen during the cyclic loading and applied vertical stress (100 kPa). The pore pressure ratio increased very rapidly during the initial loading cycles followed by a gradual increase, and finally became stable. The 'r_u' values equal to 0.9 and 0.85

were considered as the criterion for the onset of cyclic liquefaction and cyclic instability, respectively (Hazirbaba and Rathje, 2009; Thakur et al., 2021).

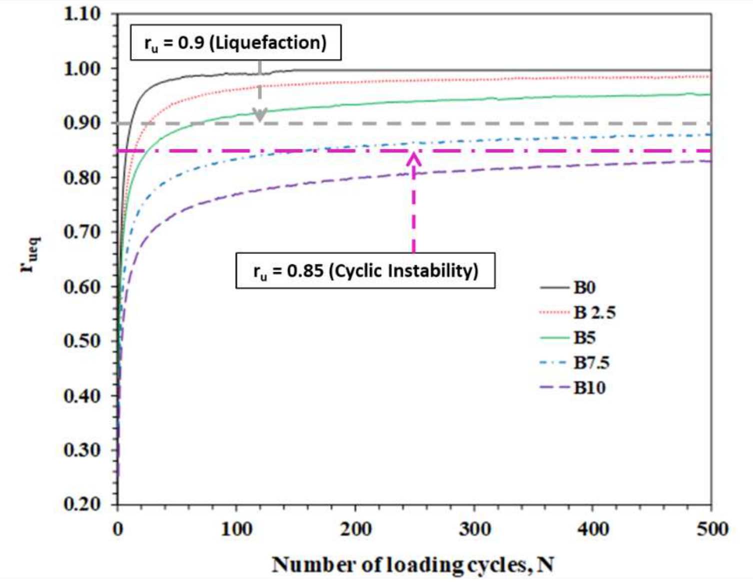

Figure 5. *Effect of bentonite treatment on pore pressure ratio in pond ash under cyclic loading*

Table 3 reports the maximum r_u values achieved and the number of cycles required to liquefy (N_L) for all the specimens. The B0, B2.5, and B5 specimens reached a r_u value of more than 0.9 causing liquefaction. However, the number of cycles required for liquefaction to occur was found to be different in these specimens. B0 and B2.5 specimens showed liquefaction in only 12 and 25 loading cycles, respectively, whereas, the B5 specimen showed a delayed liquefaction response in 63 loading cycles. B7.5 and B10 specimens showed very high resistance against liquefaction and could not liquefy in 500 loading cycles. However, the B7.5 specimen crossed a r_u value of 0.85, showing cyclic instability.

Table 3. *Effect of bentonite treatment on dynamic properties of pond ash under cyclic loading*

Sample ID	Bentonite content (%)	r_u	G_{max} (kPa)	$G^{\#}_{avg}$ (kPa)	t	D_0 (%)	$D^{\#}_{avg}$ (%)	Number of cycles to liquefy (N_L)
B0	0	1.00	3561	2573	0.4946	36	36	12
B2.5	2.5	0.99	4033	3127	0.3867	35	34	25
B5	5	0.95	4751	3877	0.2372	35	33	63
B7.5	7.5	0.88	4779	4121	0.1875	35	33	-
B10	10	0.83	5495	4807	0.1494	33	32	-

Average is taken for the first five cycles

3.2 Effect of bentonite treatment on dynamic properties of compacted pond ash

Figure 6 shows the effect of bentonite addition on the shear modulus of pond ash with the increase in the number of loading cycles. Shear modulus was found to be decreased rapidly in initial loading cycles, which reduced gradually further. The B0 specimen showed a maximum shear modulus of 3561 kPa, which showed a 54% increase with the addition of 10% bentonite (Table 3). The average shear modulus was also calculated for the first five loading cycles to incorporate the shear modulus reduction behavior of pond ash. The average shear modulus of pond ash was found to be increased continuously with an increase in the bentonite content. It was found that the avg. shear modulus was 2573 kPa for B0 specimens which increased up to 4807 kPa due to the addition of 10% bentonite following a linear trend (see Figure 7a).

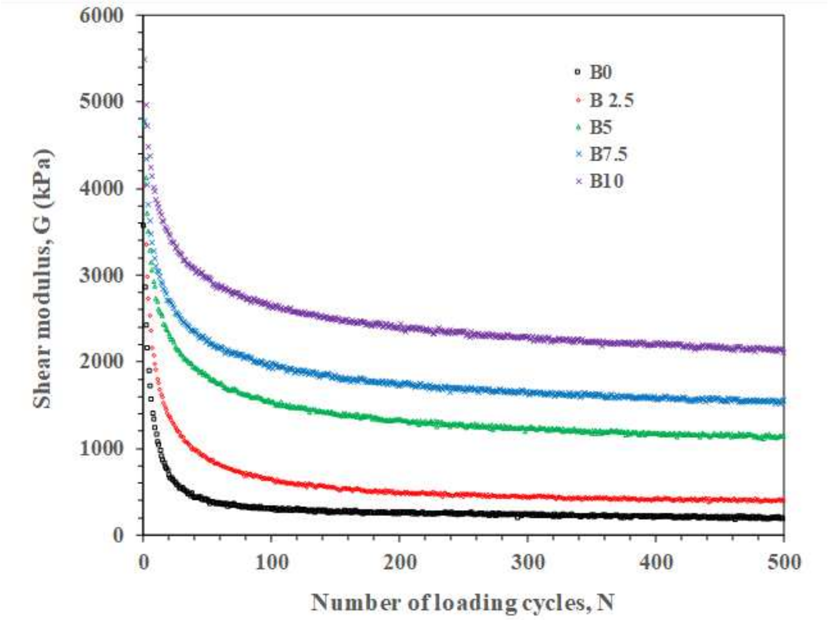

Figure 6. *Effect of bentonite treatment on shear modulus of pond ash under cyclic loading conditions*

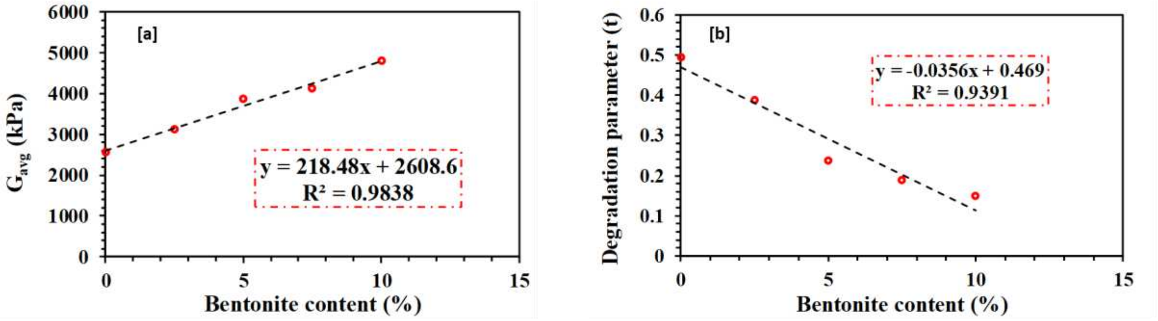

Figure 7. *Effect of bentonite treatment on (a) average shear modulus and (b) degradation parameter of compacted pond ash*

Figure 8 illustrates the effect of bentonite treatment on the cyclic degradation behavior of compacted pond ash. The cyclic degradation index (δ) at the Nth loading cycle was calculated as the ratio of shear modulus at the end of that loading cycle (G_N) to the initial maximum shear modulus (G_0). The higher value of the cyclic degradation index represents better resistance against the modulus degradation with the cyclic loading. The bentonite addition was found to increase the resistance of pond ash against the modulus degradation with the B10 specimen showing maximum resistance. The rate of degradation of the shear modulus with an increase in cyclic loading cycles was also calculated as the degradation parameter (t). The degradation parameter was found by plotting the cyclic degradation index and the number of loading cycles on a log-log scale (see Figure 9). The slope of this plot gives the value of the cyclic degradation parameter.

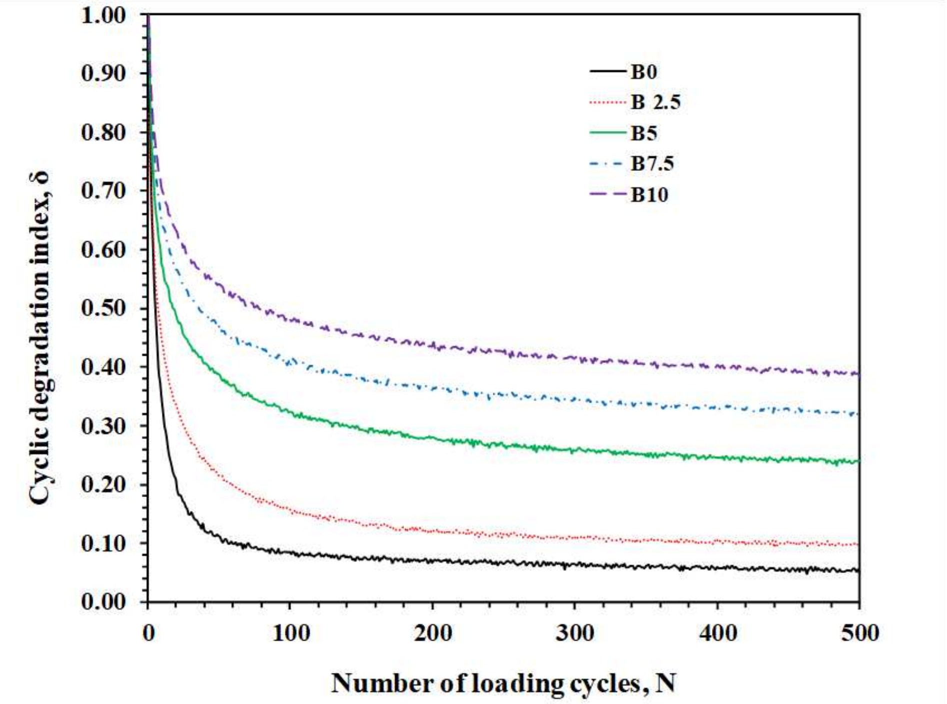

Figure 8. *Effect of bentonite treatment on cyclic degradation index (δ) of compacted pond ash under cyclic loading conditions*

The cyclic degradation parameter for the B0 specimen was found to be the highest showing its very high proneness to the reduction of shear modulus on cyclic loading as compared to the specimens treated with bentonite (see Table 3). The value of the cyclic degradation parameter (t) was 0.4946 for B0 specimens which linearly reduced to 0.1494 with the addition of 10% bentonite (see Figure 7b). The increase in average shear modulus and decrease in cyclic degradation parameter followed a linear trend with the increase in the bentonite content as shown in Figure 7. The best-fit equations for these trends with more than 0.9 R^2 values are also reported in Figure 7, which can be used for finding avg G and degradation parameters for any bentonite content between 0% and 10%. Figure 10 shows the variation of damping ratio in specimens treated with different contents of bentonite. No significant variation in the damping characteristics was found with an increase in the number of loading cycles in any specimen. However, bentonite-treated specimens showed slightly lower damping ratios. The value of the damping ratio in the first cycle and the average damping ratio for the first five loading cycles are reported in Table 3. The damping ratio decreased only by 4% with the addition of 10% bentonite to the untreated pond ash.

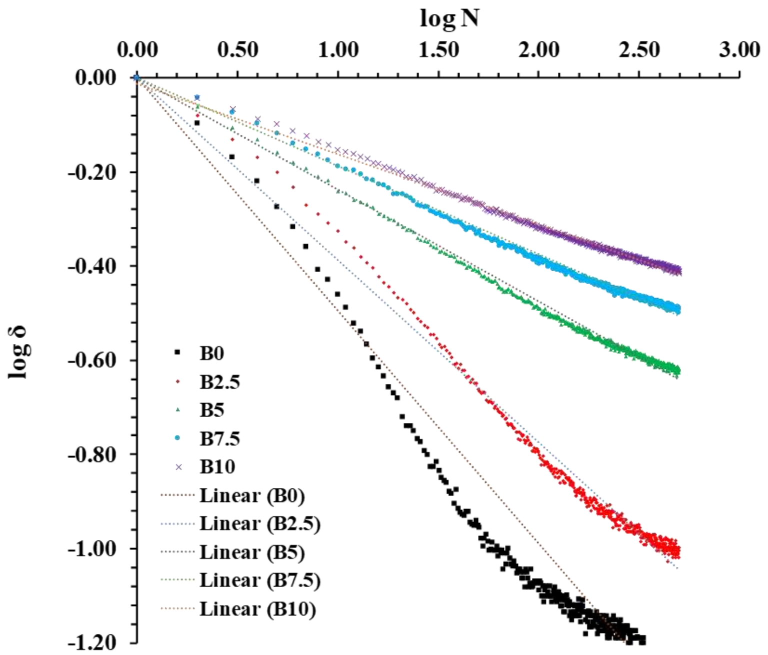

Figure 9. *Effect of bentonite on cyclic degradation parameter of compacted pond ash under cyclic loading conditions*

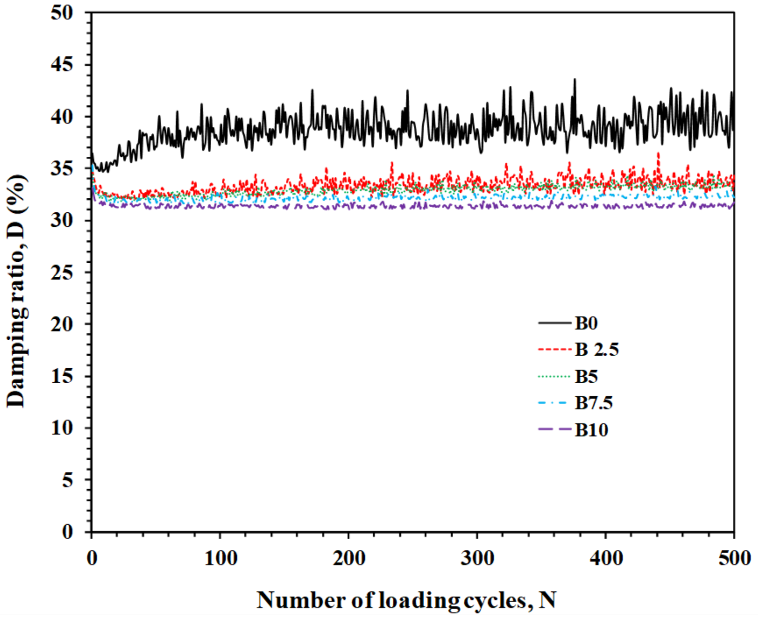

Figure 10. *Effect of bentonite on damping characteristics of compacted pond ash under cyclic loading*

Table 4 reports the values of shear modulus (G) and damping ratio (D) at a selected number of loading cycles for both untreated and bentonite-treated specimens. The shear modulus of untreated pond ash decreased from 3561 kPa to 237 kPa (almost 93% reduction) on the application of 500 loading cycles, whereas for the specimen treated with 10% bentonite, it reduced from 5495 kPa to 2109 kPa (only 61% reduction). This showed the higher resistance of bentonite treated specimen towards the cyclic degradation of shear modulus. The added bentonite might have filled the pores in the microstructure of compacted pond ash, which resulted in a denser packing (see MDD in Table 2). A similar pore-filling mechanism in the fly ash-bentonite mixture was also suggested by Kantesaria et al. (2021). Additionally, bentonite particles imparted cohesion between the non-plastic particles of pond ash. Both of these phenomena were responsible for the increased resistance of bentonite-treated specimens toward cyclic liquefaction and lower shear modulus degradation. Many researchers in the past have also reported such behavior due to the addition of plastic fines to the granular soils (Polito, 1999, Park & Kim, 2013). However, bentonite treatment was effective only for more than 5% content. The lower bentonite content might have resulted in lesser packing and weak cohesive bond formation, which was not enough to control the liquefaction of pond ash.

Table 4. *Effect of bentonite treatment on shear modulus and damping characteristics of pond ash*

Sample ID	B0		B2.5		B5		B7.5		B10	
Number of loading cycles	G (kPa)	D (%)	G (kPa)	D (%)	G (kPa)	D (%)	G (kPa)	D (%)	G (kPa)	D (%)
1	3561	36	4033	35	4751	35	4779	35	5495	33
2	2851	36	3350	34	4118	33	4336	34	4968	32
3	2413	35	2985	34	3718	33	4040	33	4722	32
4	2147	35	2729	33	3506	32	3817	32	4479	32
5	1891	35	2537	33	3292	33	3634	32	4375	32
10	1233	35	1907	32	2734	33	3105	32	3868	32
50	744	35	1375	33	1847	32	2234	32	2973	31
100	530	37	878	33	1539	32	1982	32	2643	31
200	433	38	651	32	1338	33	1728	32	2388	31
300	399	37	485	34	1229	33	1662	32	2277	31
400	303	37	433	34	1171	33	1574	33	2213	31
500	237	41	413	34	1145	33	1555	32	2109	32

Figure 11 shows the effective stress paths (ESP) followed by specimens treated with different content of bentonite during the cyclic simple shear tests. The ESP was shifted towards the right side with the addition of bentonite to the pond ash. ESP of B0, B2.5, and B5 specimens reached near the zero-shear stress while other specimens showed a higher liquefaction resistance which is evident from bigger size loops in the ESP plot.

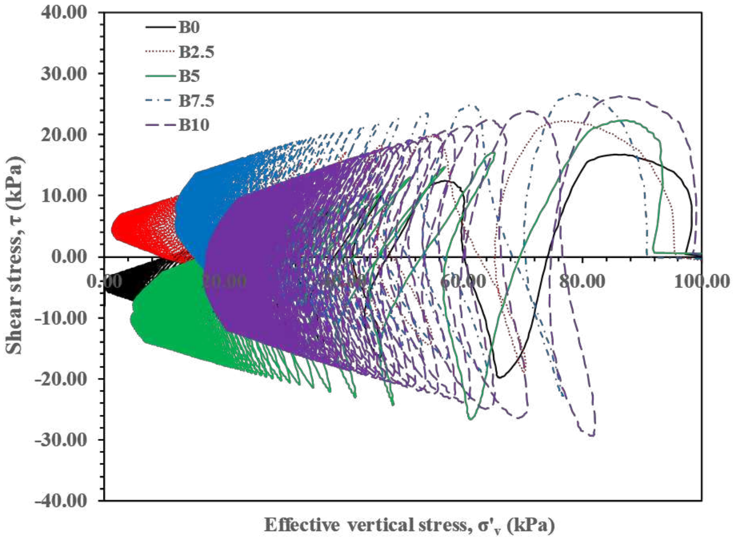

Figure 11. *Effective stress path followed by specimens treated with different contents of bentonite under cyclic loading conditions*

4 CONCLUSIONS

The present research work investigated the efficiency of commercially available bentonite on the liquefaction and dynamic properties of compacted pond ash specimens under cyclic loading conditions. Strain-controlled cyclic simple shear tests were performed to simulate the earthquake loading conditions. Bentonite was added in small percentages of 0%, 2.5%, 5%, 7.5%, and 10%. Specimens treated with 0%, 2.5%, and 5% bentonite content liquified on the application of cyclic loading. However, the number of cycles required for liquefaction increased due to bentonite addition. Specimens treated with more than 5% bentonite did not show liquefaction up to 500 cycles of loading. However, the specimen treated with 7.5% bentonite showed cyclic instability. Therefore, it can be concluded that bentonite content of more than 7.5% would be suitable for developing resistance against cyclic liquefaction as well as cyclic instability in compacted pond ash. The dynamic properties of bentonite-treated pond ash specimens were also studied. The average shear modulus increased linearly with bentonite content. The damping characteristics were not significantly affected by bentonite addition. The rate of cyclic degradation of shear modulus also decreased linearly with the increase in bentonite content. Considering the liquefaction, cyclic instability, and dynamic characteristics; it can be concluded that the addition of bentonite in small percentages (between 5% to 10%) could provide significant liquefaction resistance and high stiffness to the compacted pond ash under cyclic loading conditions which makes it a suitable construction material for ash dykes, especially in earthquake-prone regions. However, a detailed slope stability analysis and design for the ash dyke are necessary before its use.

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