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CONTROLLED LOW STRENGTH MATERIALS (CLSM) AS BEDDING LAYER — AN EXPERLMENTAL STUDY AND NUMENICAL EVALUATION

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ABSTRACT

The utilization of coal ashes to replace different natural aggregates is a standard procedure adopted nowadays for different civil engineering applications. Reutilization of these industrial waste products generated from the thermal power plants for civil engineering applications is beneficial to society and the environment in various ways. Thus, this research paper deals with the studies done to analyse the effectiveness of using pond ash for controlled low strength materials (CLSM) production. Further, stresses and strains developed on the buried pipelines where CLSM was used instead of the standard aggregate-based bedding layer were also analysed. A comparative study of the stresses and strains developed on the buried pipelines was evaluated using PLAXIS 2D software. The results from the studies showed that the plastic and in-service properties obtained for the pond ash-based CLSM mixtures are equivalent to regular aggregates used in bedding layer applications. Further, the analysis of stresses and strains developed on the buried pipelines using the Plaxis 2D numerical tool showed that the stresses and strains developed on CLSM as bedding layer-based pipelines performed better than the normal bedding layers. Thus, pond ash-based CLSM mixtures can be used as an alternative to normal aggregates as the stresses and strains developed were found to be lesser than that of normal aggregate-based bedding layers.

Key words: Bedding layer, CLSM, flowable fills, pipelines, PLAXIS, strains, stresses.

1. BACKGROUND AND INTRODUCTION

Natural and recycled aggregates such as sand, crushed concrete, crushed rock are regularly used as a bedding layer for buried pipelines. Properties such as compaction characteristics, permeability and compressibility of the aggregates have to be studied to check whether these properties meet the standard specifications before utilising the aggregates for bedding layer applications (Ratnayaka *et al.* 2009). The compaction properties required at the site are achieved by static or dynamic compaction using different rollers and tampers. In situations where the required properties are not achieved at the site, admixtures such as pulverized fuel ash, lime, silica fumes, slag, cement, or other chemicals are generally added to improve the properties (Prusinski and Bhattacharja 1998; Senol *et al.* 2002; Farnsworth *et al.* 2008; Saltan and Selcan 2008). One of the critical criteria to consider during compaction at the site is achieving at least 95% relative compaction. In practical cases, where it is not possible to attain the maximum dry unit weight, the structures constructed at the site may fail. In conditions where it is hard to accomplish the mandatory compaction characteristics by means of the surface compaction techniques, CLSM was an effective substitute to normally densified fills (ACI 229R-99 2005; Lini Dev and Robinson 2015; Ling *et al.* 2018). Researchers have considered the use of CLSM in different applications in the field of civil engineering (Ghataora and Alobaidi 2000; Chittoori *et al.* 2013; Do and Kim 2016). CLSM is a cementitious mix developed from the by-products collected from different industries.

As per the Central Electricity Authority (CEA) report (2020), nearly 72% of the electricity production in India is from coal ash-based thermal power stations. This vast power generation led to about 217.04 million metric tons of coal ashes in 2018-19. As per the CEA report, the current coal ash production will cross 600 million metric tons by 2032. This massive production of coal ash deposits has led to severe environmental issues, and thus various methods are adopted to reuse the ashes in different forms for diverse engineering applications. Fly ash generated from the thermal power stations is used for various applications such as a replacement for cement in the construction industry, reclamation of low-lying areas, manufacturing of bricks, and backfilling applications (Senapati 2011; Loya and Rawani 2014). Even though fly ash is used for different applications, according to Bhatt *et al.* (2019), utilization of fly ash for different applications in India is only about 50% of its total production.

Pond ash, usually deposited in ash ponds, is a waste product obtained from the thermal power stations. Vast acres of land are getting wasted in all the thermal power stations because of this ash disposal. Along with this, ash deposition in ash ponds leads to soil, air and water pollution. In order to avoid the severe disadvantages caused by the disposal of pond ash in ash ponds, it can be reutilised in some other forms so that the problems associated with the disposal can be reduced to some extent. Even though pond ash is used as an aggregate in construction industry and as a filling material for low lying areas, a vast quantity of pond ash is deposited in ash

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ponds. Other methods for reutilization of these ashes have to be investigated to reduce the deposition. One such method of reutilization of pond ash is the CLSM, a mixture of coal ash, cement, and water. (ACI 229R-99 2005) defines CLSM as a self-compacted cementitious material which is a mixture of coal ash, water and cement that has a higher strength than soil but less than 8.3 MPa at 28 days. CLSM is also called flowable fills, flowable mortar, k-crete and unshrinkable fill (Du *et al.* 2002; Butalia *et al.* 2004; ACI 229R-99 2005). Other waste products such as recycled aggregates, mine flotation tailings, limestone screenings, cement kiln dust, sewage sludge, bottom ash, waste foundry sand, treated oil sand are also used by various researchers in flowable fill production (Ling *et al.* 2018; Ibrahim *et al.* 2022).

Pond ash along with other fine aggregates was also considered for flowable fill production by various researchers and the properties of flowable fills for different mix proportions were studied. The studies conducted till now for pond ash based flowable fill considered the use of other fine aggregates such as fly ash, gypsum, mine tailings and excavated soil along with pond ash for flowable fill production (Langton *et al.* 1998; Kim *et al.* 2016; Do *et al.* 2017; 2019). In this study, pond ash was utilized as the aggregate along with cement and water for the production of CLSM mixtures.

CLSM mixtures are utilized for various applications such as filling abandoned mines, subgrade layer for pavement, bedding layer of pipelines and as a compacted filling material for the retaining walls (ACI 229R-99 2005; Mneina *et al.* 2018). Depending upon the properties required at the concerned site, the constituent materials used for CLSM production and the required quantity have to be decided. Lower compressive strength CLSM mixtures are used for applications where the mix has to be dug at a later age. In such situations, the unconfined compressive strength (UCS) at 28 days should be less than 0.7 MPa at 28 days (Pons *et al.* 1998; Lini Dev and Robinson 2015; Zhang and Tao 2015). In structure fills where future excavation is not required, the UCS at 28 days can be as high as 8.3 MPa (Bassani *et al.* 2015; Jadhav *et al.* 2017).

The plastic and in-service properties to be considered while utilising CLSM for different applications are flowability, segregation (bleeding), UCS, unit weight, permeability, shear strength and compressibility (ACI 229R-99 2005; Ling *et al.* 2018). Depending on the applications considered, the properties to be assessed for CLSM varies. For subgrade applications in pavements, the California bearing ratio (CBR) and resilient modulus (M_R) are the critical properties to be assessed for the CLSM mixtures (Javed *et al.* 2002; Bassani *et al.* 2015; Lini Dev and Robinson 2019). In situations where the CLSM mixtures are considered for applications such as backfill materials or bedding layer for underground pipelines, the compressive strength, elastic modulus, permeability, compressibility and shear strength are the essential properties to be assessed (Meade *et al.* 1993; Ghataora and Alobaidi 2000; Lee *et al.* 2014). This paper considers the use of pond ash-based CLSM for bedding layer applications for buried pipelines. The required properties of the CLSM mixtures for the bedding layers applications are determined as per the ASTM specifications. The stresses and strains developed in the buried pipelines were analysed using the numerical tool PLAXIS 2D.

PLAXIS 2D is a numerical tool typically used to evaluate the stresses and strains for different applications in geotechnical engineering. PLAXIS analysis of buried pipelines for different loading conditions was studied by various researchers in the past (Goltabar and Shekarchi 2010; Kliszczewicz 2013; Beju and Mandal 2017). In this paper, PLAXIS 2D analysis was carried out to analyse the stresses and strains developed on buried pipelines in situations where CLSM mixtures were used as the bedding layer material. Comparative studies were carried out with normal compacted sand as the bedding layer. The top layer considered for the study was also changed to identify the difference in the behavioural pattern of the development of stresses and strains in the pipelines. The materials considered for the study, the methodology adopted, and the results obtained based on the given study are explained in the coming sections.

2. MATERIALS AND METHODS

As explained earlier, the study aimed to identify the utilisation of pond ash in CLSM production for bedding layer applications for buried pipelines. In order to achieve this, the properties of CLSM required for bedding layer applications such as flowability, UCS, unit weight, elastic modulus, shear strength and permeability are to be determined as per the standard specifications. Further, the stresses and strains developed in the bedding layers will be analysed using PLAXIS 2D software. A comparative study has to be carried out by considering different materials as bedding and top layers to understand the performance of all the materials for bedding layer applications.

The procedure adopted for determining the properties of flowable fills includes collecting and drying the required quantity of pond ash from a Thermal Power Plant. The Power Plant selected in this regard was from Tamil Nadu, a southern state in India. Once the ash was completely air dried, the physical properties of the ash, like particle size characteristics, compaction characteristics, specific gravity and pH, were determined according to ASTM standard specifications. 53 grade Ordinary Portland Cement was used along with pond ash in flowable fill production. X-Ray Fluorescence studies were done to understand the mineralogical composition of the pond ash. The oxides present in major quantities in the ash were SiO_2 (60.78%), Al_2O_3 (23.9%), Fe_2O_3 (7.54%), TiO_2 (2.9%), SO_3 (1.71%), CaO (1.6%) and K_2O (1.5%). As the CaO content present in the ash is very low, the pond ash can be considered as Class F ash. As per ASTM specifications, the pH of the ash was found to be 7.5.

The grain size characterization of the ash was evaluated as per Indian Standard specifications which also meets the ASTM standards. Based on the grain size study, the ash contains only 6% of particles finer than 75μm. The ash contains mainly coarse-grained particles as 94% of the particle size was coarser than 75μm. The pond ash can be stated as SP-SM according to Sridharan and Prakash (2007). The specific gravity of the ash determined using kerosene as per IS 2720 specifications was 2.21. Both light compaction using standard proctor (SP) and heavy compaction using modified proctor (MP) tests were done to assess the compaction characteristics of pond ash, and the optimum moisture content (OMC) obtained was 23% and 19% for light and heavy compaction tests. The pond ash's maximum dry density (MDD) for Standard Proctor and Modified Proctor compaction test specifications is 12.1 and 13.2 kN/m^3. The obtained values of MDD and OMC are almost the values equivalent to that obtained by Kumar Bera *et al.* (2007).

After determining the index properties of the ash, the plastic and in-service properties of flowable fills were determined as per the ASTM standard specifications. The main properties considered in the present study are flowability, unit weight, UCS, elastic modulus, shear strength and permeability. The procedure for determining all the properties of flowable fills involves the mixing of dry constituent materials in the mix such as cement and coal ash in a Planetary mixer for about 15 minutes. After proper dry mixing of the constituent elements in the mix, water is added to the dry mix, and the mixing is again continued for 10-15 minutes. The final mix obtained will be tested for the required properties as per standard specifications.

ASTM D6103-04 specifications were employed for determining the flowability of flowable fills, in which the average diameter of the mix in two perpendicular directions are measured. After complete mixing, the mix obtained from the Hobart planetary mixer is transferred into a plastic cylinder of 75 mm diameter and 150 mm height. The flow cylinder is then raised to a height of 120-150 mm. The diameter of the mix is denoted as the flowability of the mix. The amount of cement in the mixture was ranged from one to four percentage of the weight of pond ash. According to ACI 229R-99 (2005), the flowability of CLSM mixtures should be between 200 and 300 mm for the mix to be in flowable condition and to reduce mix segregation during pumping of the mix. Thus, in this study, the flowability values of the mix were fixed as 200 and 300 mm. Trial studies were carried out to identify the required quantity of water to obtain the flowability values for different cement contents. Once the required quantity of water for obtaining both 200 and 300 mm flowability for all the cement contents are obtained, the samples for all the other tests are prepared for the same water content. The water content corresponding to each flowability and cement content is expressed as a proportion of the ash weight.

The samples for testing the dry density and UCS were prepared after obtaining the water contents for 200 and 300 mm flowability for all the cement contents. ASTM D 6023-07 (2007) specifications were considered for evaluating the unit weight of all the samples. The specimens were cast in steel molds of diameter 50 mm and height 100 mm. The obtained flowable fill mix from the Hobart mixer was filled into the molds, and the weight of the flowable fill mix was estimated to obtain the wet density of the mix. The dry density was computed after measuring the initial water content using the relationships of soil mechanics.

UCS is one of the main in-service properties of flowable fill, which decides whether the fill material can be considered for bedding layer applications. While considering the flowable fills for any applications, the UCS value at 28 days is considered. UCS tests for the flowable fill mixes were carried out as per ASTM D 2166/D2166M-13 (2013) specifications. Corresponding to the water contents required for 200 and 300 mm flowability values, the samples were prepared for different cement contents varying from 1% to 4%.

The two different criteria to be considered for the low strength flowable fills in UCS testing are the initial hardening of the before twenty four hours of preparation of sample and the 28th day compressive strength should be below 0.7 MPa. The samples for UCS testing were done by considering these two criteria. The mixed sample from the Hobart mixer was poured into a hollow steel cylinder of internal diameter 50 mm and 120 mm tall, and the leakage from the top and bottom ends of the container was shielded by providing cling film on two sides. Twenty-four hours of curing was done, and then a 100 mm sized sample was trimmed from the cured sample. The specimens obtained were kept in desiccators after covering with cling film for a specified curing period of 28 days. The same procedure was repeated for all the samples prepared for varying cement contents and flowability values. Initially, the samples were prepared with 1% of the weight of pond ash for both 200 and 300 mm flowability. After 24 hrs, the samples were not hardened and thus were discarded. Further, the samples were prepared by varying the cement contents from 2% to 4% of the weight of pond ash for flowability values of 200 and 300 mm. Minimum of three samples was considered for each design mix and the mean value obtained for all the three samples was represented as the UCS of the sample at the specified condition.

The other properties to be considered while using the flowable fills for bedding layer applications are the permeability and shear strength of CLSM mixtures. The samples for permeability and shear strength were prepared as per the same procedure adopted for UCS. The testing was done after a curing period of 28 days. Permeability or hydraulic conductivity of CLSM mixtures were determined as per ASTM D 5084-10 (2010) specifications. The 28 days cured samples were tested in the flexible wall permeability test set up as per the procedure stated in ASTM. Back pressure saturation was required to achieve the required B-value of 0.95. The sample was then consolidated at an effective confining pressure of 100 kPa. The permeability tests were carried out at a hydraulic gradient of 2 following the ASTM procedure of hydraulic gradient between 1 to 5. The volume changes corresponding to different time intervals were noted, and each sample's permeability was determined as per the constant head concept.

Consolidated undrained (CU) triaxial tests were done to obtain the shear strength parameters of CLSM mixtures. Confining pressures of 50, 100, 200, 400, and 700 kPa were considered for testing the samples after a curing period of 28 days. All the samples were saturated by back pressure to ascertain a B-value above 0.95. The time of failure (t_f) was calculated as per the procedure stated by Head (1986). The load and pore pressure variations with respect to the linear deformations were noted to estimate the behavior of deviatoric stress with strain and stress path behavior. An axial strain of 20% was fixed for the stoppage of shearing of the sample. The strain rate of 0.075 mm/min was fixed as per Head (1986).

Once the experimental results like UCS, dry unit weight, elastic modulus, shear strength behavior and hydraulic conductivity for the flowable fills were obtained, PLAXIS 2D analysis was carried out for different mixes for the bedding layer condition. The analysis was conducted to determine the stresses and strains developed on the pipelines for different bedding layers and top fill conditions. A comparative study was done to evaluate the performance of CLSM mixtures with other compacted fill materials utilized for bedding layer applications. The results obtained from the experimental studies conducted on different CLSM mixtures for bedding layer applications and the results obtained from PLAXIS analysis are given in the next section.

3. RESULTS AND DISCUSSIONS

3.1 Flowability

As per the procedure explained above in Section 2, the flowability studies were carried out for different mixes of flowable fills. The results obtained for different cement contents for both 200 and 300 mm flowability are given in Fig. 1. The figure clearly states that the water content required for achieving a constant flowability value depends on the cement content in the mix. From the flowability tests conducted on all the samples, the water contents for 200 and 300 mm flowability was identified. Further samples for all the tests such as UCS, unit weight, permeability and shear strength were prepared for the same cement and water contents for both flowability values. Table 1 shows the required water contents for obtaining the flowability values of 200 and 300 mm for different cement contents.

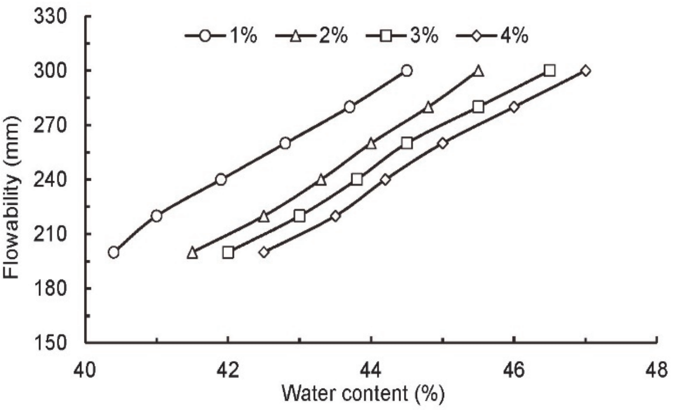

Fig. 1 Flowability variation for different mixes considered in the study

Table 1 Values of water contents required for different cement contents

Cement (%)	Flowability (mm)	Water content (%)
1	200	40.4
	300	44.5
2	200	41.5
	300	45.5
3	200	42
	300	46.5
4	200	42.5
	300	47

3.2 Unconfined Compressive Strength (UCS)

UCS samples were prepared for all the cement contents (1% to 4%) as per the procedure explained above in Section 2. With the addition of 1% cement content to the mix, the samples prepared were not hardened after 24 hrs of sample preparation. Thus, further tests of UCS were carried out for samples prepared with 2%, 3%, and 4% cement contents. The samples were tested after 28 days of curing. A rate of strain of 0.5 mm/min was adopted for testing. The stress-strain graph obtained for the different mixes of flowable fills is plotted in Fig. 2. The failure strain was found to decrease, with increase in cement percentage in the mix, showing a brittle nature. The failure strains were found to vary from 0.5% to 2%. The failure of the samples was similar to that of concrete. UCS values obtained for all the samples tested for varying cement contents and flowability conditions are given in Fig. 3.

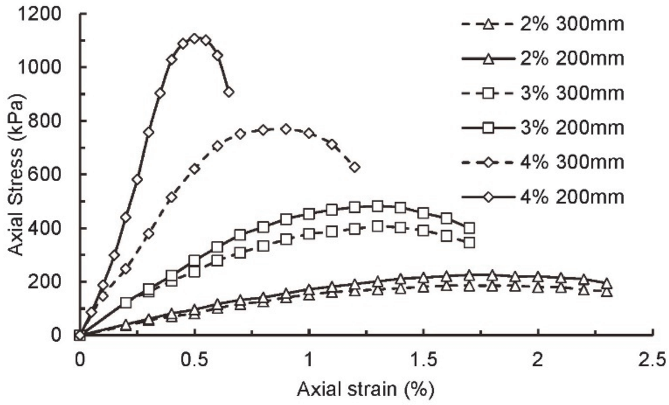

Fig. 2 Stress-strain variation for varying cement contents

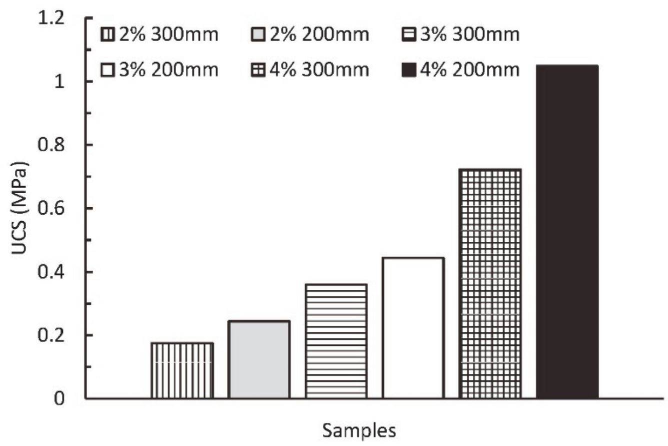

Fig. 3 UCS values at 28 days for different samples

From Fig. 3, it was observed that UCS values of all the mixes depend on cement content and flowability values. As observed by various researchers, the UCS values increased with addition of higher amounts of cement and UCS values were noticed to be decreased for higher flowability values. For the considered CLSM mixture in the study, it was also noted that the UCS values obtained at 28 days was higher than 0.7 MPa for 4% of cement content. The values obtained were 1.048 and 0.722 MPa at 28 days for 200 and 300 mm flowability samples for the cement content of 4%, higher than the specified value of 0.7 MPa for low strength flowable fills. Thus, further studies such as permeability and shear strength were only carried out for four samples prepared with 2% and 3% percentage of cement and flowability values specified above.

All samples' elastic modulus can be determined from the stress-strain curve obtained at 28 days for the UCS tests conducted. The initial tangent modulus of the sample was determined from the stress-strain plot and represented as the Elastic modulus of the sample. The obtained values of elastic modulus for all the samples are given in Table 2. The Elastic modulus values were found to depend on the flowability and the cement content in the mix. The obtained elastic modulus values were equivalent to the elastic modulus values of GW/SW soils in loose conditions and SP soils in loose to medium state conditions (Obrzud and Truty 2018). Thus, on the basis of elastic modulus attained for the tested mixes of flowable fills, it can be observed that the properties match the normal compacted aggregates used for bedding layer applications.

Table 2 Elastic modulus values of flowable fill mixes

No.	Cement (%)	Flowability (mm)	Elastic modulus (MPa)
1	2	200	25.2
		300	16.2
2	3	200	47.2
		300	40.5

3.3 Dry Unit Weight

Dry unit weight of all specimens was determined based on the procedure explained in Section 2. The wet unit weight values obtained for all the samples vary from 15.4-16.7 kN/m^3. The values obtained are analogous with the results stated by various researchers (ACI 229R-99 2005; Hwang *et al.* 2017). The dry unit weight obtained for all the samples is given in Fig. 4. The dry unit weight values for all the samples vary from 10.9-11.35 kN/m^3. The values obtained for 200 mm flowability are higher than those samples with flowability of 300 mm. The dry unit weights of flowable fills are significantly less than the values obtained for pond ash from Proctor tests. Typically, the dry unit weight of flowable fill is about 0.90 to 0.94 and 0.82 to 0.86 of the MDD attained from SP and MP tests, respectively.

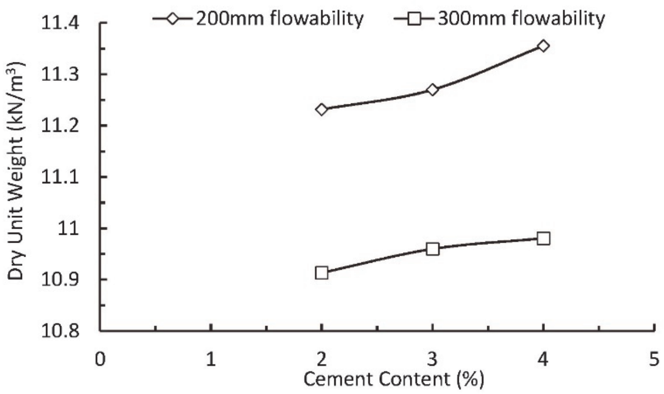

Fig. 4 Dry unit weight variation for different flowable fill mixes

3.4 Hydraulic Conductivity (Permeability)

As explained in section 3.2, permeability tests on four samples of varying cement and flowability were performed. The details regarding the samples tested and permeability values obtained for all the samples are given in Fig. 5.

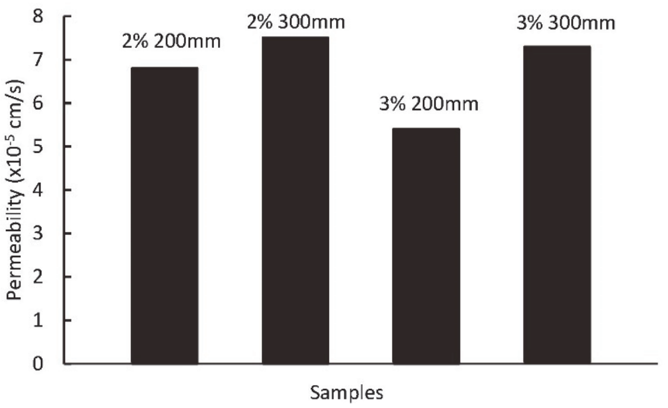

Fig. 5 Variation of hydraulic conductivity for different mixes

From Fig. 5, it was identified that the hydraulic conductivity values attained for all CLSM samples are equivalent to the values of silty sands or silty clays, whose permeability ranges from 5×10^{-4} to 5×10^{-7} cm/s (ACI 229R-99 2005; Siddique 2009). The permeability values of CLSM mixtures were found to depend on both cement content and flowability values. Thus, based on the permeability studies, it can be noted that flowable fills acquire a permeability value equivalent to the traditional bedding layer materials used in underground construction. Thus, it can be used to replace normal compacted aggregates in bedding layer applications for pipelines.

3.5 Shear Strength

The shear strength of all the samples was tested as per the procedure explained in Section 2. Tests were carried out for samples prepared with varying cement percentages of 2 and 3 and for 200 and 300 mm flowability for all the confining pressures specified in Section 2. The deviatoric stress and pore pressure were noted for all the samples to determine the cohesion and internal friction angle of the mixes. The deviatoric stress and excess pore pressure variation for 2% 200 mm samples for all the confining pressures are given in Figs. 6 and 7. The same graphs were plotted for all the CLSM mixture samples. As a representative of all the results, the graphs obtained for 2% cement content and 200mm flowability is plotted in the figures. Figure 8 shows the effective stress path obtained for 2% cement content samples for 200 mm flowability for all the confining pressures.

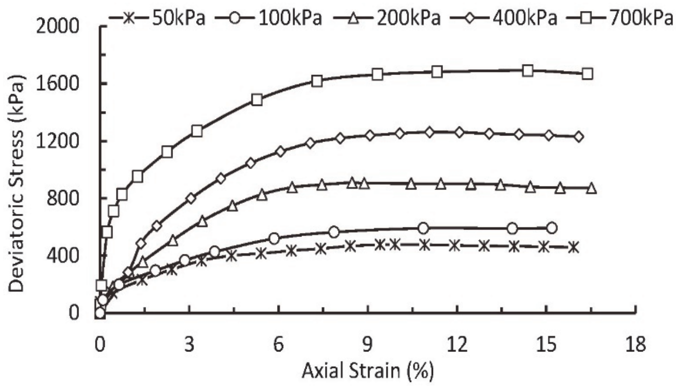

Fig. 6 Observed deviatoric stress-axial strain variation for all the confining pressures

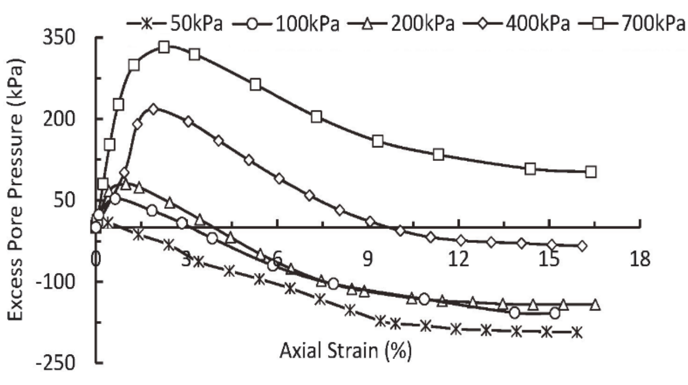

Fig. 7 Variation of excess pore pressure with axial strain for all the confining pressures

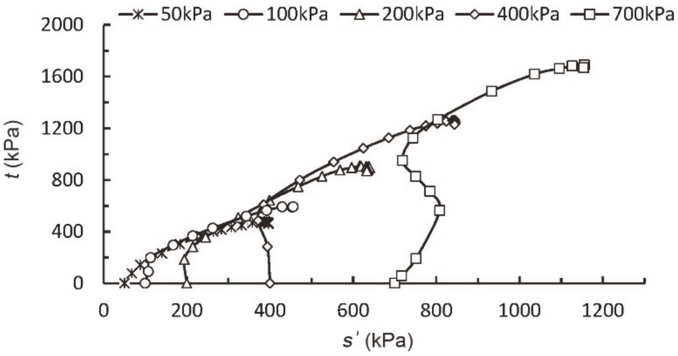

Fig. 8 Effective stress paths obtained for all the confining pressures

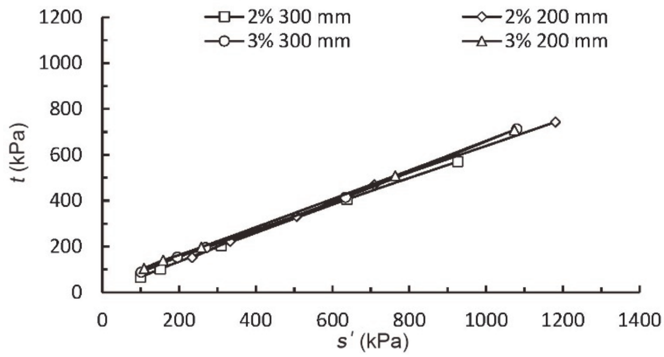

Fig. 9 Modified failure envelopes for different conditions for peak values of σ'_1/σ'_3 for flowable fill sample

The above figures show that the behavior of flowable fill material is similar to dense sand or over consolidated soil. Negative pore water pressures were found to be developed for all the samples. With increased confining pressure, the negative pore pressure developed due to dilation of sample is reduced. At higher confining pressures, the behavior changes from over consolidated to normally consolidated state. Deviator stress values were found to increase with the effective confining pressures. The increase in the values of deviator stress depends on the cement content and flowability of the sample.

The modified failure envelope for all the flowable fill samples for peak values of σ'_1/σ'_3 are given in Fig. 9. Cohesion and internal angle of friction of all the samples were calculated from the plots of s' *vs.* t where

$$s' = \left(\frac{\sigma'_1 + \sigma'_3}{2}\right) \tag{1}$$

$$t = \left(\frac{\sigma'_1 - \sigma'_3}{2}\right) \tag{2}$$

where σ'_1 is the major effective principal stress and σ'_3 is the minor effective principal stress. The parameters cohesion (c') and friction angle (ϕ') are evaluated from the modified failure envelopes based on the relation

$$\sin\phi' = \tan\Psi' \tag{3}$$

and $$c' = \frac{a}{\cos\phi'} \tag{4}$$

where $\tan\Psi'$ is the slope of the modified failure envelope, and a is the intercept on the y-axis.

The obtained values of cohesion and internal friction angle for the flowable fill samples are given in Table 3. Cohesion values were found to increase with an increase in cement content for the peak condition. Higher cohesion values were obtained for 200 mm flowability samples. The friction angle obtained for all the different mixes was found to vary from 38-39° for the peak condition. There is not much variation in friction angles with variation in cement content or flowability of the sample.

Table 3 Shear strength parameters obtained for all the tested samples

Serial No.	Samples	Shear strength parameters	
		c' (kPa)	ϕ' (°)
1	2% 200 mm	18.5	39
2	2% 300 mm	12.9	38
3	3% 200 mm	48.7	39
4	3% 300 mm	31.7	39

The experimental studies carried out on pond ash-based CLSM mixtures showed that flowable fill materials assess the properties required to utilise these materials as bedding layers in pipeline applications. The engineering properties considered, such as elastic modulus, UCS, unit weight, permeability and shear strength, were equivalent to that of silty sand or gravel type materials customarily used as aggregates in bedding layer applications. Based on the experimental results, numerical analysis was done to identify the stresses and strains developed in the underground pipelines for different bedding layer materials and top fill conditions, as discussed in Section 2.

3.6 PLAXIS 2D Analysis

Based on the experimental results obtained for flowable fills, PLAXIS 2D software was used to analyse the stresses and strains developed in pipeline applications where CLSM was used as bedding layers. The pilot model for the trench and pipeline was considered as the same suggested by Sharma *et al.* (2019). A vertical pressure of 8.5 lb/in^2 (58.6 kPa) was applied uniformly above the pipeline for all the models. Different models were considered by varying the bedding layer and top layer in the pipeline construction. The models considered for the analysis in the paper is given in Table 4. Sand and CLSM are considered as the bedding layers, and compacted fill material and clay are considered as the top fill material. Different combinations were well-thought-out for PLAXIS analysis.

Table 4 Various models considered for numerical analysis

Model 1	Bedding layer – L-1-sand Top-fill – L-4 Fill
Model 2	Bedding layer – L-1-sand Top-fill – L-4- clay
Model 3	Bedding layer – L-1-CLSM Top-fill – L-4-fill
Model 4	Bedding layer – L-1-CLSM Top-fill – L-4-clay

The properties of all the bedding layers and the top fill materials considered in the analysis are given in Table 5. The properties of sand, compacted fill material, clay and steel pipe were obtained from the research by Sharma *et al.* (2019). The CLSM mixture considered for the analysis is 3% cement content mix with 200 mm flowability. The properties for CLSM were obtained from the experimental results conducted on flowable fill samples.

Table 5 Properties considered for analysis in PLAXIS modelling

Properties	Clay	Sand	Fill	Steel pipe	CLSM
Material model	Mohr Coulomb	Mohr Coulomb	Mohr Coulomb	Linear elastic	Mohr Coulomb
Unit weight, γ (kN/m^3)	14.9	17.1	20.08	77.09	15.47
Elastic modulus (MPa)	1	40	8	206842.7	47.2
Poisson's ratio	0.33	0.3	0.3	0.3	0.18
Angle of internal friction, φ'	24	32	30	–	39
Dilation angle, ψ'	0	2	0	0	0

3.6.1 Boundary Conditions and Construction Sequence

The model's boundary condition was fixed. For the pipeline, speciality boundary conditions were applied (tunnel) as 'head' which is given as the distance between the soil's topmost surface and pipeline's topmost point.

3.6.2 Construction Sequence

- Firstly, the model is prepared with the dimensions mentioned.
- The materials are assigned, *i.e.,* sand, clay, fill and CLSM (for CLSM the properties are given and other properties are predefined).
- Boundary conditions for soil (fixed) and pipeline (head) and water table (at the base of the bedding layer) for the model is assigned. Soil and pipe interaction is taken care by the software itself.
- Loads are assigned.
- Thereafter mesh is generated.
- Points are selected in the pipe line for the stresses, strains, deformations and more observations in the desired location.

Running the program for the same model and hence the results were obtained for the given mesh and the selected points were highlighted for the ease of the observation.

Figure 10 shows the finite element model considered for the study for all the models. The numerical analysis was carried out by changing the material properties of the bedding layer and the top fill for obtaining the variation in the stresses and strains developed for all the models. Figure 11 shows the deformed mesh obtained for model 3, which considers CLSM as the bedding layer and compacted fill as the top layer. A comparison of total displacements for all the models is given in Fig. 12. The comparison of the total displacements for model 1 and model 3 shows that the total displacements developed on the pipelines where CLSM was considered as bedding layer was lesser than the sand-based bedding layer. The same observation was also noted between models 2 and 4.

Figure 13 shows the vertical displacements obtained for all the models. The results obtained for the vertical displacements for the cases where CLSM mix was used as the bedding layer was lesser than the sand-based bedding layer. Figure 14 shows the plots obtained for the effective stress distribution obtained

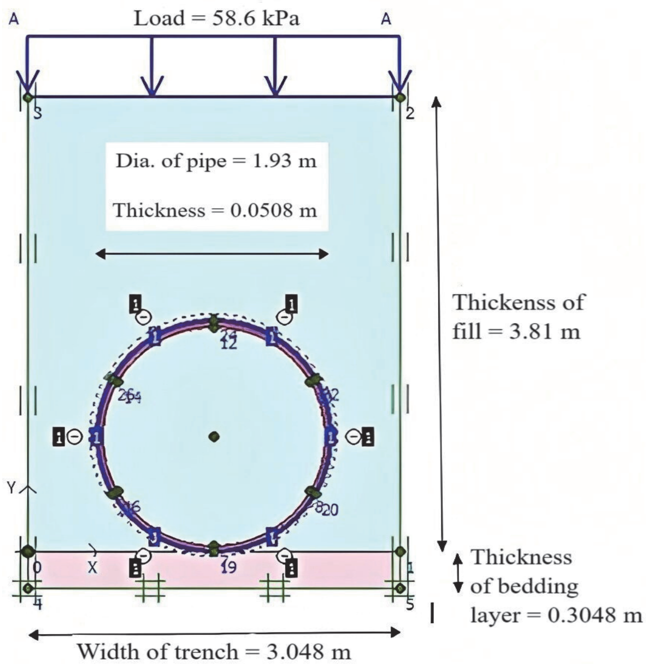

Fig. 10 Finite element model considered for all the analyses

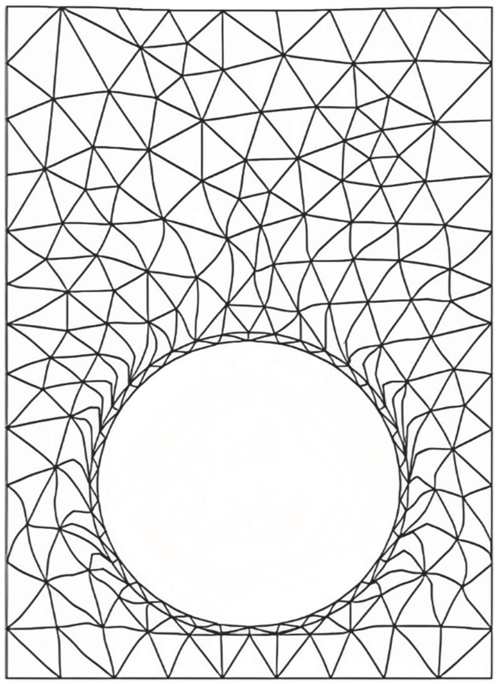

Fig. 11 Deformed mesh obtained for model 3

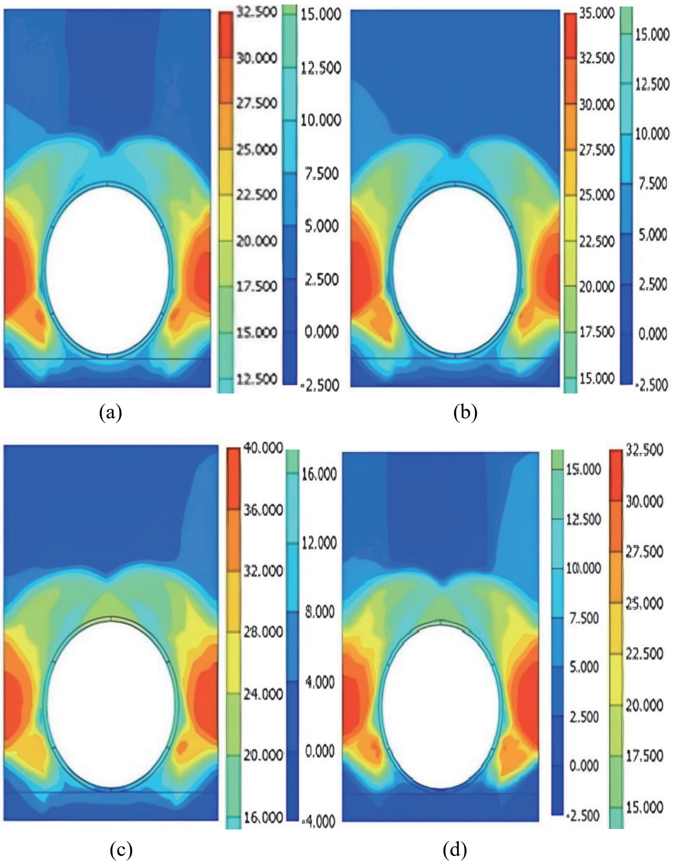

Fig. 12 Plot of total displacements (in mm) for (a) Model 1; (b) Model 2; (c) Model 3; and (d) Model 4

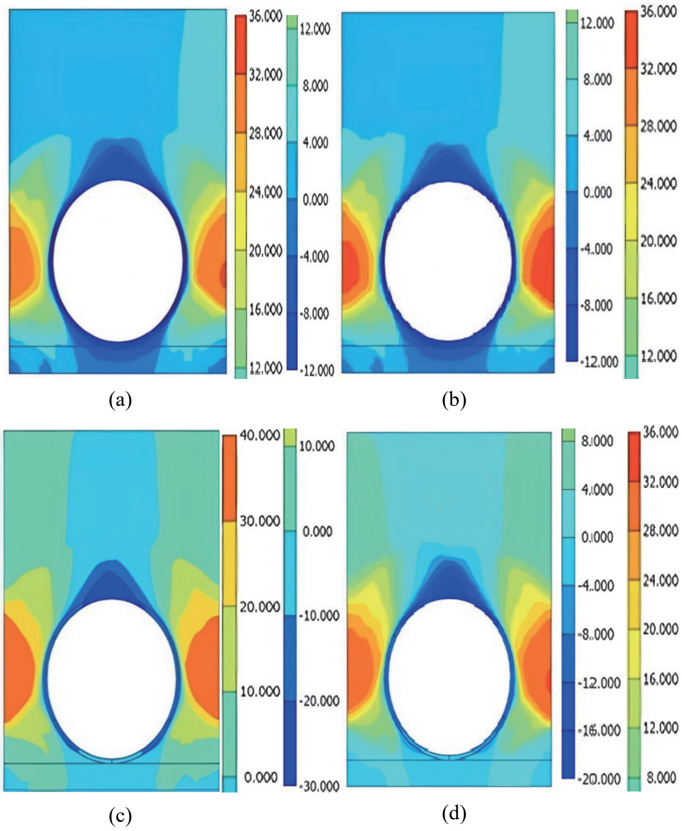

Fig. 13 Plot of vertical displacement (in mm) for (a) Model 1; (b) Model 2; (c) Model 3; and (d) Model 4

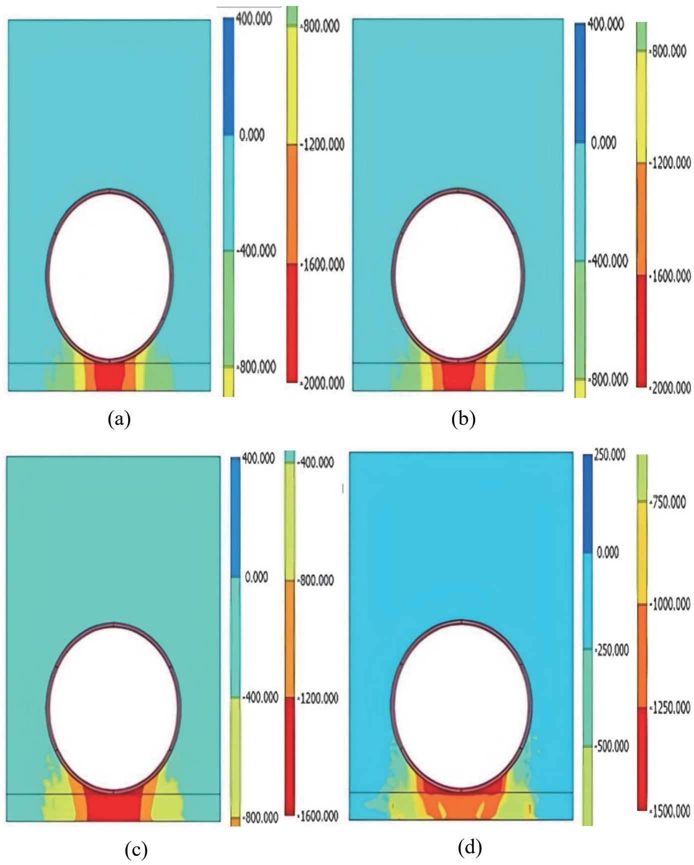

Fig. 14 Plot of effective stresses (in kPa) for (a) Model 1; (b) Model 2; (c) Model 3; and (d) Model 4

for all the models considered for the analysis. The plots showed that the stress distribution was much more comprehensive in the cases where CLSM mix was used as a bedding layer. Thus, the use of CLSM as a bedding layer reduces the stresses acting on the buried pipelines.

Comparison of the stresses and strains developed on the buried pipeline for all the four models were evaluated based on the numerical study conducted using PLAXIS and represented in Figs. 15 and 16. The comparison of model 1 and model 3 from Fig. 15 demonstrates that vertical stress developed at the crown of the pipe for model 3 was lesser than that of model 1. Both model 1 and 3, the top fill considered was compacted fill material. CLSM as the bedding material was a better alternative against the sand as the bedding material for buried pipelines. The same behaviour was noticed for the comparison studies on models 2 and 4. The vertical stress developed in model 4 was found to be lesser than that of model 2. The reason for this is due to the presence of clayey soil as the top fill material. The comparison studies on vertical strains developed on different models also showed the same behaviour pattern as stresses. The strains were lesser for the cases in which CLSM was considered as the bedding layer material.

Based on the numerical studies conducted on different bedding layers, it was observed that CLSM based bedding layers reduce the stresses and strains developed on the buried pipelines. Thus, Controlled Low Strength Materials can be well-thought-out as a well effective substitute to typically compacted bedding layers.

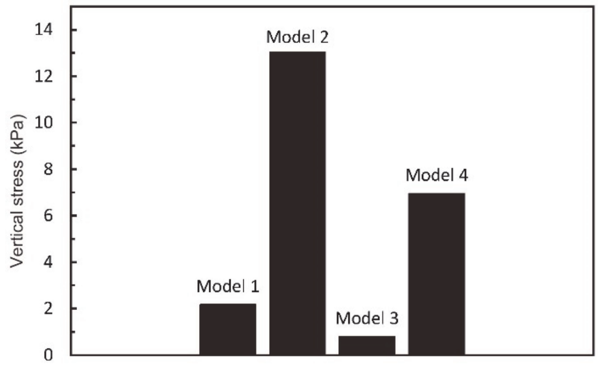

Fig. 15 Comparison of the vertical stresses developed at the crown of the pipe for different models

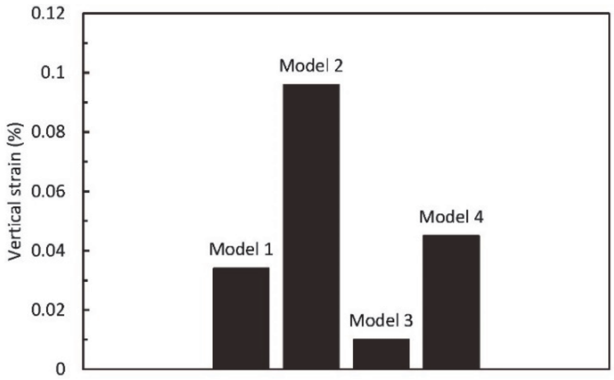

Fig. 16 Comparison of the vertical strains developed at the crown of the pipe for different models

4. CONCLUSIONS

This paper presents a study using pond ash-based flowable fills for bedding layer applications in underground pipelines. The properties of the flowable fills required for assessing the ability to be used as a bedding layer material such as UCS, unit weight, Elastic modulus, permeability and shear strength were determined as per the standard specifications. The below given conclusions are derived from the experimental studies conducted on flowable fills and the PLAXIS 2D software analysis.

- With a significantly lower percentage of 2% to 3% cement addition, coal ashes such as pond ash can be utilized in flowable fill production, meeting all the criteria suggested by ACI 229R-99 (2005).
- Addition of 1% of cement in the mix was found to produce a mix which was not hardened after 24 hrs of preparation, thus stating the requirement of 2% to 3% of cement addition for CLSM production.
- UCS values obtained at 28 days were less than 0.7 MPa, thus obtaining a low strength flowable fill. The elastic modulus values of flowable fill mixes vary from 16.2 to 47.2 MPa, equivalent to GW/SW soils.
- The dry unit weight of flowable fills was found to vary from 10.9 to 11.35 kN/m^{3,} and the unit weight values were found to depend on the cement content and the flowability of the mix.
- The permeability values of CLSM mixtures were found to depend on the cement content and the flowability of the mix, and the values are in the range of 10^{-5} cm/s.
- Shear strength tests on flowable fill mixes showed that the shear strength parameters developed on the CLSM mixture depend on the cement content and the flowability. With increase in the cement percentage in the mix, the cohesion values of CLSM mixtures were observed to be increased. There is not much variation in the angle of internal friction values obtained for different mixtures of CLSM.
- The numerical study using PLAXIS 2D software showed that the vertical stresses and strains developed on underground pipelines in situations where CLSM was used as the bedding layers was lesser than that of other materials considered for analysis. Further studies are required to study the effect of using CLSM as the top fill in the pipelines.
- Thus, based on the experimental studies and the PLAXIS 2D software analysis, CLSM using pond ash can be considered as an alternative for the normal compacted granular aggregates in bedding layer applications. The utilization of these waste products from industries using 2% to 3% of cement for flowable fill production is a viable solution to reducing ash deposition and environmental pollution.

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DATA AVAILABILITY

The data and/or computer codes used/generated in this study are available from the corresponding author on reasonable request.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

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