Int. J. of Geosynth. and Ground Eng. (2015) 1:32
DOI 10.1007/s40891-015-0035-1

ORIGINAL PAPER

Pond Ash Based Controlled Low Strength Flowable Fills for Geotechnical Engineering Applications

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Received: 14 August 2015 / Accepted: 20 September 2015 / Published online: 23 October 2015

Abstract Granular materials are conventionally used as backfills behind retaining walls and many other filling applications. Normally, the backfills are compacted in layers at a relative compaction of not less than 95 % of the Standard Proctor unit weight at desired water content. Depending on the type of backfill material, suitable compaction equipments are selected for compacting the material. Usually, coarse grained materials like gravel, sand, Pond ash, crushed rock pieces and cobble are used as backfill materials. As a replacement to the conventionally used backfill materials, controlled low strength materials (CLSM or flowable fills) are also used, especially in areas where compaction equipments cannot be mobilized. This paper reviews the effective utilization of different types of ashes in flowable fill production and the main properties, advantages and applications in geotechnical engineering practice. Experimental results of a flowable fill made of a local Pond ash are also presented in this paper.

Keywords Compacted granular fills · Controlled low strength materials · Pond ash · Flowable fills

List of Symbols

CLSM	Controlled low strength materials
γ_d	Dry unit weight (kN/m^3)
γ_b	Bulk unit weight (kN/m^3)
m_v	Coefficient of volume compressibility (kPa^{-1})
UCS	Unconfined compressive strength
CBR	California bearing ratio
OMC	Optimum moisture content
ZAVL	Zero air void line
CPA	Compacted Pond ash

Introduction

Rapid industrialization and usage of coal for power production has led to the generation of large quantity of coal ashes all over the world. About 18500T of coal ashes are produced in India every year [1]. Effective utilization of waste product is an important concern from both economic and environmental considerations. Industrial byproducts from thermal power plants like Pond ash, bottom ash and fly ash are usually deposited over large areas of land and dumping of ashes in ash Ponds leads to environmental pollution. The best way to tackle this problem is its effective utilization in other applications. Fly ash is used in the construction industry as a replacement of cement. Both bottom ash and Pond ash are utilized for filling applications.

Conventionally, granular fills are widely used for filling applications such as backfill behind retaining walls, reclamation of low lying areas and underground pipe lines, etc. In applications like filling of underground pipe lines and mine shafts, it is normally difficult to obtain the required degree of compaction using the conventional compaction equipment. In such situations, controlled low strength materials (CLSM) is considered as an effective alternative. ACI 229R-99 [2] and ASTM D 5971-07 [3] defines CLSM as “a mixture of soil, fly ash, cement, water and sometimes admixtures that hardens into a material with a higher compressive strength than soil but less than 8.3 MPa”. Fly ash is used as the main constituent material in flowable

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fills. Along with fly ash, usually foundry sand or concrete sand are also often used as the coarse grained element in flowable fills [4]. As an alternative to fly ash, other byproducts from coal and cement industry like bottom ash, slag, Pond ash, cement kiln dust etc. are also used in locations where it is widely available. The use of Class C fly ash as the finer material in flowable fills will usually result in flowable fills of higher compressive strength compared to Class F fly ash based CLSM [5]. Therefore, the cost of production of flowable fills based on Class C fly ash may be less as the quantity of cement required is less.

For low strength flowable fills, where the fill material has to be re-excavated at a later stage, the compressive strength should be less than 0.7 MPa at 28 days [2]. For such fills the percentage of cement required usually ranges from 1 to 4 %. However, in applications like permanent structural fills, the compressive strength should be greater than 8.3 MPa at 28 days. The main parameters which control the compressive strength of the flowable fills are the constituent elements in the mix, water-cement ratio and the type of ash used in the mix. Usually flowable fills are composed of fly ash, cement, sand and water. Depending on the type of fly ash used in the mix, the quantity of cement required to achieve the required compressive strength varies. In this paper, the properties of flowable fills and their applications are reviewed. The suitability of Pond ash, obtained from Ennore Thermal Power Station, Chennai, India, as flowable fill is also evaluated based on laboratory experiments.

Properties of Flowable Fills

The properties of flowable fills are usually classified as plastic and in-service properties. The details are discussed in the subsequent sections.

Plastic Properties

Plastic properties of flowable fills are relevant before hardening takes place. Understanding of these properties is important for the transportation and placing of the mix at the specified location. The plastic properties of flowable fills are comparable with the properties of concrete before setting, and the common practices adopted for flowable fills are similar to that of concrete.

Flowability

One of the main requirements of flowable fills is that it should flow easily while placing it at the site by pumping without segregation. Among many factors, water content plays a major role in determining the flowability. Flowability of the fill is usually determined as per the relevant ASTM standards. Flowability is defined as the average spread diameter of the fill prepared to the required consistency on a 75 mm diameter and 150 mm long flow cylinder made up of steel or plastic material. For a mix to be called as flowable, the flowability should be between 200 and 300 mm. The minimum flowability value of 200 mm is specified to achieve the required workability of the mix and to avoid the difficulty in pumping. For very loose mixes with high water content, there are chances for segregation of both fine and coarse materials in the mix. Therefore, an upper bound value of 300 mm is specified to obtain a mix which does not segregate after placing. The mix design is usually decided by considering the type of ash in the mix and the target compressive strength. Usually finer ash based mixes require more water to obtain the same flowability when compared to that of coarse grained ash based mixes because of the increased fineness of ashes [5–7].

Segregation

Segregation of flowable fills is usually measured in terms of bleeding or visible identification of stratification in the samples after conducting unconfined compressive strength (UCS) test. Segregation of constituent elements of flowable fill mixes usually occurs in mixes of high consistency. Hardjito et al. [8] conducted segregation studies on flowable fill samples prepared for compressive strength tests. After the UCS tests, the samples were split to two halves and the split surface was checked for stratification. The presence of stratification in the specimen shows that the fill has less segregation resistance. The fineness and the spherical shape of fly ash imparts better segregation resistance for fly ash based flowable fills along with the higher water- binder ratio of the mix [9]. Coarse grained flowable fill mixes produced from either bottom ash or slag was found to produce mix with greater segregation. The method adopted to avoid segregation of mix comprises of addition of enough quantity of fines to the mix thereby producing a mix of high cohesiveness and less void ratio thus leading to less dislocation of particles in the mix [2, 10].

Bleeding is considered as a type of segregation in cementitious materials where some of the water from the mix tends to rise to the surface of the mix, due to inability of the freshly prepared mix to hold the water in the mix during the process of hardening. Experimental studies using fly ash, quarry dust and bottom ash as a flowable fill material showed that the bleeding is inversely proportional to the cement content and directly proportional to the bottom ash content in the mix. The percentage of bleeding varies from 1.2 to 5.2 % depending on the cement and bottom ash content in the mix [8, 10]. Flowable fill mixes using waste foundry sand and fly ash as the aggregates showed that the component proportion and material properties are important parameters which affect the percentage of bleeding [11].

Subsidence

The reduction in volume due to self-weight by the release of water and entrapped air is referred to as the subsidence of flowable fill [2]. The magnitude of subsidence depends on the amount of water and the type of aggregates present in the mix. Usually mixes with higher flowability are found to show greater subsidence when compared to that of lower flowability mixes [2]. Subsidence is usually measured by filling the flowable fill mixes to a plastic or steel cylinder of 150 mm diameter and 300 mm height and measuring the percentage reduction in height of the fill during initial set of fill [12].

Hardening Time

Hardening time is referred to as the approximate time required for the flowable fill to change from the initial plastic state to hardened state with an appropriate strength to handle the weight of a person in the field [2]. Hardening time of flowable fill in the field is measured using Kelly Ball apparatus as per ASTM standards. The procedure involves raising and dropping the Kelly ball to the flowable fill specimen of 400 × 400 × 150 mm and measuring the indentations produced on the upper surface of the fill. Hardening time is represented as the time taken for the fill material to obtain an indentation diameter of less than 76 mm on the surface of the fill [2, 12]. The laboratory determination of hardening time is generally done by visual identification. In general, the hardening time of flowable fills is less than 5 h for low flowability mixes [13, 14]. The hardening time depends on the fineness of the ash used in the mix. Usually coarse grained flowable fill mixes are found to harden within less time when compared to that of finer ash based flowable fills [6].

Pumpability

Flowable fills are usually pumped and placed at the site using the conventional concrete pumping equipment. The easiness of pumping depends on the water- binder ratio and the cohesiveness of the mix. Blockage will usually happen in mixes prepared with coarse grained mixes because of segregation on the sides of pumps. Experimental studies on three Pond ashes from different ash Ponds [15] showed that all the mixes had good pumpability even though the ashes were of different fineness with flowability values greater than 200 mm. The use of fly ash as fine aggregate in flowable fills was found to improve the pumpability [16]. Proper proportioning of the ingredients in the mix will enhance the flowability of the mix thereby reducing the pumping pressure in the pumps [2]. Usually, it is noted that the high flowability mixes are easily pumpable when compared to lower flowability mixes. Fox [17] showed that mixes having flowability in the range of 51 mm can be easily delivered using concrete pumps. Thus it can be concluded that even though flowability is a parameter which affects the pumpability of mix, adequate void filling and cohesiveness of the mix are the two important parameters which affect the flowability of a mix.

In-Service Properties

In- service properties are related to the behaviour of the fill after hardening. These properties are comparable with that of soils and the methods adopted for soils are mainly used to determine these properties. The main in-service properties of CLSM are compressive strength, unit weight, settlement, permeability, compressibility and excavatability. Other properties like California Bearing Ratio (CBR) can be also considered as in-service property.

Unconfined Compressive Strength (UCS)

Compressive strength of flowable fill mixes is usually expressed in terms of the unconfined compressive strength (UCS). The compressive strength of flowable fill mixes is usually determined at different ages (curing periods) to identify the short and long term compressive strength gain. Samples for compressive strength measurement of flowable fill mixes are usually cylindrical in shape, prepared at either 50 or 75 mm diameter by keeping a height to diameter ratio of 2.

Compressive strength of flowable fills depends on the type of binder elements in the mix, type of ash and the water cement ratio of the mix. Compared to Class C fly ash, class F fly ash based flowable fill mixes show less compressive strength due to the difference in chemical composition of the ashes which in turn affect the reactivity. Fine grained ash mixes give a lower compressive strength for the same cement content because of the higher specific surface area which leads to higher water demand for obtaining the same flowability [6, 18, 19]. Studies on increasing the mixing time for flowable fills [20, 21] showed a reduction in compressive strength for mixes prepared by a prolonged mixing time of more than 30 min. It was observed that increasing the mixing time by more than 30 min will reduce the workability of the mix. Thus in order to obtain the required flowability if retempering is done at later stages, a reduction in compressive strength was noticed.

Predictive models were also attempted to determine the compressive strength of flowable fill mixes by considering parameters like age, type of ash and binder materials used in the mix [6]. Studies conducted on Class C fly ash based flowable fill [9, 22] showed that the rate of compressive strength gain reduces after 28 days and the rate of compressive strength gain at later ages depends to a large extent on the quantity of finer materials present in the mix. Chittoori et al. [23] conducted studies on a native clay based flowable fill using three different binders such as cement, lime and fly ash and showed that the type of binder used in the mix has a significant effect on the compressive strength of the mix. It was also reported that the use of clayey soil as fine aggregate reduces the durability of the CLSM mix.

Unit Weight (Density)

The procedure for the determination of bulk unit weights (γ_b) involves mixing the materials for the specified time and weighing it after filling into moulds of standard volume. The bulk unit weight of regular flowable fill mixes usually varies from 18.40 to 23.20 kN/m^3 [2]. However, experimental studies on different types of fly ashes varying in lime, carbon and ammonia contents as flowable fill material showed that the unit weight values ranges from about 14–17 kN/m^3 [24]. Unit weight values ranging from about 13–22 kN/m^{3}are reported when industrial byproducts like copper slag, cement kiln dust and incineration ash were used as the ingredients along with sand and cement in varying proportions [25, 26]. Empirical relationship were also developed for the determination of the dry unit weight from 28 day compressive strength for fly ash based flowable fills [27]. Unit weight of flowable fills are often reduced by adding light weight aggregates to the flowable fill mixes. Studies on crumb rubber as light weight aggregate in flowable fill mixes showed that the unit weight varies from 12 to 16 kN/m^3 [28]. Studies on the use of the recycled aggregates as fine aggregate in CLSM showed a trend in the reduction of unit weight with addition of air entraining admixtures in the mix [29]. It was noted that the unit weight of the mix varies from 14.3 to 17.6 kN/m^3 with increase in the amount of admixtures and recycled aggregates in the mix. Thus it can be concluded that the unit weight of flowable fill varies depending on the ingredients in the mix.

Permeability (Hydraulic Conductivity)

The permeability of the flowable fill mixes are usually determined using the flexible wall permeability apparatus as per ASTM standards. Permeability values of flowable fills were reported to vary from about 10^{-4} to 10^{-5} cm/s [2], which is the range for sandy silts and silty clays. Addition of more fines to the flowable fill mix will reduce the permeability. CLSM mix with higher permeability can be obtained by reducing cementitious materials in the mix or by increasing the aggregate content. Experiments conducted on flowable fill mixes with different mix proportions of fly ash and foundry sand showed that the permeability of the mix varies with water-cement ratio and the amount of foundry sand in the mix. The values ranges from about 3×10^{-6} to 7.6×10^{-5} cm/s which is comparable to compacted granular fills [30]. Studies on recycled bottom ash along with fly ash, sand and cement in different proportions as a flowable fill material showed that the permeability ranges from 10^{-5} to 10^{-7} cm/s. These values are comparable to the permeability of silty clay [31]. The permeability values of air modified flowable fill mixes varies from 1.7×10^{-2} to 1.2×10^{-3} cm/s compared to that of a regular flowable fill which shows permeability value of 1.8×10^{-4} cm/s [13]. Higher permeability values obtained for air-modified flowable fills may be attributed to the lighter unit weight (higher void ratio) of the mix compared to normal flowable fill mixes.

Compressibility

The compressibility of the flowable fill mixes are generally determined after 28 days of curing using one-dimensional consolidation apparatus as per ASTM standards. Experimental studies on the compressibility behavior of both regular and air modified CLSM mixes showed that the coefficient of volume compressibility (m_v) improves as the mix gets hardened. The values (m_v) ranged from 3.6×10^{-4} to 3×10^{-6} kPa^{-1} for different mix designs which is equivalent to dense sand/dense gravel category with increase in age from 16 h to 28 days [13]. Studies on the use of a low plastic silty clay in CLSM as a subgrade material for pavement showed that the compressibility of CLSM mix was negligible due to cementation effect. The compressibility was found to reduce with increase in the cementation in the mix [16]. Compressibility studies on a bedding layer of CLSM showed that the CLSM mix behaves like dense gravel after the curing period due to cementation [32].

Settlement

The reduction in thickness of fill due to self-weight or applied load is referred to as the settlement of a fill material. Compared to compacted granular fills, the settlement of CLSM fill after hardening was found to be less. Fly ash based fills shows less settlement when compared to that of other coarse grained industrial byproducts based fills [2]. The presence of fines improves the cohesiveness and imparts strong particle to particle interaction thereby reducing the settlement of fly ash based fills. A case study on a flowable fill of a 37 m shaft project in Seattle for fly ash based fills showed that the settlement due to self weight stresses ranged from 2 to 3 mm [2]. Light weight aggregates like crumb rubber in flowable fills usually produce CLSM mixes of lower bulk unit weight which reduces the self weight stresses resulting in reduced settlement [28]. Use of a low plastic silty—clay as finer material in CLSM as a subgrade material for pavement resulted in lesser settlement compared to the native clay because of the cementation in the mix [16]. Preconsolidation pressure (yield stress) of the soil based CLSM mix was found to be ten times greater than the untreated clay which resulted in lesser settlement for the CLSM mix [16]. Field study conducted on different flowable fill mixes in a bridge abutment as part of a National Highway Research program by Folliard et al. [33] showed that no differential settlement was seen at the approach sections after two months of placement.

Excavatability

Excavatability of CLSM mix is an important parameter when the mix has to be used as a bedding layer for pipelines. In situations where the CLSM has to be excavated at a later stage, the compressive strength of the mix should be less than 0.7 MPa at 28 days. CLSM mixes of compressive strength less than 0.3 MPa can be excavated manually. Mechanical equipments are usually required for excavating CLSM mixes of compressive strength in the range of 0.3–0.7 MPa [2]. Fine grained CLSM mixes can be easily excavated compared to other industrial byproducts based CLSM mixes. Experimental studies on a flowable fill mix produced from fly ash and a sludge from acid mine drainage showed that the compressive strength values obtained at 28 days for less percentage of cement was found to be less than 0.7 MPa thereby providing a mix which can be excavatable at later ages. The CLSM mixes with 10 % cement was found to have compressive strength more than 2 MPa thus providing a mix which can be used as a permanent fill [14].

California Bearing Ratio (CBR)

Information about CBR values of flowable fills is important when the flowable fill mix is used as a pavement base or subbase material. The field CBR values obtained for regular CLSM mixes after 6 days of placement was reported to be comparable with a poor subgrade layer used in pavement and after 45 days of curing the value was comparable withto that of compacted aggregate base material. The values of CBR observed for quick setting flowable fill mixes varies from 40 to 45 % after 24 h of placement. Flowable fill mixes prepared with excavated native clay along with cement showed a CBR value of 46–64 % for mixes with cement- water ratio of 0.5 and 0.7. The values are comparable to that of compacted well graded aggregate base and sub-base material [16]. Investigations on air-modified flowable fills showed that the CBR values ranges from 20 to 30 % at a curing period of 3 days and the CBR values increased to 30–80 % after 56 days of curing [13]. Studies on the use of bottom ash and quarry dust showed that the CBR values of varies from 5 to 59 % for different proportions of bottom ash and quarry dust [34]. Thus the flowable fill produced from quarry dust and bottom ash can be used as a subbase and subgrade material.

Applications of CLSM

CLSM finds many applications in geotechnical engineering practice.

- *Backfill behind retaining walls* CLSM can be used as a back fill material behind retaining walls instead of the conventional granular fills. CLSM mixes does not require any compaction for achieving the required characteristics. After hardening of the flowable fill, the earth pressure on the retaining wall is expected to be less compared to the compacted fill.
- *Structural fills* Flowable fills of higher compressive strength (>8.3 MPa) can be used as fills below foundations and slabs as a structural fill. Horiuchi et al. [27] conducted studies on the use of fly ash based flowable fill for high rise buildings and the construction of a manmade islands. They showed that the use of CLSM mix improves the mechanical properties and stability against sliding failure.
- *Erosion control* Based on experimental and field studies was conducted on CLSM mixes, it was proved that the CLSM mixes show better performance against erosion when compared to other soils [2].
- *Pavement bases* Flowable fills can be used as a sub base, base and subgrade course in pavements. The fill material can be directly placed at the site by pumping. Depending on the requirement at the site, the compressive strength of the mix is usually varied from 2.8 to 8.3 MPa. Wu and Lee [16] considered the use of native clay in CLSM mix and showed that the mix achieves the required compressive strength and compressibility parameters for application as a subgrade for pavement.
- *Conduit bedding* Flowable fills are used as bedding material for both concrete and flexible pipes. As compaction is not required for flowable fill mixes, the width of the trench for providing pipes can be reduced

thus reducing the construction cost. Watkins et al. [35] considered the use of different materials as bedding layer for pipelines and showed that CLSM can be considered as a better alternative to native soil in terms of strength and stiffness.

- *Void filling* Flowable fill materials are used to fill abandoned mines and shafts. The main criteria to be considered here is that the mix should be flowable in nature so that it can flow a longer distance and fill the whole voids. ACI229R-99 [2] reported different case studies showing the application of CLSM mix to fill tunnel shafts and mines.

Advantages of Flowable Fills

The advantages of flowable fills when compared with conventional fills are

- *Utilization of industrial by-products* Industrial byproducts like fly ash, bottom ash, Pond ash, Ground Granulated Blast furnace Slag, Cement Kiln Dust, wood ash and foundry sand which are otherwise considered as waste can be effectively utilised as the constituent material for the production of CLSM [2, 10, 36].
- *Easiness in delivering and placement of fill* Conventional ready mix trucks can be used for delivering the mixed flowable fill to the construction site. The mix is then conveyed to the required location using concrete pumps. As compaction is not required, the trench width for pipes can be reduced in cases where the fill material is used as a bedding layer [37–39].
- *Durability and strength* Required compressive strength for the flowable fill mixes can be suitably designed. Higher compressive strength mixes can be obtained by the addition of more percentage of cement to the mix. Durability studies on CLSM mixes through repeated freezing-thawing and wetting- drying cycles in the laboratory and field proved that the flowable fill mixes are durable under adverse conditions [31, 40].
- *Improvement in construction safety* In cases where the compacted granular fills are used as bedding layer for pipelines at deeper depths, the workers have to compact the fill in the trenches. As there is no requirement of compaction in case of flowable fills the safety of workers are ensured [41–43].
- *Excavatable at later ages* In situations where the fill material has to be excavated at a later age, the mix design can be varied in order to obtain a compressive strength less than 0.7 MPa at 28 days. Those fill mixes can be easily excavated using conventional digging equipments [2].
- *Hardens in less time* The cementitious property of CLSM mixes helps in easy hardening of the mix. Usually CLSM mixes gets hardened within 5 h of placement of fill [2]. Addition of admixtures to the mix will help in faster hardening in situations where it is necessary [44–46]. It was also noticed that the settlement of CLSM mixes after hardening was about 2-3 mm only depending on the mix design adopted [2].
- *Economical* Cost comparison analysis carried out on CLSM mixes has showed that the initial cost of construction is higher than that of other backfill materials. As the maintenance cost involved in CLSM based projects are very less, CLSM is considered as economical in the long run of the project [2, 40].

Limitations of Flowable Fills

The main limitations of flowable fill include

- *Lateral pressure before hardening* High lateral pressure will be exerted at the time of placing the fill behind the retaining walls as the fill is in fluid form. Therefore, the fill material is placed in lifts of suitable thickness. Sufficient time should be allowed for hardening of each lift before placement of next layer.
- *Requirement of confinement before hardening* The presence of large quantity of water in the fill material while pumping will make the material to flow to the nearby areas. Therefore in such situations adequate confinement has to be provided to avoid the movement of fill mix.
- *Difficulty in excavation for high compressive strength mixes* For mixes of compressive strength greater than 8.3 MPa, heavy equipments are required to re-excavate the fill material at later ages. Therefore, in situations where excavation is required at later ages, the mix design has to be properly decided in such a way to obtain compressive strength in the specified range.
- *Anchorage requirement for pipes* In situations where flowable fill mix is used as a base and side support for flexible buried pipes, some anchorage has to be provided at the supports to avoid the floating of pipes.

Pond Ash Based Flowable Fill

Out of the coal ashes, fly ash has commercial value as it is used in the cement industry. However, large volumes of Pond ash are generated and stored in ash Ponds. Utilization of Pond ash is a viable option as a structural fill. In the present investigation, it is attempted to use Pond ash as a flowable fill. The Pond ash was obtained from Ennore

Thermal Power Station, Chennai, Tamil Nadu, India. Basic properties of the Pond ash such as particle size distribution and specific gravity were determined as per ASTM standards. The grain size distribution curve is shown in Fig. 1. The ash predominantly contains sand sized particles with very little fines (<75 micron) content. Modified Proctor compaction test was conducted on the sample so as to obtain the compaction parameters. The compaction curve is shown in Fig. 2. The optimum moisture content (OMC) and maximum dry unit weight along with basic properties are listed in Table 1. Cement of grade 53 was used as the binding material for the production of CLSM mixes.

Plastic properties such as flowability, bleeding and in-service properties such as compressive strength, compressibility, permeability and CBR were determined as per the procedures mentioned in the previous sections as per the relevant ASTM standards. The details of experiments and the results are discussed in the following sections.

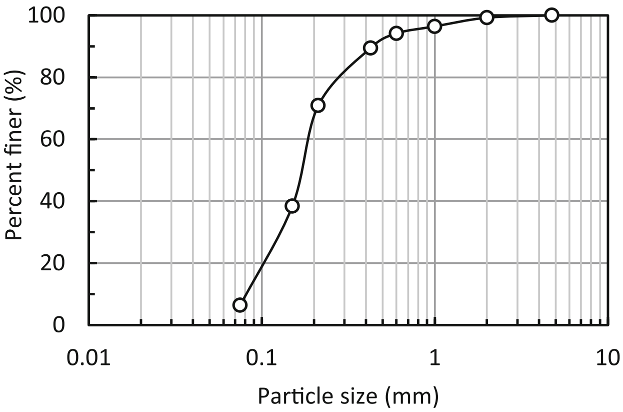

Fig. 1 Particle size distribution curve of Pond ash

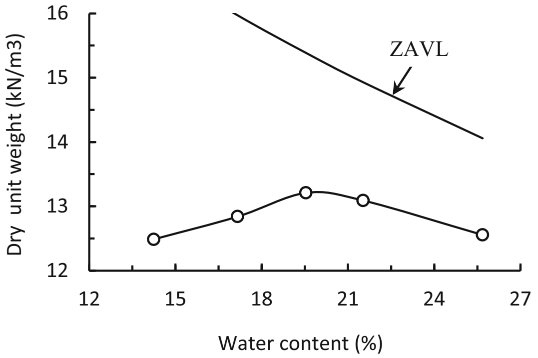

Fig. 2 Modified Proctor compaction curve of Pond ash

Table 1 Index properties of Pond ash

Property	Value
Grain size analysis	
Gravel size (%)	0
Sand size (%)	94
Fines (<75 μm) (%)	6
Classification	SP-SM
Specific gravity	2.21
Modified Proctor compaction test	
Optimum moisture content (%)	19.5
Maximum dry unit weight (kN/m^3)	13.2

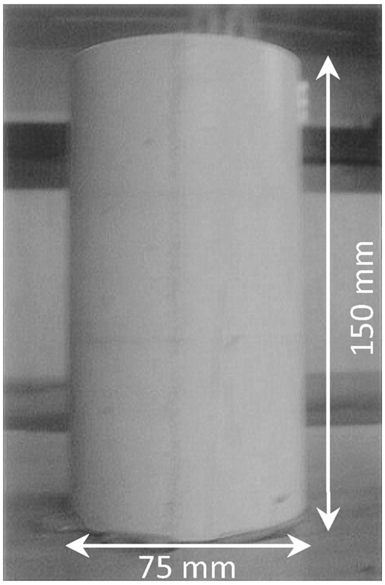

Fig. 3 Flow cylinder

Flowability of Pond Ash Based CLSM

Flowability of the mixes was determined as per ASTM standards. After dry mixing the constituents for about 10–15 min, water was added to the required consistency, and mixing is continued to obtain a mix with no segregation. The mix obtained was poured into a flow cylinder of 75 mm diameter and 150 mm height (Fig. 3) and lifted to a height of 150 mm. The average spread diameter (Fig. 4) of the fill is represented as the flowability of the mix. The water content of the mix was varied to obtain the flowability values between 200 and 300 mm as per ACI 229R-99 [2] guidelines. Both water and cement content used in the mix is represented as percentage of weight of Pond ash in the mix. The variation of flowability with water content for different cement contents is shown in Fig. 5. It can be noticed that the flowability increases with increase in water

Fig. 4 Flowable mix for measuring spread diameter

content in the mix, as is expected. Cement content also affects the flowability. For the same flowability, water required increases as the cement content is increased.

From the flowability test results, the water content corresponding to different cement percentages for flowability values of 200 and 300 mm were obtained. Table 2 shows the water content required for different percentages of cement for obtaining the flowability values of 200 and 300 mm.

Bleeding

The bleeding property of the mix was determined as per ASTM standards. The material was mixed to the required flowability and poured into a 1000 ml graduated jar until the volume was about 800 ± 10 ml. The reading corresponding to the upper surface of the grout and bleed water is noted for every 15 min till a constant reading was obtained for two successive readings. The bleed water was finally collected in a 100 ml measuring jar and the volume of water was noted. The percentage of bleeding is obtained with respect to the initial volume of sample. As per ACI229R-99 [2] the bleeding in a flowable fill mix should be less than 2 %.

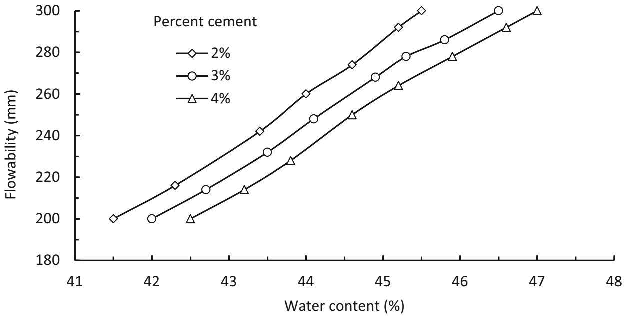

Fig. 5 Flowability variation with water content for different cement contents

Table 2 Values of water content for different flowability

Serial no.	Cement (%)	Flowability (mm)	Water content (%)
1	2	200	41.5
		300	45.5
2	3	200	42
		300	46.5
3	4	200	42.5
		300	47

The bleeding results for different mixes of flowable fills are given in Table 3. For the samples with 3 and 4 % cement contents, the bleeding values are less than 2 % meeting the requirements of ACI 229R-99 [2]. For the 2 % cement content, the bleeding values are higher than 2 %, probably due to low percentage of cement, which is not able to bind the particles. It can also be noted that the bleeding values increases with increase in flowability and the percentage of bleeding was found to be inversely proportional to the cement content in the mix.

Unconfined Compressive Strength

Unconfined compressive strength tests at water contents corresponding to flowability values of 200 and 300 mm were conducted as per ASTM standards. The samples were prepared in stainless steel moulds of 50 mm diameter and 100 mm long. The mix with required flowability was directly poured into the mould without compaction. Care was taken to ensure that no air bubble got entrapped during the process. Prior to pouring, the mould was lubricated with silicon grease so that the samples can be ejected easily. The ends of the moulds were covered with plastic sheets to avoid evaporation loss. The samples were removed from moulds after 24 h and were kept for curing

Table 3 Values of bleeding for different mixes

Cement (%)	Flowability (mm)	Bleeding (%)
2	200	2.2
	300	2.74
3	200	1.85
	300	1.97
4	200	1.25
	300	1.72

till the specified age. Typical photograph of sample ejected out from the mould after 24 h is shown in Fig. 6. Curing of the sample was done after wrapping the sample with cling film (Fig. 7) in a desiccator filled with water. The samples were tested at specified curing periods of 7, 14, 28, 56 and 90 days [47] and the average compressive strength obtained from a minimum of three samples is reported as the compressive strength of the mix. The compressive strength obtained at 28 days is generally reported as the compressive strength of the flowable fills.

Typical stress–strain curves obtained for UCS test at 28 days of curing for different cement contents and flowability values of 200 and 300 mm are shown in Fig. 8. It can be noticed that the failure pattern is brittle in nature with failure strains in the range of 1–2 %. It can also be observed that the strain at failure tends to decrease with increase in the cement percentage showing a more brittle behaviour. The variation of UCS values with curing period for diferent percentage of cement are shown in Fig. 9. It can be noticed that the compressive strength increases with increase in cement content as expected. The compressive strength obtained for 200 mm flowability mixes were higher than that of 300 mm mixes for all the percentage of cement. The increase in compressive strength with curing period was found to be rapid till 28 days of curing. The rate of gain of compressive strength decreases after 28 days. The samples prepared with 1 % cement content did not gain sufficient strength even after 24 h. Therefore the experiment were carried out for 2, 3 and 4 % cement contents for different flowability. As the compressive strength obtained for 4 % cement content samples were greater than 0.7 MPa, other in-service properties of flowable fill mixes were determined only for 2 and 3 % cement content samples for both 200 and 300 mm flowability.

Fig. 6 Ejected sample from mould

Fig. 7 Sample wrapped with cling film

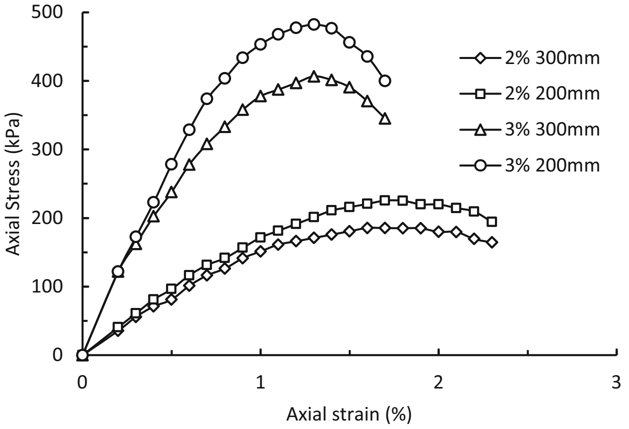

Fig. 8 Typical strain-strain curves for different cement percentages and flowability

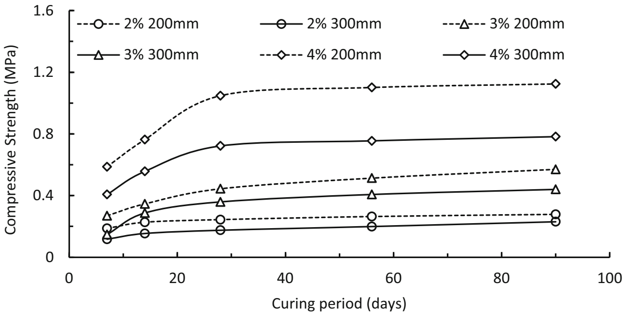

Fig. 9 Compressive strength variation with curing periods for different percentages of cement

Permeability (Hydraulic Conductivity)

The permeability of the flowable fill mixes were determined by conducting the flexible wall permeability test as per ASTM standards. The sample preparation and curing procedures are the same as that for UCS test. The tests were conducted after a curing period of 28 days. Samples of 50 mm diameter and 100 mm height were used. The samples were saturated by applying back pressure to obtain a B-value of at least 0.95. Back pressure values of 300 kPa were necessary to saturate the sample. After saturation, the sample was allowed to consolidate at an effective confining pressure of 100 kPa. Hydraulic gradient of 2 was used for the test which is within the limit of 1–5 specified in ASTM standards.

The results obtained for all the samples are summarised in Table 4 along with the results of compacted Pond ash without treatment. The permeability values are in the range of 10^{-5} cm/s similar to that reported in the literature. Slight decrease in permeability values were noted for samples having higher cement content. It can be noted that the void ratio obtained for compacted Pond ash (CPA) sample is lesser than that of flowable fills because of compaction. But, the permeability values obtained for CPA are comparable with that of flowable fills. This may be due to the cementation bonds in flowable fills which affect the rate of flow. In spite of this variation in permeability, it can be seen that the permeability values obtained for flowable fills are comparable with that of compacted granular fills.

Compressibility

The compressibility of the flowable fill mixes was determined at 28 days of curing as per ASTM procedure-standards. The flowable fill mix was directly prepared in a consolidation ring of 60 mm diameter and 20 mm thick. The sample with the ring was covered with a cling film and kept for curing for 28 days in a desiccator. After curing the sample for 28 days, one-dimensional consolidation test was conducted using a load increment ratio of 1.

The results of one-dimensional consolidation test for all the samples are shown in Figs. 10 and 11. It can be noticed

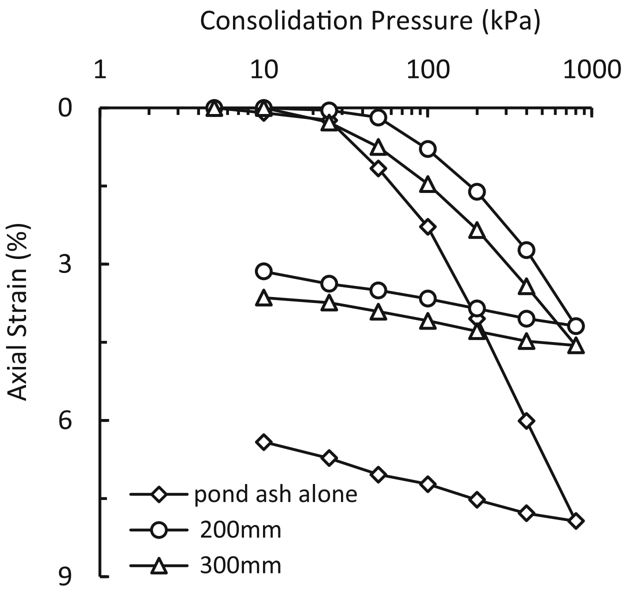

Fig. 10 Compressibility behavior for 2 % cement content samples

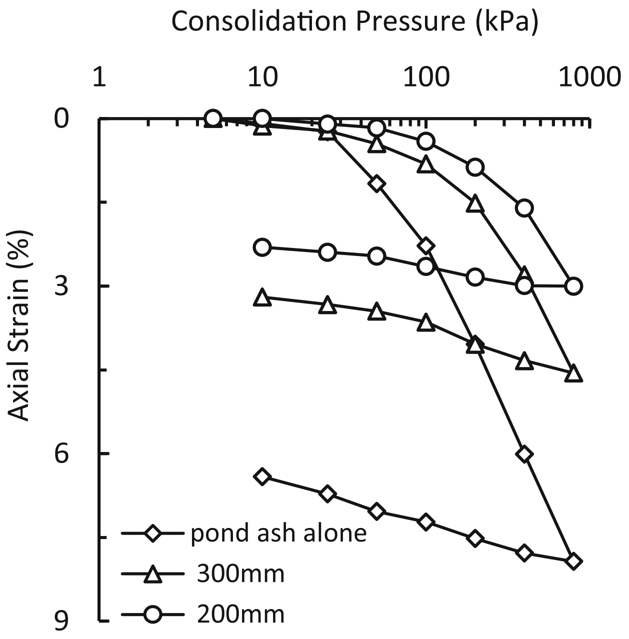

Fig. 11 Compressibility behavior for 3 % cement content samples

Table 4 Permeability values obtained for all samples

Serial no.	Cement (%)	Flowability (mm)	Permeability (cm/s)	γ_d (kN/m^3)	Void ratio (e)
1	2 %	200	6.8×10^{-5}	11.02	0.963
		300	7.5×10^{-5}	10.92	0.986
2	3 %	200	5.4×10^{-5}	11.25	0.933
		300	7.3×10^{-5}	10.98	0.981
3	Compacted Pond ash	–	8.5×10^{-5}	12.69	0.733

Table 5 Yield stress values for all samples

Samples	Yield stress (kPa)
2 % 200 mm	80
2 % 300 mm	60
3 % 200 mm	200
3 % 300 mm	160
Compacted Pond ash	55

that the samples with flowability of 200 mm are less compressible than samples with flowability of 300 mm for the same cement content. It can be also noted that samples with 2 % cement content are more compressible than samples with 3 % cement content. From the consolidation behaviour shown in figures, it can be noticed that the compacted granular fills are more compressible than the flowable fills. The yield stress values were calculated using the log(1 + e) versus log (σ_v') method [48]. The yield stress values obtained for all the samples are shown in Table 5. From the table, it can be noticed that the yield stress values depends on both flowability and cement content. The yield stress values were found to increase with increase in the cement content and a reduction in yield stress values were observed with increase in the flowability values.

California Bearing Ratio (CBR)

The CBR tests for all the samples was done as per ASTM standards. The flowable fill mix was prepared to the required flowability and filled into CBR moulds of 150 mm diameter and 178 mm height. The samples were kept for curing for a period of 28 days. Experiments were conducted on both soaked and unsoaked conditions. The unsoaked specimens were tested on the 28th day. Samples prepared for soaked CBR tests were kept in water for 96 h after 28 days of curing and the experiments were conducted after 96 h. For comparison purposes, compacted Pond ash (CPA) samples were also prepared at OMC and maximum dry unit weight for both soaked and unsoaked conditions. CBR is expressed as the ratio of unit load on the piston to penetrate 2.5 and 5 mm of the test soil to the load required to penetrate a standard material as specified in the ASTM standards.

The CBR test results for both 2 and 3 % cement content samples are shown in Figs. 12 and 13. Table 6 gives the CBR values obtained for all the samples. As expected the CBR values increases with increase in cement content and lower flowability. The values are comparable with that of results reported in the literature [34]. The CBR values obtained for CPA samples are found to be comparatively lesser than that of flowable fill materials. It is also noted that soaking substantially reduces the CBR values of untreated compacted Pond ash. However, the effect of soaking is not very significant for the flowable fills. Therefore, Pond ash based flowable fills can be used for pavement applications also.

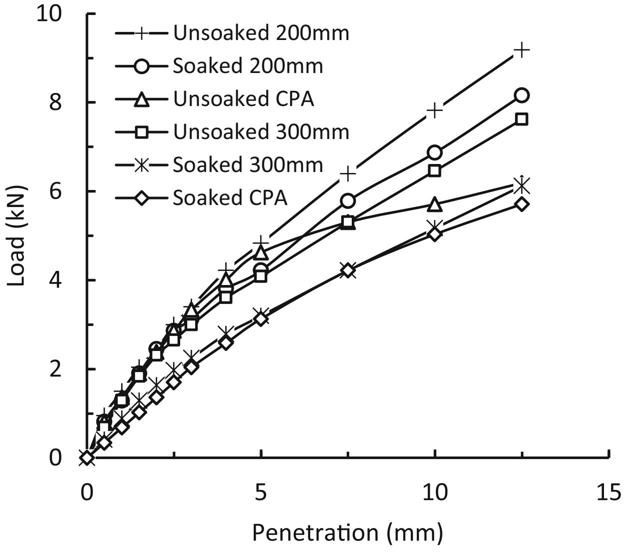

Fig. 12 Load–penetration curves for 2 % cement content samples

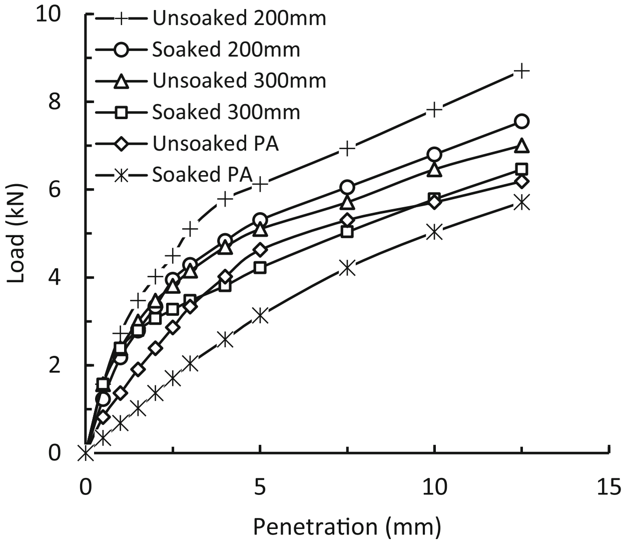

Fig. 13 Load–penetration curves for 3 % cement content samples

Conclusions

A detailed review of literature about different materials used in the controlled low strength flowable fill, their properties and applications are presented in this paper.

Table 6 Summary of CBR values of samples

Serial no.	Cement (%)	Flowability (mm)	CBR (%)	
			Soaked	Unsoaked
1	2 %	200	21	22
		300	14	19
2	3 %	200	29	33
		300	24	28
3	Compacted Pond ash	–	12	21

From the literatures review, it is brought out that different industrial byproducts can be utilized as components in flowable fill production. The type of fine and coarse aggregates used in flowable fill was found to have immense effect on both plastic and in-service properties.

Further, suitability of a Pond ash obtained from Ennore Thermal Power plant, Chennai, India, as flowable fill was investigated. Experiments were carried out for three different percentages of cement and for two different flowability values. The main outcomes of the study are as follows.

- Both cement and water content used in the mix affect the properties of flowable fill materials. The water content was found to vary from 41.5 to 47 % for cement percentages of 2–4 for obtaining flowability values of 200 and 300 mm, respectively.
- Plastic properties like flowability and bleeding were found to increase with increase in the water content in the mix. In-service properties like unconfined compressive strength and CBR were also found to get reduced with increase in flowability values.
- The compacted Pond ash fill material was found to be more compressible than the flowable fills.The flowable fill mixes with a flowability value of 300 mm was found to be more compressible than the flowable fills of flowability 200 mm.
- The permeability of flowable fills was found to be in the range of 10^{-5} cm/s. The permeability values obtained are comparable with that of compacted Pond ash. The permeability values obtained for higher flowability mixes were slightly higher than that of lower flowability value mixes.
- It was also observed that a maximum of three percent of cement was required to achieve the flowability and UCS requirements for a regular excavatable flowable fill for the considered Pond ash. Addition of chemical admixtures was not required for obtaining the required properties for the fills. Thus the Pond ash and cement together can be used effectively for CLSM production thereby reducing the waste disposal and environmental pollution.

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