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Effect of Guar Gum Biopolymer on Shear Strength and Liquefaction Response of Coal Ash

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Abstract. Improvement in geotechnical properties of coal ash is required for its better utilization in large infrastructure projects. Lime and cement are the most commonly used material to stabilize coal ash for railway and highway embankment construction. However, these admixtures have negative impact on the environment. This experimental study explores the viability of commercially available guar gum biopolymer, as an eco-friendly and cost-effective additive for coal ash stabilization. Guar gum biopolymer is chosen because of its pH stability, cold water dissolving characteristics and formation of hydrogen bonds along with being inexpensive. Different concentrations (1% - 5%) of guar gum biopolymer was used to treat the coal ash collected from Gandhinagar thermal power plant. A series of shear strength tests were conducted on coal ash before and after its treatment with guar gum biopolymer at different concentrations and curing time/conditions. Scanning electron microscopy (SEM) images of guar gum treated coal ash specimens were also obtained to evaluate the morphological characteristics of stabilized coal ash. Stress-strain and pore pressure response of guar gum treated coal ash were studied by conducting CU (Consolidated Undrained) triaxial tests. Effect of gaur gum on Liquefaction response of coal ash was also evaluated by conducting cyclic triaxial tests with pore pressure evolution.

Keywords: Coal ash, Guar gum, Shear strength, Pore pressure, Liquefaction.

1 Introduction

Coal ash is a major waste product from the thermal power plant generated by the burning of coal. It is considered as an alternative material to natural soils for the construction of road embankments. Coal ash is highly prone to liquefaction (Boominathan and Hari, 2002; Dey and Gandhi, 2008; Mohanty & Patra, 2014; Zand et al., 2009). It also causes air erosion in dry weather due to its low specific gravity. Various additives (lime and cement) have been used earlier for the stabilization of coal ash in order to improve its shear strength, durability and erosion resistance (Usmen and Bowders, 1990; Ghosh and Subbarao, 2007; Sivapullaiah and Moghal, 2011; Chore and Vaidya, 2015; and

Kumar & Sharma, 2018). However, these additives have limitations as the production of lime and cement contributes to greenhouse gas emissions (Hataf et al., 2018). Globally, 5% of the annual carbon dioxide source is due to the production of cement, which also produces nitrogen oxides and air pollutants (Bremner, 2001). Lime and cement also make the coal ash very brittle after mixing it for stabilization, which leads to the large improvement in shear strength of treated coal ash, but creates other damages due to its brittle nature.

Biopolymers are environment friendly, carbon-neutral and sustainable materials produced by living organisms. They are usually obtained from plants and bacteria. In India, Guar gum biopolymer is cheaper than other biopolymers like gellan gum and xanthan gum as it is extracted from guar beans, which has huge production in the country. Unlike other biopolymers, gaur gum can be dissolved in cold water easily (Ayeldeen et al., 2016). Previous researches have shown that biopolymers can serve as an erosion control technique for mine tailings and soils (Chang et al., 2015; and Chen et al., 2015). Biopolymers are also reported to be good additive to strengthen the soils (Chen et al., 2013; Khatami and Kelly, 2013; Chang et al., 2015; Chang et al., 2015; Smitha et al., 2016; Ayeldeen et al., 2016; Ayeldeen et al., 2017; and Dehghan et al., 2019). However, effect of gaur gum biopolymer on shear strength and liquefaction response of coal ash is yet to be explored.

The current research work evaluates the capability of gaur gum biopolymer for improving the shear strength (without making it brittle) and liquefaction response of coal ash under earthquake type loading conditions. Stress-strain and pore pressure response under monotonic and cyclic loading conditions were evaluated by performing consolidated undrained and cyclic triaxial tests. UC strength of gaur gum treated coal ash was evaluated under different curing conditions. Scanning electron microscopy (SEM) tests were conducted on guar gum treated coal ash to analyze the particle level interactions of biopolymer/additive with coal ash particles.

2 Material Properties

The Physical properties of Gandhinagar coal ash are listed in Table 1. The grain size distribution tests reported that coal ash particles varied from 425 μm to 2 μm. The specific gravity of coal ash was determined to be 2.27. The maximum dry density (MDD) and optimum moisture content (OMC) of coal ash were obtained to be 1.44 g/cm^3 and 19.69%, respectively. The liquid limit of coal ash was found to be 29% using the cone penetrometer test. The XRD results showed that coal ash particles consisted of 1.5% of CaO indicating lower capability of pozzolanic reaction. Guar gum biopolymer is a naturally occurring polysaccharide consisting of galactose of sugar and mannose. In the present study, guar gum (GG-3.5) was procured from Oriental Gums and Biopolymers, India. Gaur gum is inexpensive as compared to other biopolymers in India. Also, it has some unique characteristics such as pH stability etc. The specifications of guar gum are listed in Table 2.

Table 1. Physical properties of Gandhinagar coal ash

Properties	Values
Visual appearance	Grey
Specific gravity	2.27
Particle size: 1 mm - 425 μm	0%
Particle size: 425 μm - 75 μm	10%
Particle size: 75 μm - 2 μm	90%
Liquid limit	29%
Plastic limit	Non-Plastic
Mullite	50%
Quartz	20%
Alumina	10%
Calcium oxide	1.5%
Other minerals	18.5%
Maximum dry density (MDD)	1.44 g/cc
Optimum moisture content (OMC)	19.69%

Table 2. Specifications of guar gum biopolymer

Appearance	Free flowing yellowish powder
Ionic nature	Non-ionic
Chemical nature	Galactomannose Derivatives
Solubility	Cold water soluble
Moisture	12% max
pH	9 to 10
Viscosity	22000 cps at 25^0C ± 3000 cps

3 Experimental Program and Specimen Preparation

Unconfined compression (UC), Consolidated undrained (CU) and Cyclic triaxial tests were conducted on guar gum treated coal ash. Different percentages (0%, 1%, 2%, 3%, 4% and 5%) of guar gum were used to treat the coal ash. The higher viscosity of guar gum above 5% exhibited large reduction in workability of treated coal ash, hence the use of guar gum biopolymer was kept limited to 5% only. All the coal ash specimens were prepared at 95% MDD and OMC using moist tamping technique. The guar gum concentration was defined as the percentage dry weight of guar gum to that of the required quantity of water for the specimen. Three different types of curing techniques were adopted: (a) Incubator curing conditions (C1), (b) In-laboratory curing conditions

(C2), and (c) Out laboratory curing conditions (C3). Table 3 presents the temperature and humidity under each curing conditions.

Table 3. Details of curing conditions for guar gum biopolymer treated coal ash

Curing series	Curing series description	Curing conditions	
		Curing temperature (^{0}C)	Curing humidity (%)
C1	Incubator curing	20 ± 1	60 ± 5
C2	In-laboratory curing	25 ± 2	30 – 50
C3	Out-laboratory curing	18 - 42	20 - 80

Note: C2 and C3 conditions refer to room temperature and under sunlight conditions, respectively.

Test series T1, T2 and T3 were conducted on guar gum treated coal ash to evaluate the effect of curing conditions and curing time on the UC strength of coal ash (Table 4). T4 test series was performed to see the effect of mixing temperature of guar gum solution on UC strength of coal ash. The specimens were sheared at 1.25 %/min. Another test series S1 was conducted on untreated and treated coal ash under CU triaxial conditions to evaluate the shear response of coal ash under saturated conditions (Table 5). CU triaxial tests were performed under an effective confining pressure of 100 kPa and shearing rate of 0.05%/min The saturation of specimen was completed in three stages: CO2 flushing, water flushing and back pressure saturation. Skempton's pore water pressure parameter B of 0.95 was achieved before the consolidation and shearing stages to insure the complete saturation of the specimen. In addition to this, S2 series was also conducted to evaluate the dynamic properties of guar gum treated coal ash under cyclic triaxial testing conditions (0.5% amplitude and 0.1 Hz frequency).

Table 4. Experimental program for unconfined compressive strength of guar gum biopolymer treated coal ash

Test series	Test performed	Curing conditions	Biopolymer mixing conditions	Biopolymer content (%)	Curing time (Weeks)
			Temperature (^{0}C)		
T1	UC	C1	R	0, 1, 2, 3, 4, 5	1, 2, 3, 4, 5
T2	UC	C2	R	0, 1, 3, 5	1, 2, 4
T3	UC	C3	R	0, 1, 3, 5	1, 2, 4
T4	UC	C1	25, 40, 60, 80	0, 1, 2, 3, 4, 5	1

Note: R-specimens prepared at room temperature

Table 5. Experimental program for CU triaxial and dynamic triaxial tests of guar gum biopolymer treated coal ash

Test series	Test name	Strain rate (%/min)	Effective confining pressure (kPa)	Biopolymer content (%)	Curing time (weeks)
S1	CU triaxial	0.05	100	0, 1, 2, 3, 4, 5	1
Test series	**Name of the test**	**Frequency and amplitude**	**Effective confining pressure (kPa)**	**Biopolymer content (%)**	**Curing time (weeks)**
S2	Cyclic triaxial	0.1 Hz and 0.5%	100	0, 1, 2, 5	1

**All specimens were cured at C1 conditions*

4 Results and Discussion

4.1 Shear strength of coal ash under different curing conditions

Fig. 1 shows the effect of guar gum on UC strength of coal ash under C1 curing conditions at different curing periods. Increase in the content of guar gum exhibited remarkable increase in UC strength of coal ash for all curing time periods. At 1 week curing time, UC strength increased from 149 kPa to 331 kPa for 0% to 5% guar gum, respectively. Guar gum is a neutrally charged polysaccharide (Chudzikowski, 1971) with numerous hydroxyl groups, which forms hydrogen bonds leading to the formation of aggregations inside the pore spaces of soil matrix. Increase in guar gum concentration increased the viscosity of the solution leading to the improvement in degree of cross linking inside the pore spaces of coal ash. The strength of guar gum treated coal ash showed maximum value at one week of curing and was observed to decrease at all concentrations of guar gum with increase in curing period. In this curing conditions, the prepared specimens were wrapped using plastic sheets and placed in an incubator at a constant temperature and humidity, which prevented the loss of moisture from the hydrogel. Since the specimens were not allowed to dehydrate, the strength of guar gum treated coal ash decreased slightly after one week curing time and became constant after certain weeks of curing.

Under C2 curing conditions, UC strength of guar gum treated coal ash was observed to be high at the beginning but it decreased with the increase in curing time (Table 6). The increase in UC strength of 5% guar gum was found to be 7668%, 7000%, and 4507% as compared to untreated coal ash after 1, 2 and 4 weeks of curing time, respectively. At C2 conditions, specimens were kept at room temperature and room humidity, causing the specimens to dehydrate. During dehydration, the loss of water increased the concentration of guar gum hydrogel in the pore spaces causing strengthening of coal ash. This could be the reason of higher UC strength of treated coal ash at C2 conditions as compared to C1 conditions. When the guar gum treated coal ash was placed in drying

conditions, the concentration of hydrogel increased, which could have attached to the surface of coal ash particles, and formed stiff surface coats and menisci on and between the particles. Table 6 depicts the UC strength of guar gum treated coal ash under C3 curing conditions. Untreated coal ash showed a very low strength for all curing time. As the percentage of guar gum increased, UC strength increased. After 1 week curing time, 1% guar gum content exhibited the UC strength of 384 kPa, while 5% guar gum addition showed 3527 kPa of UC strength. This could be attributed to the fact that dehydration of guar gum would cause the transformation of gel state into the glassy state. With 3% concentration of guar gum, the UC strength increased from 2081 kPa at the first week to 2679 kPa at the end of fourth week. However, untreated coal ash showed strength of 28 kPa at 1 week curing time and 40 kPa at 4 week curing time, thus improved the shear strength of guar gum treated coal ash. C3 conditions reported the maximum strength as compared to C2 and C1 conditions, suggesting that temperature and humidity plays a very important role in dehydrating the hydrogel.

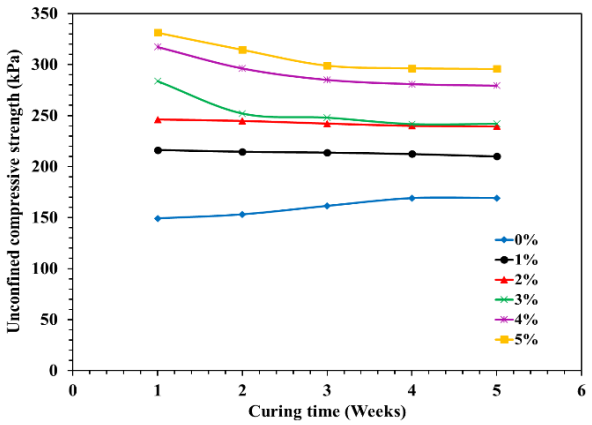

Fig. 1. UC strength of guar gum treated coal ash at different curing time under C1 curing conditions

Table 6. UC strength of guar gum treated fly ash at C2 and C3 curing conditions

Biopolymer content	UCS (kPa)					
	C2 Curing condition			**C3curing condition**		
	Curing time (weeks)			**Curing time (weeks)**		
	1	**2**	**4**	**1**	**2**	**4**
0	22	25	41	28	31	40
1	295	390	404	384	502	584
3	1420	1556	1705	2081	2580	2679
5	1709	1775	1889	3527	3706	3967

4.2 Effect of mixing temperature on UC strength response of guar gum treated coal ash

Fig. 2 represents the UC strength of guar gum treated coal ash at different mixing temperature of guar gum solution after 1 week curing time. Untreated coal ash exhibited UC strength of 149 kPa, while 1% guar gum addition without thermal treatment (at 25^0C) improved the UC strength up to 216 kPa. Thermal treatment of guar gum produced higher UC strength i.e., 230 kPa at 40^0C, 236 kPa at 60^0C and 240 kPa at 80^0C and made the specimens to become more brittle. 1% guar gum concentration was found to provide higher UC strength at higher temperature because of easy solubility of guar gum with water at low concentration. At temperature between 25-40^0C, maximum viscosity of guar gum is obtained (Mudgil et al., 2014). This is the reason why the strength of 1% guar gum concentration increased suddenly at 40^0C and then only slight variations in UC strength of specimens were observed at higher temperatures. However, at higher guar gum concentration, the UC strength was found to decrease with increase in mixing temperature. Coal ash specimens with 5% guar gum concentration, prepared at room temperature (i.e., 25^0C) exhibited compressive strength of 331 kPa. On heating the guar gum solution, UC strength of treated coal ash specimens reduced to 292 kPa and 273 kPa at 40^0C and 80^0C, respectively. The reduction in UC strength was due to the reduction in viscosity of guar gum solution at higher temperature (Gupta et al., 2009). Additionally, elevated temperatures can have degradative effect on guar gum solutions having higher concentration (Mudgil et al., 2014), which might have caused decrease in UC strength of guar gum treated coal ash specimens at higher temperatures. This study suggested that lower concentration of guar gum can be used at 25-40^0C temperature while higher concentration should be mixed at lower temperature to achieve higher UC strength of guar gum treated coal ash.

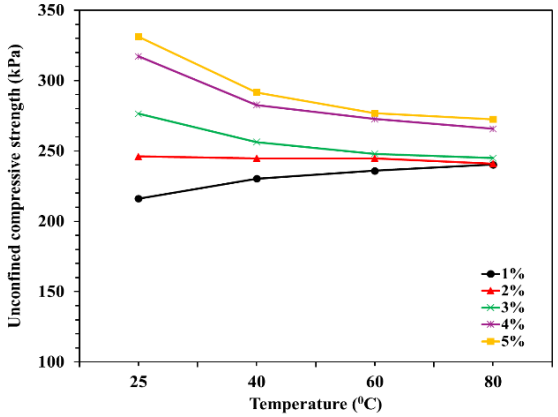

Fig. 2. Effect of mixing temperature on UC strength of guar gum treated coal ash at 1 week curing time

4.3 Microstructural analysis of guar gum treated coal ash

The scanning electron microscopic (SEM) images of guar gum treated coal ash after 1 week curing time are shown in Fig. 3. The micrographs revealed biopolymer accumulations inside the coal ash particles, which created linkages that hold the coal ash particles together. Untreated coal ash specimens exhibited a loose structure with empty

voids, whereas guar gum treated coal ash had a denser structure with voids filled with guar gum gel-coating. Guar gum formed a coating on the surface of the coal ash particle resulting into the increase in contact area, and resulted in improved strength. The interaction of coal ash particles with guar gum is clearly visible in the form of coating, connection bridges, aggregate formation and cross linking of hydrogels.

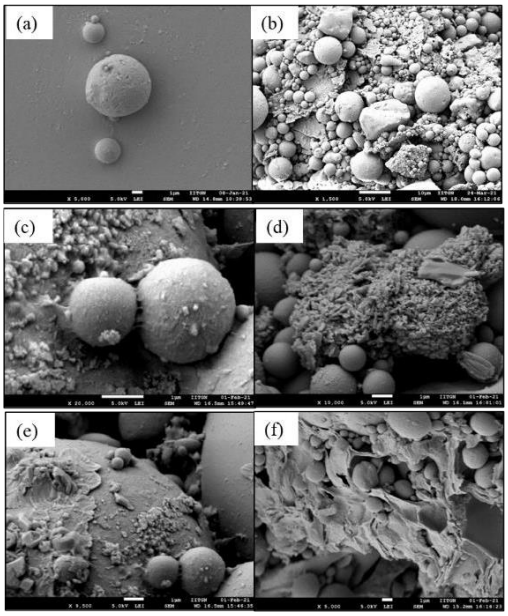

Fig. 3. SEM images of coal ash treated with guar gum: (a) Coal ash particles; (b) Guar gum hydrogel; (C) Connection bridges; (d) Aggregate formation; (e) Coating; (f) Cross- linking

4.4 Strength characteristics of guar gum treated coal ash under CU triaxial conditions

Fig. 4a and 4b illustrates the stress-strain and excess pore water pressure response of the guar gum treated coal ash, respectively. Untreated coal ash specimen exhibited the maximum peak deviatoric stress of 417 kPa and then decreased with axial strain. Significant improvement in the peak deviatoric stress was observed on guar gum addition. Peak deviatoric stress of guar gum treated coal ash increased to 600-733 kPa as compared to untreated coal ash. Highest peak deviatoric stress was observed for 5% guar gum treated coal ash specimen. Slight post peak softening response was observed for untreated coal ash, however, guar gum treated coal ash specimen exhibited no post peak softening response. Guar gum treated coal ash indicated delayed axial strain at failure (ϵ_f) compared to untreated coal ash. Higher initial stiffness was observed for guar gum treated coal ash as compared to the untreated coal ash, which indicated stiffer matrix of guar gum treated coal ash. Excess pore water pressure response displayed increased contractive response at initial axial strain levels, which became more dilative with guar gum addition at greater axial strains. At failure, the dilative response of guar gum treated coal ash increased with higher concentration of guar gum. The excess pore water

pressure at failure (u_f) decreased from -36 kPa to -134 kPa for 0% and 5% guar gum treated coal ash, respectively.

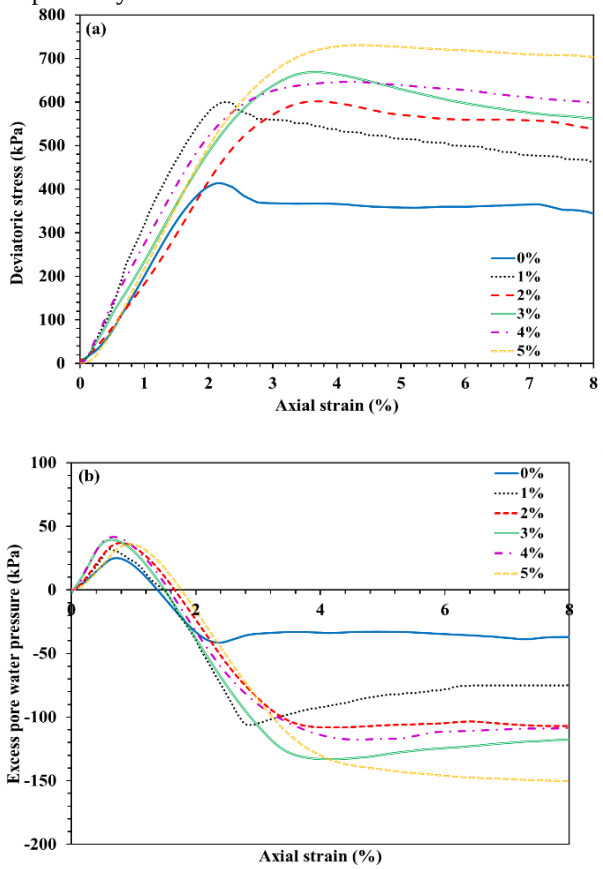

Fig. 4. Strength characteristics of guar gum treated coal ash under CU triaxial conditions: (a) Stress-strain; (b) Excess pore water pressure

4.5 Liquefaction characteristics of guar gum treated coal ash under cyclic triaxial conditions

The hysteresis response of guar gum treated coal ash is shown in Fig. 5a. For 1% and 2%, guar gum treated coal ash, the deviatoric stress was lower as compared to un-treated coal ash under both compression and extension sides. However, a sudden increment in the deviatoric stress was observed for 5% guar gum treated coal ash specimens. The tests were conducted until 100 loading cycles, but to show the clear response, the hysteresis loops are presented until 5 cycles only. The maximum deviatoric stress was observed to be 137 kPa, 113 kPa, 109 kPa and 142 kPa for guar gum content of 0%, 1%, 2% and 5% on the compression side. Continuous stress reversal from repeated compression to extension loading caused the loss in inter-particle contacts due to smooth surfaces between the coal ash particles. However, at 5% guar gum content, aggregates formation between the coal ash and guar gum led to a higher load-carrying capacity of specimen. The excess pore water pressure ratio (r_u) response of guar gum

treated coal ash specimens is shown in Fig. 5b. Liquefaction was said to occur when the excess pore water pressure ratio became equal to 1. The results indicated that r_u reached one for untreated coal ash, however, guar gum treated coal ash did not attain r_u equal to one. The value of r_u was obtained to decrease with increased guar gum concentration. This indicated that guar gum treatment was effective in controlling the liquefaction of coal ash. The results were in confirmation with the CU results, where the specimen was found to become more dilative with an increase in guar gum content. Coal ash with 1% and 2% guar gum content, achieved r_u equivalent to 0.71. Moreover, for 5% guar gum content, r_u further decreased and attained a maximum value of 0.57. The number of cycles to liquefaction was observed to be 23 for untreated coal ash, whereas no liquefaction occurred for guar gum treated coal ash.

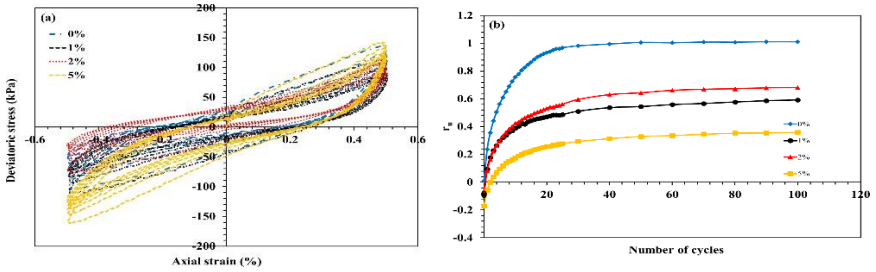

Fig. 5. Dynamic properties of guar gum treated coal ash: (a) Hysteresis response; (b) Pore water pressure ratio (r_u)

Dynamic properties (shear modulus and damping ratio) were evaluated at different number of loading cycles for guar gum treated coal ash and are mentioned in Table 7. It was observed that shear modulus decreased, while damping ratio remained almost constant with the increase in number of loading cycles. For 1% and 2% guar gum content specimen, the shear modulus decreased rapidly with an increase in the number of cycles. However, for 5% guar gum content, shear modulus degraded partially.

Table 7. Dynamic properties of guar gum treated coal ash at different number of loading cycles

Number of cycles	Biopolymer content (%)							
	0		1		2		5	
	G (MPa)	D (%)	G (MPa)	D (%)	G (MPa)	D (%)	G (MPa)	D (%)
1	23.7	34	18.0	35	18.2	30	29.4	33
2	20.0	33	14.8	32	16.1	33	27.5	31
3	18.0	32	12.5	32	14.6	33	26.2	31
4	15.8	32	10.9	32	13.7	32	25.1	31
5	13.8	33	9.4	32	12.6	32	24.0	31

10	8.3	32	5.5	31	8.9	33	21.8	30
20	3.0	32	2.4	31	5.6	31	19.3	30
40	0.7	35	1.0	31	2.8	30	17.3	29
60	0.3	44	0.5	31	1.9	31	15.8	29
80	0.2	51	0.5	31	1.4	33	15.0	29
100	0.2	57	0.3	30	1.2	33	14.4	30

4.6 Conclusion

The current study evaluated the strength and liquefaction characteristics of guar gum treated coal ash by performing UC test, CU triaxial and cyclic triaxial tests. The effect of different curing conditions and curing times were also explored. Moreover, microscopic analysis using SEM was also investigated. Guar gum treatment enhanced the UC strength of coal ash, however, there was no effect of curing of the guar gum at constant moisture content. The heating of guar gum solution at low concentration (up to 1%) improved the UC strength of guar gum treated coal ash. In contrast, the UC strength of treated specimens decreased at higher temperatures for higher guar gum concentrations (above 1%). An increase in guar gum content increased dilatancy, thus increased the peak deviatoric stress. The addition of guar gum with coal ash effectively controlled the liquefaction of coal ash.

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