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Performance appraisal of industrial waste incineration bottom ash as controlled low-strength material

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ABSTRACT

Controlled low-strength material (CLSM) is slurry made by mixing sand, cement, ash, and water. It is primarily used as a replacement for soil and structural fillings. This paper presents the findings of a preliminary investigation carried out on the performance of industrial waste incineration bottom ash as CLSM. CLSM mixes were designed using industrial waste incineration bottom ash, and cement. Tests for density, setting time, bleed, and compressive strength on cubes under various curing conditions, corrosivity, and leaching of heavy metals and salts were carried out on the CLSM mixtures, and the results discussed. Compressive strength for the designed CLSM mixtures ranged from 0.1 to 1.7 MPa. It is shown that the variations in curing conditions have less influence on the compressive strength of CLSM at high values of water to cement ratio (w/c), but low values of w/c influences the strength of CLSM. The CLSM produced does not exhibit corrosive characters as evidenced by pH. Leaching of heavy metals and salts is higher in bleed than in leachate collected from hardened CLSM. Cement reduces the leaching of Boron in bleed. It is concluded that there is good potential for the use of industrial waste incineration bottom ash in CLSM.

1. Introduction

Developing countries are witnessing tremendous growth in the production and manufacturing sectors. This leads to the accumulation and accelerating the output of industrial wastes. These wastes must be properly managed and disposed without causing any harmful environmental effects. Hence, civil engineers are left with the challenge of managing the industrial wastes. Research works are being undertaken to look into the aspect of managing, treatment, reuse, and disposal of these wastes. The scheduled industrial waste generation in Malaysia in the year 2007 is 1,138,839 metric tonnes according to the Malaysia Environmental Quality Report 2007, Department of Environment, Malaysia. Around 120,000 metric tonnes of industrial wastes are treated by Kualiti Alam Sdn Bhd, Malaysia. Wastes with a Total Organic Carbon more than 10% are sent to incineration which produces around 14,000 metric tonnes of bottom ash. The bottom ash is sent to secured landfills. But disposal by land filling is not a sustainable solution.

Hence various methods of using the bottom ash and fly ash need to be developed. Incineration byproducts, if reused, will offer many advantages viz., ensures sustainability, reduces pollution and environmental degradation, generates revenue, and preservation of natural resources, etc.

One of the ways of using the incineration byproducts is to use them as controlled low-strength material (CLSM).

CLSM, in its simplest form, is a slurry made by mixing sand, cement, ash, and water. It is self compacting, flowable, and used primarily as replacement for soil and structural fillings. American Concrete Institute ACI committee 229 [1] defines CLSM as a material having a compressive strength of 8.3 MPa or less. The CLSM is flowable, self compacting, and offers many advantages compared to conventional soil fills. Some advantages of CLSM over conventional back fills are easy placement with no vibration, less onsite labor requirements, ease of placing in intricate locations, no settlement problems, strong, durable, and flexibility to incorporate any locally available non-conventional materials. Waste materials like flue gas desulfurization material, foundry sand, wood fly ash, dry scrubber ash, glass cullets [2] are successfully tried in CLSM. However the reuse of industrial waste incineration bottom ash as CLSM has not been done yet. This is because of the worry of leaching of hazardous materials from the bottom ash and consequently refraining the researchers from thinking about the potentials of reusing the bottom ash. This paper aims to bring about a paradigm shift in the civil engineering fraternity to start investigating ways and means of reusing the industrial waste incineration bottom ash which are otherwise not utilized.

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Table 1
Chemical composition of cement and bottom ash.

Material	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	TiO_2	P_2O_5	MnO	LOI
Cement	65.20	21.27	6.19	3.64	0.88		0.71	0.19	0.22	0.09	0.08	1.53
Bottom ash	4.14	43.85	8.37	11.91	0.79	0.57	0.71	2.73	2.71	1.73	0.12	22.10

This paper presents the findings of a preliminary experimental investigation carried out on CLSM mixtures made using the industrial waste incineration bottom ash. CLSM mixes were made with the bottom ash, cement, and water. Various tests were conducted on the CLSM mixes in fresh and hardened states. The CLSM mixes were also tested for corrosivity and concentration of heavy metals and salts. The behaviour of CLSM under various curing environments with regard to strength has been discussed. The results from this investigation can be used on other industrial waste incineration bottom ash and the behaviour of CLSM incorporating such incineration bottom ash can be established.

2. Experimental methods

2.1. Materials

Ordinary Portland cement confirming to Malaysian Standard 522 part 1-2003 was used in this investigation. Bottom ash was obtained from the industrial waste incineration plant operated by Kualiti Alam Sdn Bhd, Malaysia. The bottom ash contains particles of various sizes from fine powder to 60 mm. This was first dried in an oven at 105 °C until constant mass, and then sieved through a 10 mm size sieve to eliminate particles larger than 10 mm size. This is because more than 95% of the particles of the bottom ash is less than 10 mm size, and, using <10 mm size particles will enable the CLSM to more flowable and hence the need of using admixtures in order to make it flowable may be eliminated. The chemical compositions of cement and bottom ash are shown in Table 1. The grading curve for bottom ash is shown in Fig. 1. The fineness modulus of bottom ash was 3.06, specific gravity 1.84, uncompacted bulk density 911 kg/m^3, and the compacted bulk density 964 kg/m^3. The percentage of particles of bottom ash finer than 75 μm was 12%. As per BS 882 [3], the grading of slag falls in the range of coarse and medium fine aggregate. Potable water is used in the investigation.

2.2. Mix proportions, and sample preparation

The mix formulations used in the investigation are shown in Table 2. The bottom ash, and cement were first placed in a tilting type mixer, and dry mixed for one minute. Sufficient quantity of water was then added and the contents mixed for two minutes.

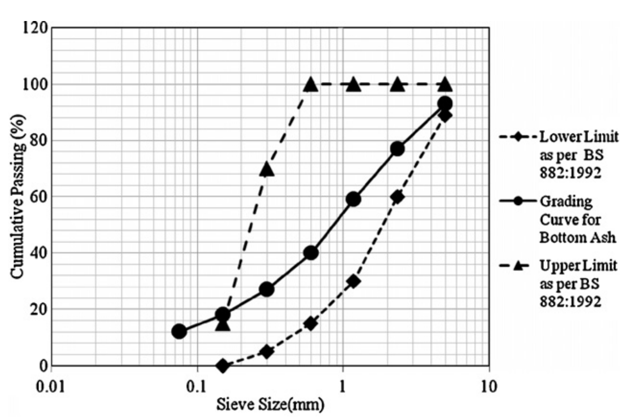

Fig. 1. Grading curve for bottom ash.

The sample was then tested for flow consistency as per ASTM D 6103 [4]. If the flow was less than 200 mm, more water was added to get the flow more than 200 mm. The contents were then mixed for another 2 min. Resulting mix was then taken for further testing in fresh state, also filled in three numbers of 50 mm 5 gang cube moulds. The cubes were kept covered with wet burlap over night, and then transferred to various curing environments in order to understand the behaviour of bottom ash with regard to compressive strength under these conditions. Any odd behaviour of bottom ash can be predicted from the results and the findings can be useful in the future course of investigation.

The curing environments in which the CLSM cubes were kept are as below:

a) NCDODT—Normal curing in plastic containers, demoulded on the day of test. Moulds were kept over water surface in closed plastic storage boxes. The boxes were kept in an air conditioned room. The temperature was 22 °C and the relative humidity within the box was more than 95%.
b) NCOE—Normal curing in plastic containers, demoulded 2–3 weeks earlier. The cubes were demoulded on seventh day and were kept in the same curing environment as in 1 above.
c) DC—Dry curing. The moulds were wrapped in plastic bags, and kept in a dry place in the laboratory environment. The demoulding was done on the day of testing.
d) DWC—Deionized water curing. Cubes were kept as in 1 above for first one week. The cubes were then demoulded and immersed in deionized water and kept in air conditioned room at 22 °C until the day of testing.

2.3. Tests

Tests for compressive strength, stiffening time, fresh and hardened densities, bleeding, corrosivity, and leaching of heavy metals and salts were carried on the CLSM mixtures in this investigation.

The compressive strength of CLSM was measured at 7, 14, and 28 days. The size of the cubes was 50 mm which is five times the maximum size of the coarse material used. Universal testing machine of 100 kN capacity was used for the testing. The loading rate was kept low at 0.6 mm/min. The slow loading rate enables the test to be more accurate as it is a low-strength material. It took 4–8 min for failure of each specimen. Five cubes were tested on each day and average values reported.

Setting time test was done as per BS EN 13294 [5] on mortar sieved from the fresh CLSM using a 5 mm sieve. The containers were then closed with a lid, and kept covered with wet burlap in the air conditioned room at 21 °C at a relative humidity of around 60% for the entire duration of testing. The penetration load was measured by a deflectometer with an accuracy of 0.002 mm which is attached

Table 2
Mix formulations.

Mix Id	Bulk proportion (kg/m^3)				w/c	c/BA	Flow (mm)
	Cement	Bottom ash	Water	Total			
SM-2	20	986	522	1528	26.5	0.02	330
SM-5	48	968	514	1530	10.7	0.05	250
SM-8	77	962	512	1551	6.6	0.08	360
SM-10	97	970	493	1560	5.1	0.10	310

to a calibrated proving ring that is attached to the penetrometer. First reading was taken at two hours from the addition of water to CLSM mixtures. Subsequent readings were taken at 30 min intervals until the initial setting is reached. Duplicate readings were taken for each observation. The initial setting time is the time to get a penetration resistance of 0.5 MPa starting from the time of water addition.

The density of CLSM at fresh state was measured by filling a 1.5 L copper container with CLSM and measuring the weight using a scale accurate to 5 g. The copper container was pre calibrated for its volume. Average of two observations was taken for the fresh density. Hardened density of CLSM was measured by measuring the weight of each 50 mm cubes before testing for compressive strength. Average of 5 values was taken for the hardened density.

Test for bleeding of CLSM was done by filling about 800 mL of fresh CLSM in 1000 mL measuring jar. The jar was closed and kept in air conditioned room at 21 °C. After the CLSM was stabilized, the volume of CLSM, and the bleed that was accumulated above the CLSM were then recorded. The bleed is then expressed as a percentage of the initial volume of CLSM.

Corrosivity is a means to identify materials that are potentially a hazard to human health or the environment due to their ability to mobilize toxic metals if discharged into the environment, to corrode handling, storage, transportation, and management equipment, or to destroy human or animal tissue in the event of inadvertent contact. Corrosion can occur when water or leachate water reacts with metal parts. A solid waste exhibits corrosivity if a representative sample of the waste has the property that is aqueous and has a pH less or equal to 2 or greater than or equal to 12.5 [6]. However, this range is not applicable to the corrosion or passivity of all materials. For example, higher pH values provide passivity to exposed steel but may corrode glassy material. The corrosivity of CLSM was measured as pH of bleed and leachate collected from the CLSM. Bleed water collected from the bleed test was used. The leachate was collected by placing three numbers of 50 mm cubes in three liters of deionized water on day 7 in a plastic container (L/S = 8). The container was kept closed in air conditioned room at 21 °C. Cubes were removed from the container on 28th day, and the water in the container was used as leachate.

The toxicity of the CLSM was studied by measuring the concentration of heavy metals and salts in the bleed water and in the leachate. Samples that were used in pH tests were used in this study. Inductively coupled plasma optical emission spectrometer was used for these tests except mercury for which an atomic absorption spectrometer was used.

3. Results and discussion

3.1. Fresh properties

3.1.1. Setting time

The initial setting time for the CLSM mixes tested are given in Table 3. The initial setting time for the mixes tested was found to be in the range of 4.5 and 26.1 h. The general range of hardening time of CLSM mixtures as given in the ACI committee 229 [1] is 3–5 h for supporting the weight of a person which is at a penetration resistance of 344 kPa (50 psi) [6]. The initial setting time and w/c ratio are plotted as shown in Fig. 2. Initial setting time is linearly related to w/c ratio as indicated in Fig. 2. There is a sudden increase in the initial setting time when w/c ratio reaches 10.6 as shown in Fig. 2. This is because the excess water added fluidize the CLSM and hence delays the initial set. This aspect is also reflected in Fig. 3 which gives the relationship between initial setting time and bleed. Setting time is more for CLSM with more bleed which has more w/c values. The presence of accumulated bleed water at the surface of the mortar increases the setting time.

Table 3
Bleed, flow, initial set, and pH.

Mix Id	Bleed capacity ($\times10^{-3}$ L/mL)	FLOW (mm)	Initial setting time (h)	pH	
				Bleed	Leachate
SM-2	72	330	26.8	11.5	8.0
SM-5	56	250	6	11.7	10.9
SM-8	51	360	4.8	11.9	11.2
SM-10	12	310	4.5	12.0	11.3

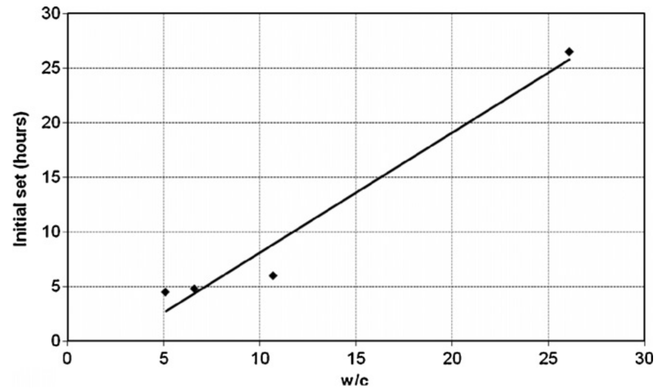

Fig. 2. Relationship between initial setting time and w/c.

3.1.2. Bleeding

The excess water added to maintain the required flowability of CLSM comes out as bleed. The bleed percentage recorded varies from 1.2 to 7.2. Tikalsky [6] reported a value of 0–8.73% in CLSM made using excess foundry sands. Hence the bleed recorded in this investigation is normal. The bleed is also expressed as bleed capacity in liters/mL of CLSM (L/mL). Bleed capacity is the fraction of initial volume of CLSM that has separated out as bleed water during the entire course of the test. The values of bleed capacity are shown in Table 3. CLSM is considered stable of the sedimentation of solids, which is in turn called as bleed, is less than 5% at 2 h [7]. The bleed capacity is influenced by w/c and c/BA ratios as evidenced in Figs. 4 and 5. Bleed capacity increases with w/c, and decreases with c/BA. This is because adding water more than that is needed for hydration is given out as bleed. Adding increased quantities of cement reduces bleeding due to the absorption of excess water by cement particles.

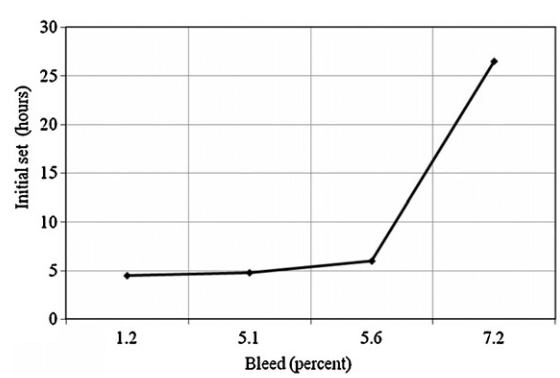

Fig. 3. Initial setting time and bleed.

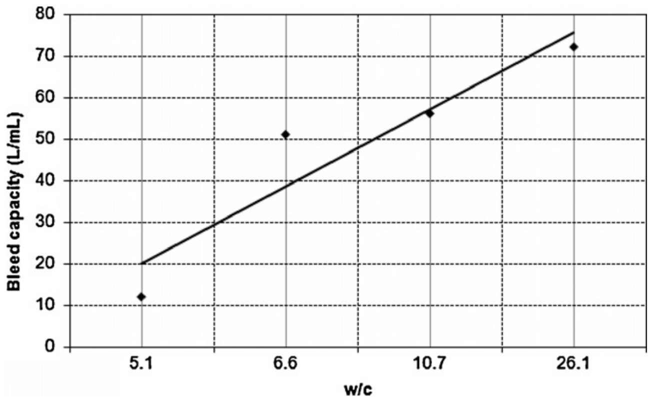

Fig. 4. Bleed capacity and w/c.

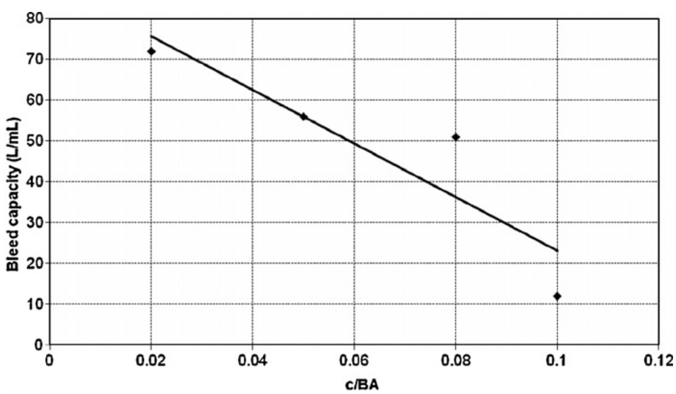

Fig. 5. Bleed capacity and c/BA.

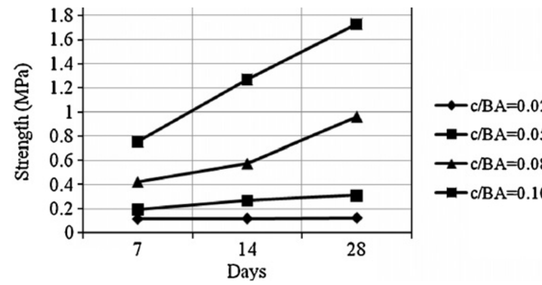

Fig. 6. Compressive strength development under NCDODT curing.

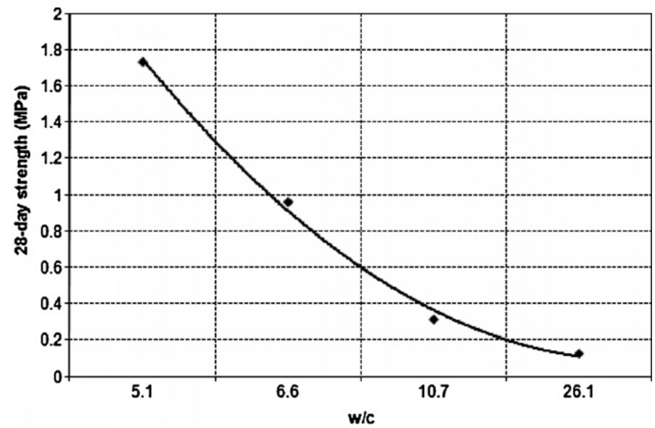

Fig. 7. Strength and w/c ratio.

3.2. Hardened properties

3.2.1. Compressive strength

The compressive strength of CLSM mixes cured under various conditions was measured at 7, 14, and 28 days as shown in Table 4. The strength at 28 days varies from 0.125 to 1.731 MPa. Strength of 0.3–0.7 MPa equates to the allowable bearing capacity of a well-compacted soil [1]. Hence the CLSM mixes developed in the investigation are a suitable replacement for compacted soil and structural filling applications. The compressive strength development of various mixes cured under NCDODT is shown in Fig. 6. Mix with c/BA of 0.1 produces more strength, and mix with c/BA of 0.02 gives less strength. Relation between strength at 28 days for NCDODT curing and w/c ratio is shown in Fig. 7. Strength increases with age and decreases with increase in w/c. The 28 days strength is plotted against w/c ratio for various conditions of curing in Fig. 8. It is observed that deionized water curing (DWC) gives lowest strength. This may be due to the lower rate of hydration in the presence of deionized water. Dry curing in laboratory conditions (DC) gives more strength for higher w/c values. This is because of the formation of further bonds in the cement paste fraction when it is dried and strength increases rapidly [8]. Curing in a curing condition at a relative humidity of more than 95% and at 22 °C gives more strength at low w/c ratio and gives strength between DC and DWC values at higher w/c ratio values. The standard deviation of strength values at w/c ratio of 5.1 is 0.35 whereas the same at a w/c ratio of 10.7 is 0.07. Hence, the variations in curing conditions have less influence on the strength at high w/c ratios whereas it does influence the strength at low values of w/c ratio. The behaviour of bottom ash is not abnormal with regard to strength in various curing conditions. Hence, further investigations can proceed with the standard curing conditions as specified in the various standards. The standard curing condition given in ASTM D 4832 will be followed in further testing on CLSM using the industrial waste incineration bottom ash.

The density values of CLSM mixes are given in Table 5.The hardened density for the CLSM mixes tested range from 1474 to 1584 kg/m^3. This is comparable to that of sand and sandy loam soils whose bulk density values range from 1200 to 1800 kg/m^3 [9]. Hence the CLSM mixes designed in this investigation can be used as excavatable soil filling material.

Table 4
Compressive strength results (MPa).

Mix	7D (NCDODT)	14D (NCDODT)	28 Days			
			(NCDODT)	(NCOE)	(DC)	(DWC)
SM2	0.117	0.120	0.125	-	-	-
SM5	0.195	0.269	0.313	0.256	0.383	0.227
SM8	0.422	0.579	0.960	0.691	1.024	0.587
SM10	0.753	1.269	1.731	1.545	1.430	0.909

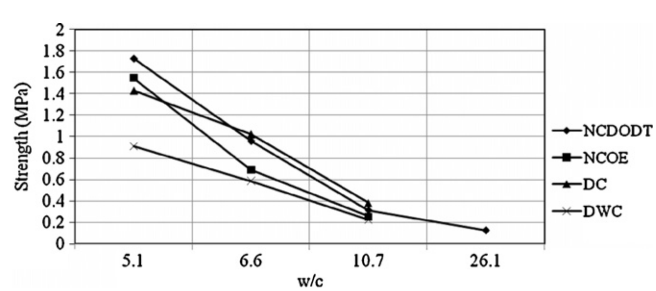

Fig. 8. Strength and w/c ratio for various curing conditions.

Table 5
Density development.

Mix ID	Fresh density (kg/m^3)	Hardened density (NCDODT)(kg/m^3)		
		7 Days	14 Days	28 Days
SM-2	1528	1584	1487	1487
SM-5	1536	1511	1500	1516
SM-8	1551	1482	1490	1533
SM-10	1560	1474	1520	1512

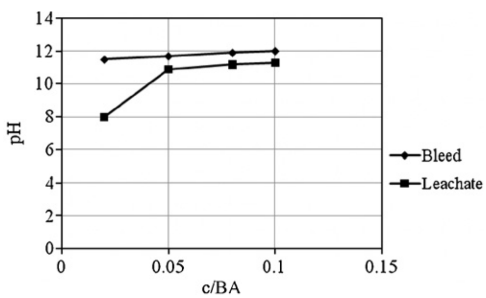

Fig. 9. Relationship between pH and c/BA.

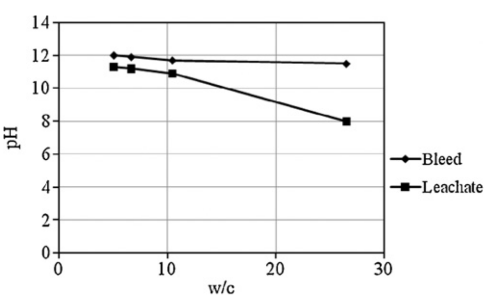

Fig. 10. pH and w/c.

3.3. Corrosivity

The pH of bleed and leachate samples collected from the CLSM mixtures are given in Table 3. The pH varies from 8 to 12. This range is neither less than 2.5 nor more than 12.5. Hence the CLSM does not possess corrosivity from the aspect of pH. The pH of bleed is higher than that of leachate for all the mixes. The pH of bleed is related to c/BA ratio as shown in Fig. 9. Similar relation is obtained

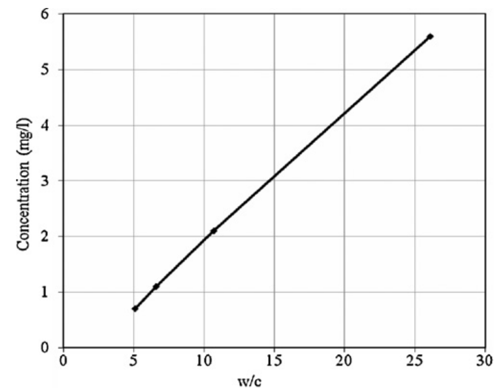

Fig. 11. Boron concentration in bleed and w/c.

for pH and w/c as shown in Fig. 10. Based on the relationships, it is concluded that pH of bleed is influenced by c/BA ratio.

3.4. Leaching

The bleed and leachate samples were analyzed for ten heavy metals and salts. The results are given in Table 6. The limits given in Table 6 are based on leaching test recommended acceptance criteria for suitability of industrial wastes for landfill disposal [10]. All the metals tested are well within the limits in leachate. Hence, the hardened CLSM samples are classified as non-hazardous. Concentration of elements in bleed water is much higher than that of the leachate. The concentration of metals follows the following ascending order for all the CLSM mixes tested: Cadmium, Boron, Chromium, Nickel, Tin, Copper, Barium, and Zinc. The trend for the concentration of heavy metals is different for each metal. The concentrations of Boron in bleed are plotted against w/c and c/BA ratios in Figs. 11 and 12. Boron concentration is linearly related to w/c ratio, and inversely related to c/BA ratio. Based on the test data, it is concluded that addition of cement is able to control the leaching of Boron in the bleed.

The total metal salts are the sum of calcium, iron, magnesium, potassium, and sodium. The maximum concentration of total metals salts observed in bleed is 7027 mg/L. Concentration in leachate is in the range of 272–485 mg/L. These concentrations do not pose any health risk except that the water will be unpalatable. Total dissolved solids concentration above 1000 mg/L will usually yield poor tasting water. Levels above 2000 mg/L are considered undrinkable due to taste, and levels more than 10,000 mg/L are defined as undrinkable

Table 6
Results of leachable substances in bleed and leachate.

Parameter	Bleed (mg/L)				Leachate (mg/L)				Limits
	SM2	SM5	SM8	SM10	SM2	SM5	SM8	SM10	
Arsenic	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	0.3	5
Barium	19.1	55.7	18.8	33.9	0.5	0.6	0.6	1.1	100
Boron	5.6	2.1	1.1	0.7	<0.7	<0.7	<0.70	<0.70	
Cadmium	0.02	0.06	0.02	0.03	0.01	0.02	0.01	0.01	1
Copper	17.9	48.4	15.6	31.6	0.38	0.34	0.2	0.22	100
Mercury	<0.01	<0.01	0.01	0.016	<0.10	0.13	<0.01	<0.01	0.2
Nickel	7.09	17.4	5.57	12.7	0.09	<0.01	<0.03	0.02	5
Tin	13	30.1	9.65	22.2	<0.07	<0.07	<0.07	<0.07	
Chromium	1.62	3.63	1.39	2.64	<0.01	<0.01	<0.01	<0.01	5
Zinc	34.2	79.1	29.9	60.8	1.7	0.28	0.54	0.31	100
Calcium	1950	3950	3720	3980	1240	249	127	314	
Iron	434	670	436	826	5.96	1.19	0.9	0.73	100
Magnesium	9.37	32.3	11.6	27	0.47	0.21	0.1	0.17	
Manganese	12.7	34.1	10.3	21.2	0.19	0.01	0.01	0.02	50
Potassium	482	530	582	754	42.3	30.4	64.5	78.5	
Sodium	1430	1320	1360	1440	977	73.9	79.3	91.9	
Total salts	4305	6502	6110	7027	2266	355	272	485	

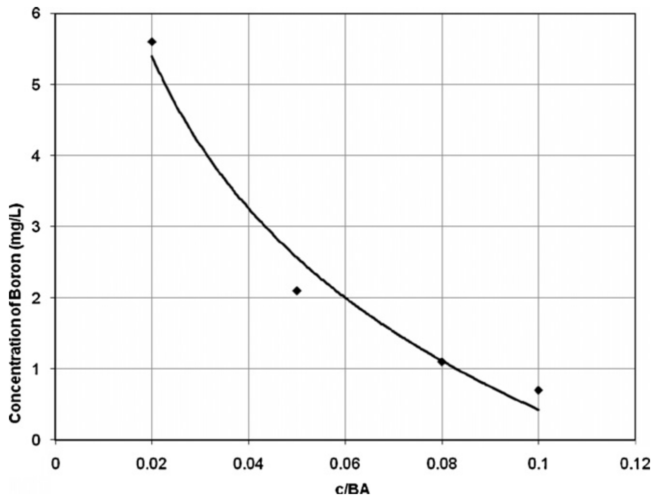

Fig. 12. Boron concentration in bleed and c/BA ratio.

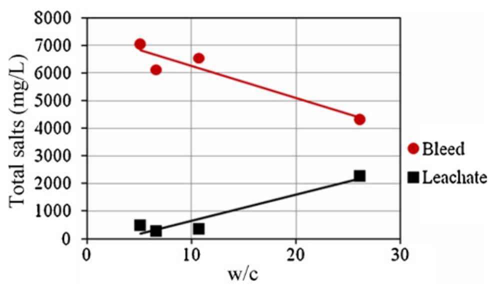

Fig. 13. Relationship between total salts and w/c ratio in bleed and leachate.

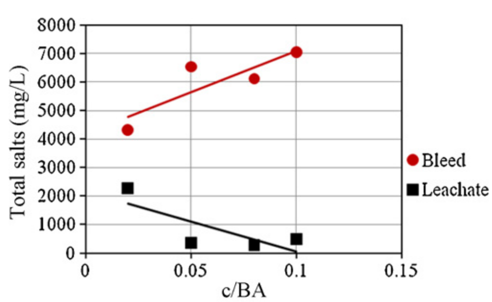

Fig. 14. Relationship between total salts and c/BA ratio in bleed and leachate.

[11]. But the leachate has very less values and if they are discharged into ground water, there will not be any harm. Bleed water, if discharged into ground water will eventually get diluted. Assuming a dilution factor of 100, the bleed water also will be harm less. The concentration of total salts in bleed and leachate are plotted against w/c and c/BA ratios in Figs. 13 and 14. Concentration of total salts in bleed is less when w/c ratio is more as shown in Fig. 13. Also the concentration is more when c/BA ratio is increased. These trends are reversed for the concentration values observed for leachate. Hence it is concluded that the leaching mechanism of total salts is different for bleed and leachate. However, detailed investigations will be done to establish the actual leaching mechanism.

4. Conclusions

The fresh density values of CLSM mixes studies are in the range of 1528–1560 kg/m^3. Fresh density can be linearly related to c/BA ratio. The density of CLSM mixes designed is comparable to that of sand and sandy loam soils. Hence the designed CLSM mixes can be used as soil filling material.

The strength of CLSM mixes tested is in the range of 0.125–1.731 MPa. For the CLSM to be excavatable, the strength should be less than 1.7 MPa. Hence the designed mixes in this study are suitable for use as excavatable CLSM. Water to cement ratio influences the compressive strength. Variations in curing conditions have less influence on the compressive strength of CLSM at high values of w/c whereas it does influence the strength at low values of w/c ratio.

Initial setting time is in the range of 4.5–26.1 h. The set time is influenced by bleed and w/c. Also, w/c and c/BA have influence on the bleed capacity of CLSM. More water and less cement addition gives more bleeding.

The CLSM produced does not have corrosivity as evidenced by pH tests on bleed and leachate samples. All the heavy metals tested on the leachate samples are well within the limiting values. Values of heavy metals and salts for bleed are more than that for leachate. Addition of cement reduces the leaching out of Boron in bleed. Concentration of total salts in the bleed is higher for higher values of w/c, and lower for higher values of c/BA.

Based on the investigations done so far, it can be concluded that the industrial waste incineration bottom ash can be successfully used in CLSM. Further detailed investigations need to be done in order to fully reap the benefit of using the industrial waste incineration bottom ash in CLSM.

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References

[1] ACI committee 229R, Controlled Low-strength Materials, American Concrete Institute, Farmington Hills, MI, USA, 1999, p. 2.
[2] Jenny L. Hitch, Amster K. Howard, Warren P. Baas, Innovations in controlled low-strength material (flowable fill), ASTM STP 1459, 2002, p. 3, 15, 31, 41, 51.
[3] BS 882: 1992, Specification for aggregates from natural sources for concrete, British standards institution, 1992, Table 4, p. 5.
[4] ASTM D 6103-00, Standard test method for flow consistency of controlled low-strength material (CLSM), American society for testing and materials, PA, USA, 2000.
[5] BS EN 13294: 2002, Products and systems for the production and repair of concrete structures- Test methods- Determination of stiffening time, British standards institution, 2002.
[6] P.J. Tikalsky, H.U. Bahia, A. Deng, T. Snyder, Excess foundry sand characterization and experimental investigation in controlled low-strength material and hot-mixing asphalt, Final report, U.S. department of energy, Contract No. DE-FC36-01ID13794, October 2004, p. 202.
[7] M.A. Gabr, John J. Bowders, Controlled low-strength material using fly ash and AMD sludge, Journal of Hazardous Materials 76 (2000) 251–263.
[8] G.D. Taylor, Materials in Construction—Principles, Practice and Performance, second ed., Longman, UK, 2002, p. 263.
[9] Kim Howard Tan, Soil Sampling, Preparation, and Analysis, second ed., CRC press, 2005, p. 182.
[10] Leaching test- recommended acceptance criteria for suitability of industrial wastes for landfill disposal, National Environmental Agency, Singapore, downloaded from the url: www.nea.gov.sg/cms/pcd/leachtest.pdf, accessed in March 2008.
[11] http://www.wellowner.org/awaterquality/basics.shtml#totaldissolvedsolids. Accessed in February 2008.