Performance Assessment of Cementless Controlled Low-Strength Material (CLSM) Utilizing Coal Ashes

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ABSTRACT

CLSM is a self-compacting flowable fill which is primarily used as backfill material in lieu of conventional compacted soil. This paper reports the results of an investigation conducted on CLSM made without cement. Various CLSM mixtures were developed using coal bottom ash, fly ash and lime. The cementitious property of CLSM was achieved by adding sodium hydroxide into the mixture. The mixtures were inspected for a series of tests in fresh state and hardened state. All the mixtures exhibited acceptable flowability and segregation resistance. The CLSM mixtures showed non-corrosive behavior with good durability characteristics. Compressive strength of all the CLSM specimens ranged from 1.1 to 3.35 MPa. It is concluded that the increment of lime and NaOH leads to an increase in the strength of cementless CLSM.

KEYWORDS: CLSM, Fly ash, Bottom ash, Strength, Sodium hydroxide, Bleeding.

INTRODUCTION

ACI describes CLSM as materials having compressive strength of less than 8.3 MPa at 28 days (ACI 229R-99, 1999). There are other terminologies associated with CLSM, such as controlled density fill, unshrinkable fill, flowable mortar, flow-crete, flowable fill, liquid dirt and fly ash flow. Cement, sand, fly ash and water are typical ingredients of flowable fill. CLSM can be placed without the need for vibrating or tamping due to its self-leveling capability. When removability of CLSM in future is taken into account, the late-age strength can be 2.1 MPa for mechanical excavation and 0.5 MPa for hand excavation.

According to the Department of Environment in Malaysia, roughly 1,138,839 metric tons of industrial wastes were generated in 2007 (Razak et al., 2010). Most of industrial wastes are landfilled which is not a sustainable solution. Bottom ash and fly ash are examples of by-products of power plants in coal combustion process. Bottom ash, fly ash and other industrial wastes have potential possibility to be used in CLSM production. By incorporating wastes and eliminating cement in CLSM production, it is possible to reduce the demand to landfill, lessen CO_2 emission, preserve natural resources and hence, contribute to sustainable development.

In this investigation, sodium hydroxide (NaOH) is used as a cementitious material which replaces cement and acts as an activator for pozzolanic reaction. One of the potential chemicals that can be used with sodium hydroxide is calcium oxide (CaO) or quicklime. Combination of these two substances will contribute to the strength development of cementless CLSM.

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MATERIALS AND METHODS

Fly ash class F, bottom ash, lime, NaOH and tap water were used in this investigation. Fly ash and bottom ash were obtained from Kapar Thermal Power Plant, Kapar, Selangor, Malaysia. Concentration of silica and aluminum contents of fly ash was 48.76% and 17.17%, respectively. Amount of aluminosilicate concentration of fly ash was good enough to react with alkali reagent. Fine fly ash particles were used directly without any sieving, whereas the bottom ash was sieved using 10 mm sieve prior to use. Since the bottom ash had some moisture, the bottom ash was exposed to laboratory environment for the entire project. As an alternative, the drying process could be carried out by oven-drying for one day. Sodium hydroxide with 99% purity in pellet form was obtained from Mey Chern Chemicals Sdn. Bhd., Malaysia.

Mixture Proportions and Casting

The mixture proportions used in this investigation are given in Table 1. The proportions were selected based on preliminary trial mixtures which gave satisfactory flowability. For each mixture, the water content was added to get a flowability of more than 220 mm.

Table 1. Mix proportion of CLSM (kg/m^3)

Mixture ID	Water/ binder	FA/ binder	BA/ binder	Lime/ binder	NaOH/ binder	Water	Bulk proportions			
							FA	BA	Lime	NaOH
A3/B1.5/F70 (M1)	0.98	0.7	1.5	0.286	0.0299	389.6	281.1	562.3	112.6	11.8
A4/B1.5/F70 (M2)	0.81	0.7	1.5	0.287	0.0447	394	347.7	695.3	139.2	21.8
A6/B1.5/F70 (M3)	0.72	0.7	1.5	0.285	0.060	336.7	334.1	668.3	133.8	28.1
A8/B1.5/F70 (M4)	0.77	0.7	1.5	0.31	0.081	340.5	337.8	675.8	135.4	35.5
A3/B0.5/F100 (M5)	0.47	1	0.50	0.099	0.0298	350.6	743.3	371.6	74.3	22.2
A4/B0.5/F100 (M6)	0.53	1	0.50	0.099	0.0449	379.7	715.6	357.8	71.5	32.2
A6/B0.5/F100 (M7)	0.53	1	0.50	0.099	0.060	378.5	713.2	356.6	71.3	42.8

A denotes alkali, followed by percentage of solid NaOH in the binder quantity by weight.

B denotes bottom ash, followed by ratio of bottom ash to the binder quantity by weight.

F denotes fly ash, followed by percentage of fly ash in the binder quantity by weight.

NaOH pellets were diluted in 1 liter of water using a reagent bottle 30 ± 5 min before each casting. Caution was taken not to dissolve pellets into hot or tepid water. Fly ash, bottom ash and lime were dry-mixed in a concrete drum mixer for 2.5 minutes; after which the NaOH solution and a sufficient quantity of water were added and mixing was continued for another 2 min. The mixture was then tested for flowability to ensure that it has a flowability of more than 220 mm. In the event that flowability was not adequate, some quantity of water was added and mixed for another 2 minutes. Since most portions of mixture consisted of fine particles, the mixer was covered with a plastic bag to prevent popping of materials out of the mixer.

The moulds used were 70 mm cubes for the purpose of casting. One hour before the mixing stage, all moulds were lubricated with waste oil to facilitate demoulding. Fresh CLSM were filled into moulds without any compaction. Using trowel, four sides of each mould were tapped to remove entrapped air. Then, the surfaces of the specimens were leveled with masonry trowel to strike off the extra content.

Specimens were covered with wet gunny to provide sufficient hydration for cubes. Specimens were left in the laboratory environment for a period of one day. Due to low strength nature of CLSM and early demoulding, one should be cautious while demoulding, as the cubes are still unhardened and could break with minor force.

To prepare the curing environment for specimens, plastic storage boxes were filled with 50 ± 5 mm of water, after that some bricks were laid at the bottom of the boxes to place the CLSM cubes on them. All of the cubes were kept sealed in curing chambers, which were located in an air-conditioned room with temperatures from 25°C to 27°C and a relative humidity of more than 95%. Cubes remained in curing boxes till their testing dates.

Testing

The CLSM specimens were examined for flowability according to (ASTM D6103-97, 2005), fresh density, bleeding according to (ASTM C 232-99, 2005) and segregation resistance in fresh state as per (EFNARC, 2004). In hardened state, UPV in accordance with (ASTM C 597–02, 2005), water absorption as per (BS 1881-part 122, 1983), compressive strength based on (ASTM C 39, 2005) and hardened density were tested. Universal testing machine with a loading rate of 0.1 mm/min was used for compressive strength to apply the load until the failure occurs. The corrosivity was studied by measuring the pH of bleed as well as leachate at 28 days. The leachate was obtained by immersing the hardened cubes in deionized water with a solid to water ratio of 1:8 on the 7^{th} day and taking out the leachate on the 28^{th} day.

RESULTS AND DISCUSSION

The results of fresh density, flowability and segregation resistance are presented in Table 2; while the results obtained from hardened state tests are set out in Table 4. Comparison between pH measurements of bleed and leachate is provided in Table 3. To simplify the discussion, the graphs were normalized; where all values on the Y axis were divided by the biggest value on that axis.

Flowability

In this investigation, water content is described as the combination of water and 1L of NaOH solution in the CLSM mixture. It is apparent from Figure 1 that as the amount of FA/binder increases, the flowability of the mixture decreases. This is due to the imbibe of water by fly ash particles which cause flowability to fall. Since bottom ash has lesser fine particles and rougher surface than fly ash, more water was needed to fill the voids (Lee et al., 2013; Naganathan et al., 2012).

Fresh Density

It can be seen from Table 1 that the last three mixtures with 100% FA have slightly higher fresh density in comparison with 70% FA mixtures. The reason is because FA has a bigger value of un-compacted bulk density than BA; which means that denser materials have more density regardless of water quantity and NaOH solution (Naganathan et al., 2012). It is apparent that when the binder was FA+lime, the values of fresh densities increased by increasing the water content (Razak et al., 2010).

Segregation Index

Based on EFNARC specifications, all specimens have a segregation index of less than 20%. When the quantity of FA/binder or BA/binder was increased, the segregation index increased as well. Due to high fluidity nature of the mixture, the addition of bottom ash leaves space and voids, in turn followed by segregation (see Fig. 3). This caused mixtures with 70% FA to have higher values of segregation index (Naganathan et al., 2012). Despite that, the addition of fly ash increases the uniformity of the mixture, and because of its powdery nature, it fills the gaps among particles (Bouzoubaâ and Lachemi, 2001).

Table 2. Fresh state properties

Mix ID	Flowability (mm)	Fresh Density (kg/m^3)	Segregation Index (%)
M1	280	1557.3	14
M2	285	1538.2	20
M3	300	1500	15
M4	280	1524.8	16
M5	285	1563.2	18
M6	280	1556.4	12
M7	300	1562.2	14

Table 3. Measurement of pH from bleed and leachate

Mixture ID	M1	M2	M3	M4	M5	M6	M7
bleed	12.29	12.49	12.98	13.36	12.67	13.11	13.28
leachate	9.91	8.57	9.09	8.42	9.78	10.91	11.51

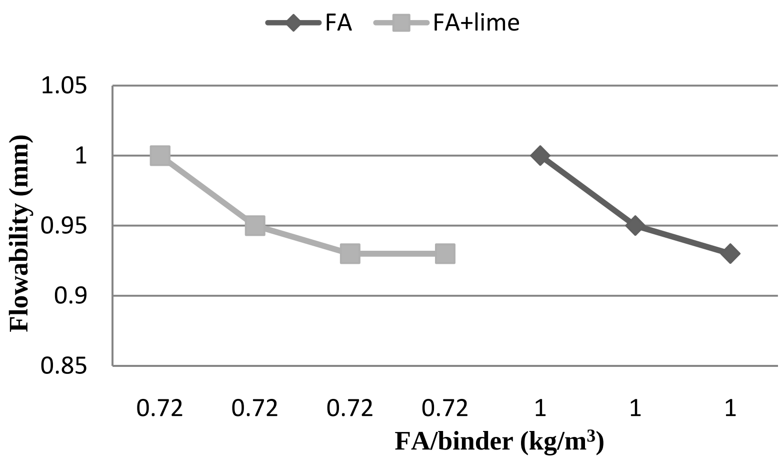


Figure (1): Relationship between flowability and FA/binder

Table 4. Properties of hardened state

Mix ID	Hardened Density (kg/m^3)	UPV (km/s)	Water absorption (%)	Strength (MPa)	Strength of leachate (MPa)
M1	1660.1	2.5	33.66	1.1	1.55
M2	1666.2	2.54	30.3	3.35	3.36
M3	1663.03	2.59	32.11	2.34	2.78
M4	1679.14	2.64	31.15	2.32	2.77
M5	1559.24	3.34	32.53	2.44	2.13
M6	1667.09	3.2	29.98	1.49	1.38
M7	1670.4	3.1	31.34	1.71	1.56

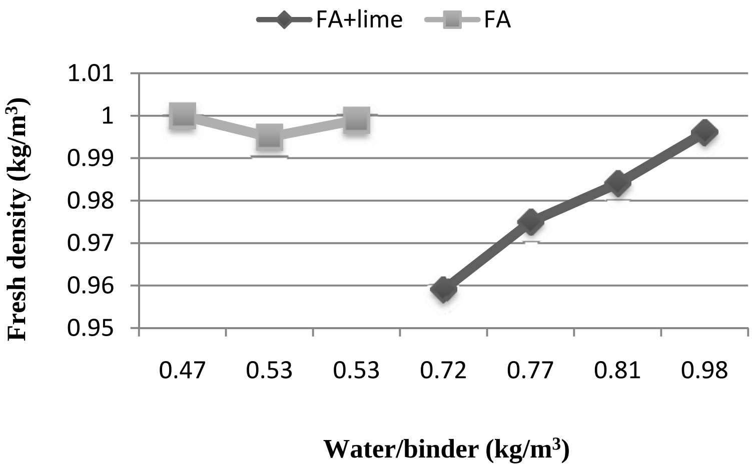


Figure (2): Relationship between fresh density and water/binder

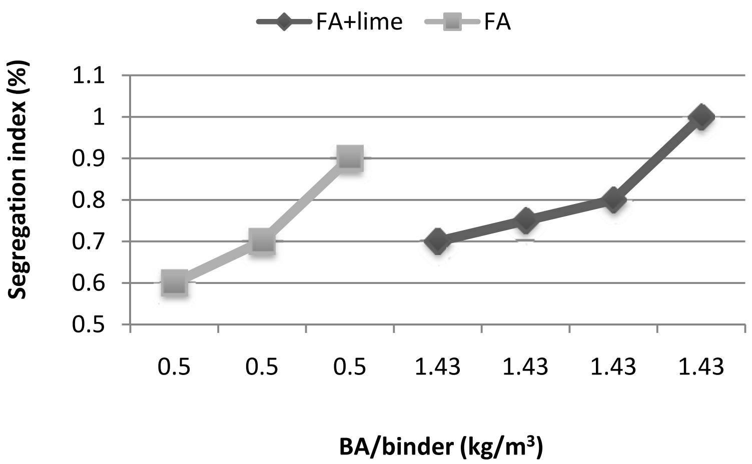


Figure (3): Relationship between segregation and BA/binder

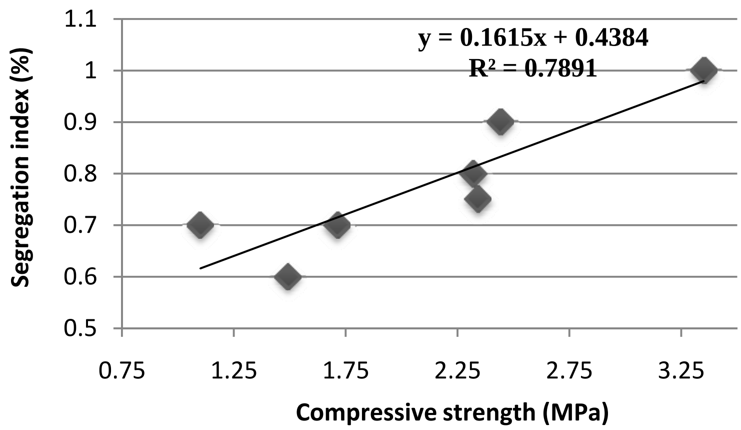
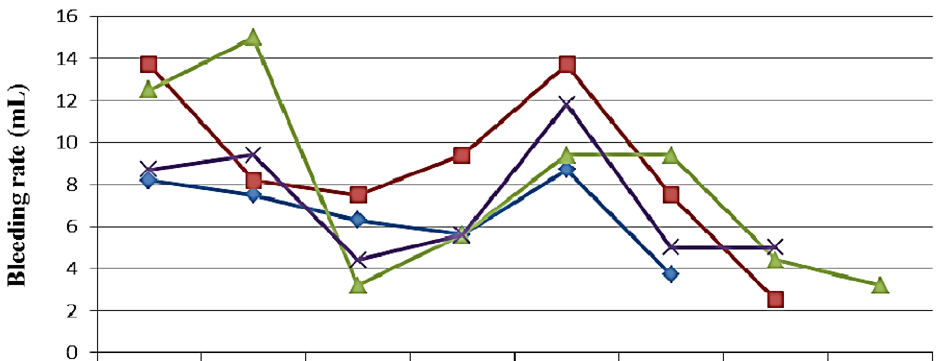


Figure (4): Relationship between segregation index and compressive strength



	10 min	20 min	30 min	40 min	70 min	100 min	130 min	160 min
M1	8.2	7.5	6.3	5.6	8.7	3.7		
M2	13.7	8.2	7.5	9.4	13.7	7.5	2.5	
M3	12.5	15	3.2	5.6	9.4	9.4	4.4	3.2
M4	8.7	9.4	4.4	5.6	11.8	5	5	

Time (min)

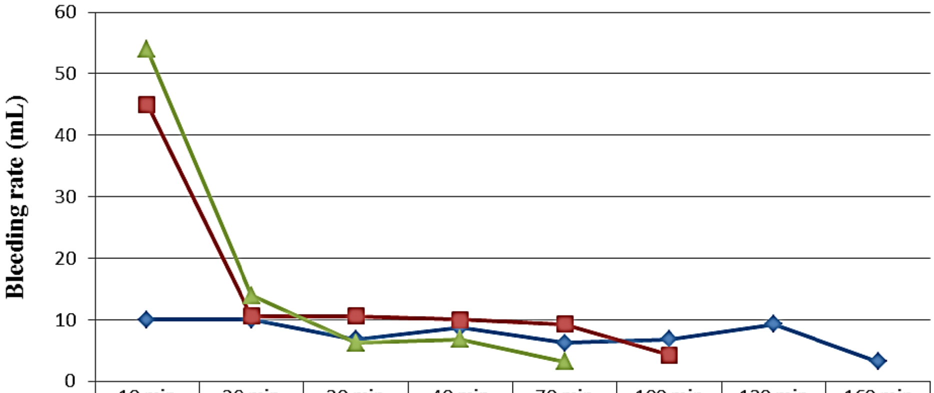
Figure (5): Relationship of bleeding *versus* time (M1-M4)

Bleeding

In Figure 5, the bleeding rate ceased at approximately 2 to 2.5 hours after the test was initiated. M3 had the longest bleeding rate with water/binder ratio of 0.81 kg/m^3. The highest bleeding rate was for M2 with BA quantity of 695.3 kg/m^3; while the lowest bleeding rate was for M1 with BA quantity of 562.3 kg/m^3. From the data in Figure 6, the longest duration of bleeding was for M5 with BA quantity of 371.6 kg/m^3. In addition, the highest bleeding rate contributed to M7 with water quantity of 0.53 kg/m^3. Due to the voids among bottom ash particles, more water was needed to fill the free spaces. As a result, the excess water which was more than required for the hydration process exuded to surface (Lee et al., 2013). In spite of this, mixtures having 100% FA undertook shorter duration of bleeding. This is due to fineness of fly ash which did not displace the water and had more adequate interconnection bond compared to bottom ash particles (Naganathan et al., 2012).

Based on Figure 7, the trend of bleeding rate is increased by increasing the water quantity. The observed correlation might be explained by that higher amount of water causes more sedimentation of particles to happen. As the particles settle down, water dislocates and upheaves to surface. Therefore, water content could be a major factor, if not the only one, causing bleeding rate to increase (Razak et al., 2009).

Based on Figure 8, the percentage of bleeding is higher for mixtures having higher flowability; except for mixture M6. There was a significant decrease in bleeding for mixtures with 100% FA after first 10 min interval, after which the bleeding gradually stopped. As previously mentioned, the flowability of all specimens was in the range of 300 ± 20 mm. Excess water which was added to increase the flowability of the mixture came out as bleed water.



	10 min	20 min	30 min	40 min	70 min	100 min	130 min	160 min
M5	10	10	6.8	8.7	6.2	6.8	9.3	3.2
M6	45	10.6	10.6	10	9.3	4.3		
M7	54	14	6.2	6.8	3.2			

Time (min)

Figure (6): Relationship of bleeding *versus* time (M5-M7)

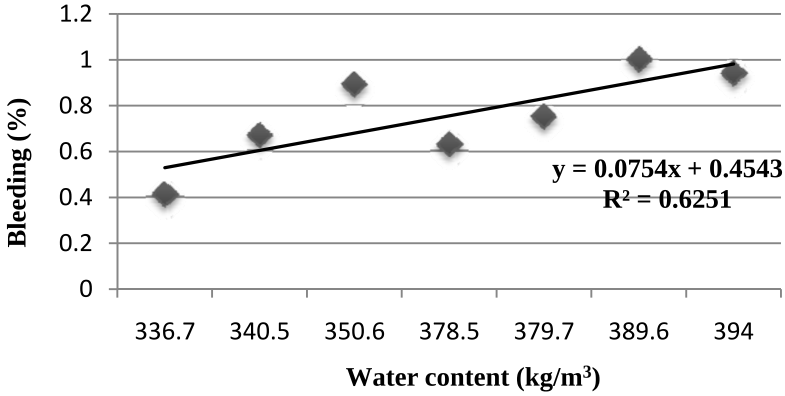


Figure (7): Relationship between bleeding rate and water content

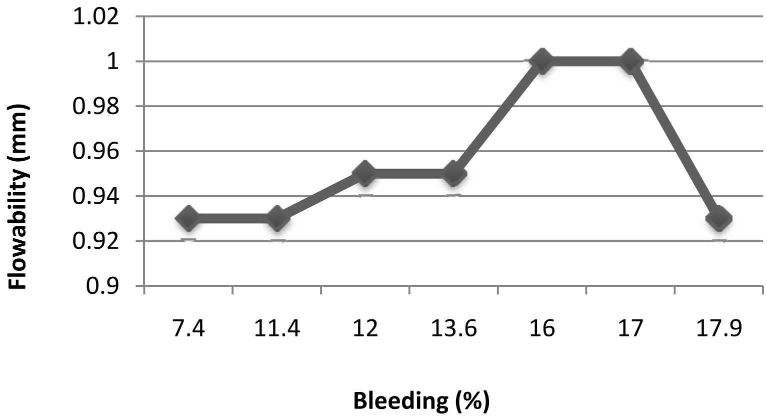


Figure (8): Relationship between flowability and bleeding

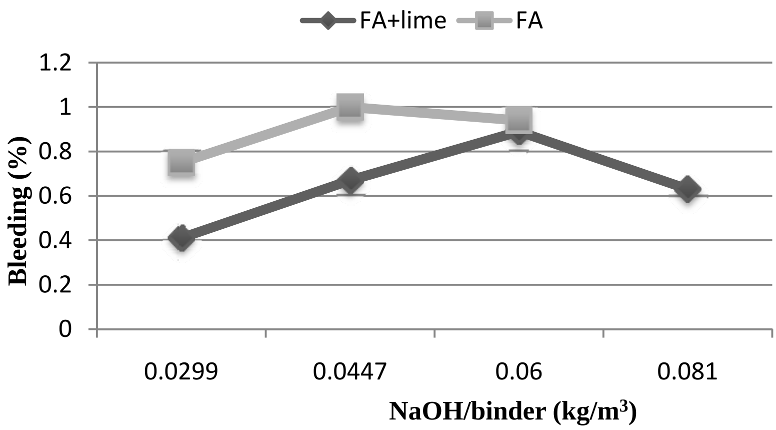


Figure (9): Relationship between bleeding rate and NaOH/binder

The addition of more NaOH pellets led to a more powdery mixture, which in turn increased the bleeding rate, except for M4 which had a water quantity of 340.5 kg/m^3. Besides, the suspension of NaOH in the mixture due to the delay which occurred to react with lime caused moving the water to the surface (Lee et al., 2013).

Measurment of pH

Compatible to expectations, all specimens exhibited pH more than twelve. Range of pH scale for alkali substances is from 7 to 14, while pH of hydrated cement is from 12 to 14 (Naganathane et al., 2013). Due to the alkalinity of NaOH, the addition of NaOH increases the pH spontaneously.

As the quantity of water increased, the pH value decreased. More water dilutes the mixture, and since the pH of water is 7, it reduces the pH of the mixture by neutralizing the effect of alkali (Naganathan et al., 2013).

The pH of leachate for all mixtures is in the range of 8 to 12. The highest pH was for mixture

A6/B0.5/F100 with NaOH molarity of 42.8. Corrosive materials are described as those that are dangerous to environment or human health due to their possibility of mobilizing toxic metals in case of disposal to environment, corrode storage, handling, management equipment and transportation, or destroy animal or human tissues when contacting them. Waste materials with pH of more than 12.5 or less than 2 are considered as corrosive; however, this range does not apply to corrosivity of all materials (Razak et al., 2009). Therefore, all the CLSM specimens produced do not possess any corrosive behavior as the pH of all specimens falls in the range of specified limits.

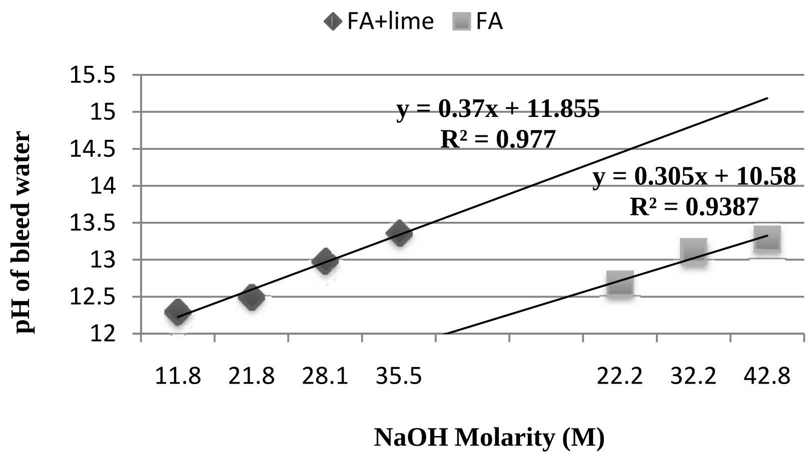


Figure (10): Relationship between pH of bleed water and NaOH molarity

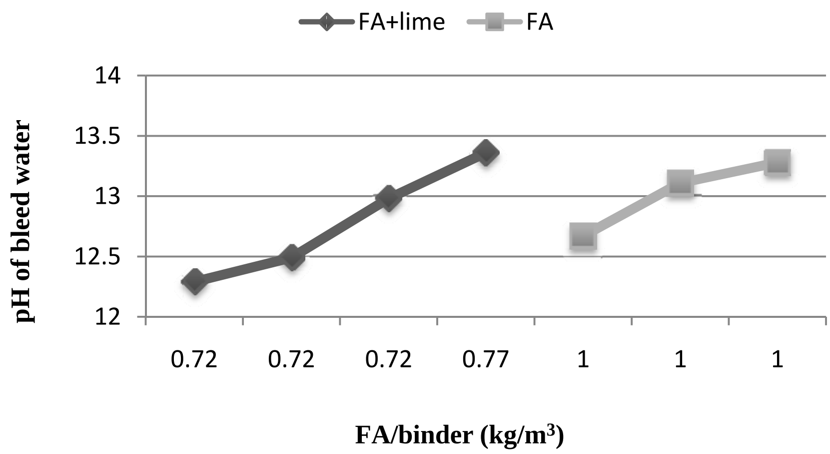


Figure (11): Relationship between pH of bleed water and FA/binder

In Figure 12, there is a clear trend of increasing in pH value when the NaOH/binder ratio increases. This is correct for mixtures with FA or FA+lime as main binder. There is an increase associated with pH value as the amount of FA/binder augmented. In contrast to fly ash, quantity of Silica dioxide and Aluminum dioxide in bottom ash is comparatively lower.

Based on Figure 12, increment in the amount of NaOH molarity did not increment the pH value when the main binder was FA+lime. However, when the binder was only FA, the pH of leachate water followed the behavior of bleed water and increased by increasing the quantity of solid NaOH. This could be a result of more cementitious substances which existed in the composition of fly ash (Razak et al., 2010).

Decrement in pH values occurs as the quantity of lime in the mixture increases. The percentage by weight of lime for all mixtures was 20% of bottom ash. The lime content of 71.3 kg/m^3, 71.5 $kg/m^3$and 74.3 kg/m^3 are for the mixtures having 100% FA. Nonetheless, when fly ash is used as main binder, pH of leachate water is following the pattern of bleed water's pH by increasing its value. Hence, this can be linked to cementitious properties of fly ash. The pH measurement was recorded from leaching water extracted from the cubes during the curing process. Most portions of lime reacted with NaOH; however, this reaction was not entirely successful as the deposit of unreacted lime and NaOH remained inside the cubes and did not complete the hydration process. This phenomenon led to reduction in pH values as the majority of NaOH remained chunks with lime particles.

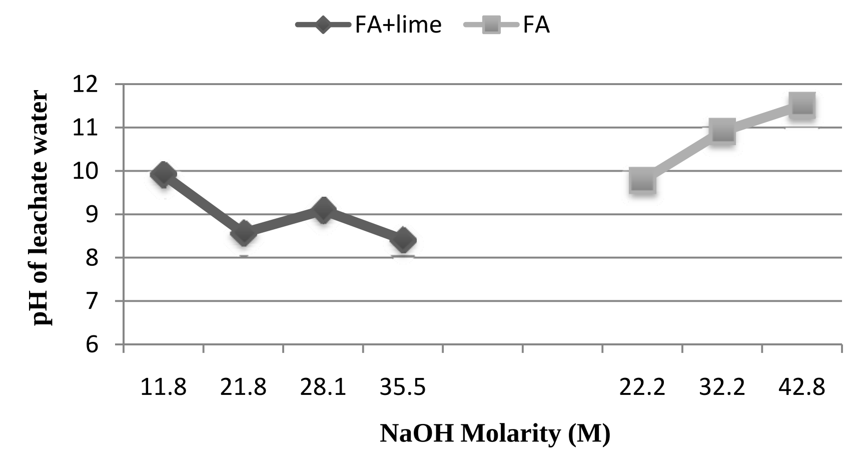


Figure (12): Relationship between pH of leachate water and NaOH molarity

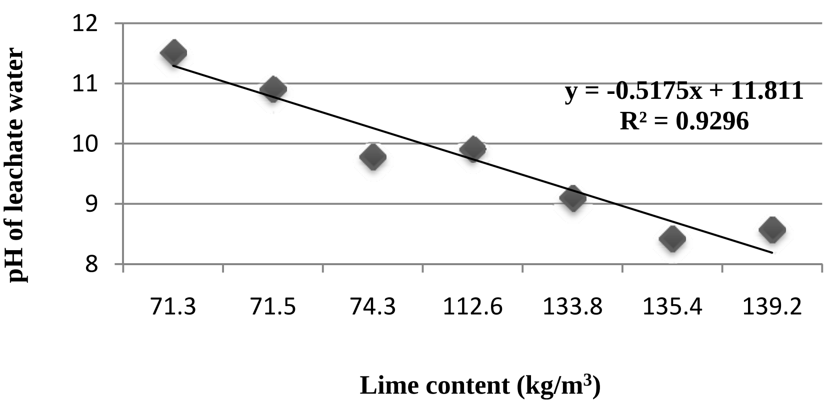


Figure (13): Relationship between pH of leachate water and lime content

Hardened Density

Results from five test specimens were averaged for hardened density determination. The hardened density values of all specimens are relatively higher in comparison with fresh density values (Razak et al., 2010). The addition of bottom ash increases the hardened density. Since hardened density values are more than 800 kg/m^3, the produced alkali-activated CLSM are considered as normal weight CLSM based on ACI committee 299. Also, measured hardened densities of alkali-activated CLSM are similar to bulk densities of sandy soil and loam with bulk densities from 1200 kg/m^3 to 1800 kg/m^3 (Tan, 2005). Hence, all specimens of cementless, alkali-activated CLSM have potential implications for use as subgrade for light-weight structures and excavatable earth filling applications.

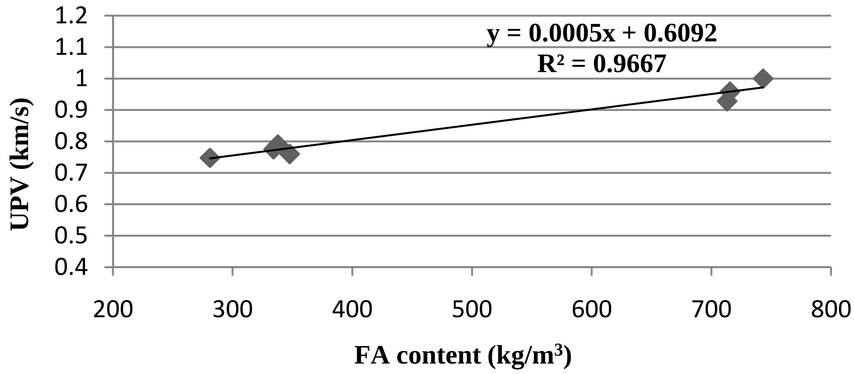


Figure (14): Relationship between UPV and FA content

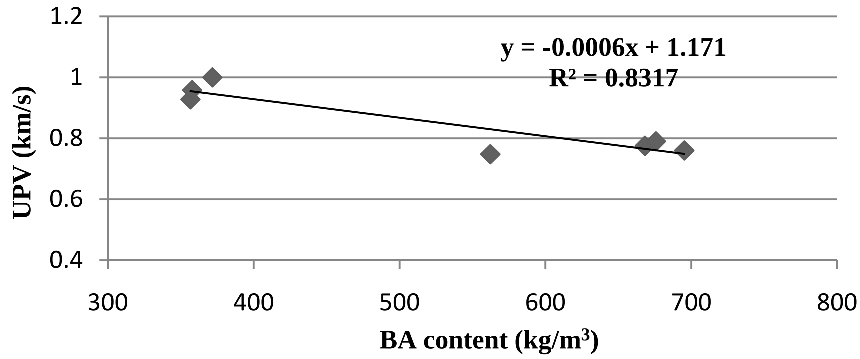


Figure (15): Relationship between UPV and BA content

Ultrasonic Pulse Velocity (UPV)

In general, transit of ultrasonic pulse is faster in specimens with lesser voids and gaps. Hence, the observed increase and decrease in UPV values are mostly because of size of particles and their molecule bond. The factor which is causing increment is fineness of fly ash; owing to closely spaced interconnection of particles which eliminate the creation of pores and voids (Her-Yung, 2009).

The reduction in UPV value is chiefly due to voids among bottom ash particles. Moreover, bottom ash is not as dense as fly ash and therefore, more voids would create among bottom ash particles. The observed increase in UPV could be due to the reaction between lime and NaOH, that despite higher bottom ash quantity increases the UPV values. Another factor can probably be the discrepancy between fly ash and NaOH. NaOH cannot react well with cementitious properties of fly ash and hence, it creates fragments of NaOH which delay the transmission of ultrasonic pulse.

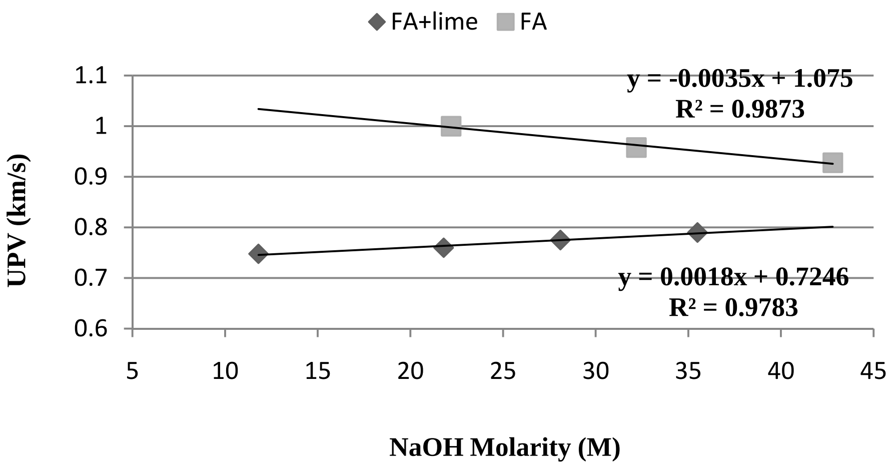


Figure (16): Relationship between UPV and NaOH molarity

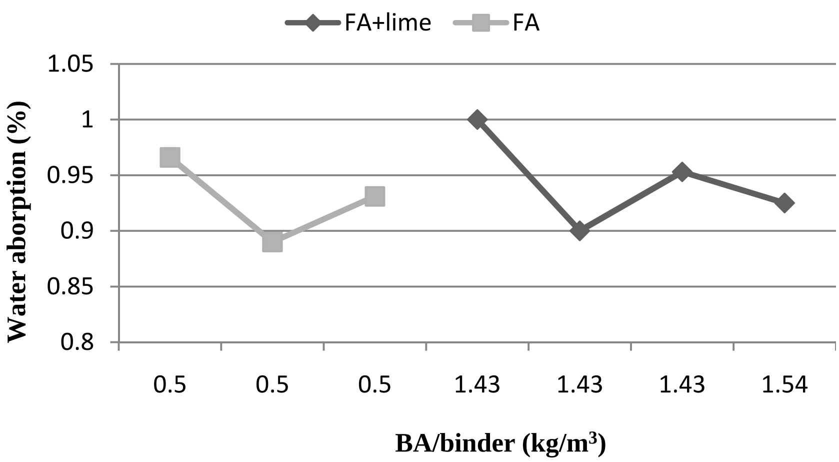


Figure (17): Relationship between water absorption and BA/binder

Water Absorption

The average of three specimens was reported for water absorption determination. Mixtures with more quantity of bottom ash experienced a higher rate of water absorption (Nataraja and Nalanda, 2008). Corrected absorption rate has a falling pattern as the amount of BA/binder ratio increases (Lee et al., 2013). However, there is an exception for M7 and M3 with BA/binder ratio of 0.5 kg/m^3 and 1.43 kg/m^3, respectively. The similarity between these two mixtures is that both of them have NaOH/binder ratio of 0.06 kg/m^3. A sudden increase in the absorption rate can be identified when the NaOH/binder ratio is 0.06 kg/m^3 for both binders.

Compressive Strength

The compressive strength of various CLSM mixtures is given in Table 4. The strength at 28 days ranges from 1.1 to 3.35 MPa. Since the percentage by weight of lime in the mix design was based on bottom ash quantity which was 20%, the portion of lime is more for the mixtures with FA+lime as main binder. Addition of lime increased the compressive strength for the lime/binder ratio of 0.285, 0.287 and 0.31 as indicated in Figure 18. The differences between strength gained due to lime content are the result of lime and NaOH reaction. Residue of lime remained in the cubes after the curing period. This indicates that lime reacts with NaOH at a certain capacity which can lead to an increase in strength. Otherwise, the excess amount of lime remains unreacted and forms chunks of lime.

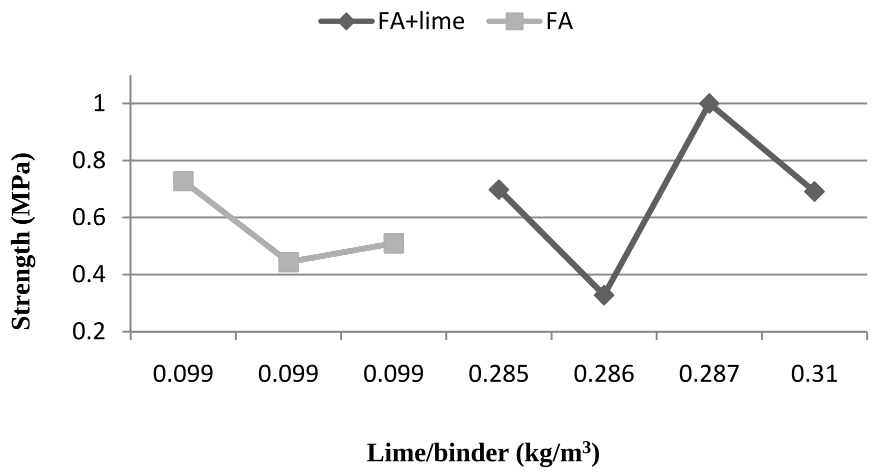


Figure (18): Relationship between compressive strength and lime/binder

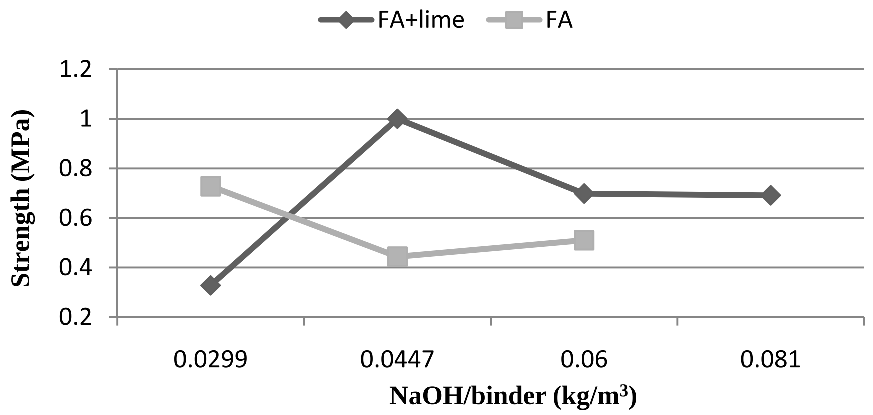


Figure (19): Relationship between compressive strength and NaOH/binder

In the case of FA as binder, the slope of strength *versus* NaOH/binder ratio is identical to that of lime/binder ratio. Also, an increase in strength occurs at ratios of 0.447, 0.06 and 0.081 for mixtures with FA+lime, with lime/binder ratios of 0.287, 0.285 and 0.31, respectively. Therefore, M2 with strength of 3.35 MPa and M5 with strength of 2.44 MPa have the most optimum interaction between NaOH and lime.

Strength of leachate specimens is higher for M1 to M4; while strength of normal specimens is higher for M5 to M7. Leachate specimens were removed from curing condition on the 7th day of curing, placed in water and kept sealed in plastic storage until 28 days of curing. Leachate specimens experienced higher strength than normal specimens for FA+lime as binder; while placing the specimens in water did not lead to increase the strength for specimens with FA as binder. Thus, variation in curing condition was favorable only for FA+lime specimens.

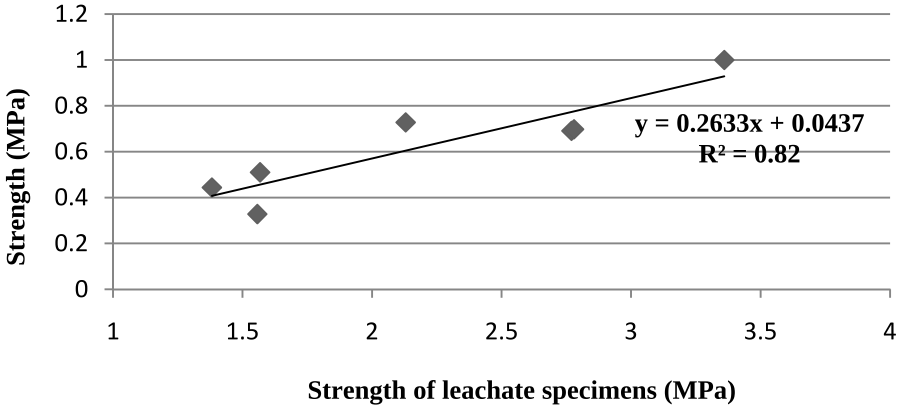


Figure (20): Relationship between normal strength and strength of leachate specimens

Based on excavability requirement, compressive strength of less than 2.1 MPa is considered excavatable with mechanical equipment like backhoe and is applicable for non-structural filling; while strength of less than 8.2 MPa is for structural filling application. Therefore, M2, M3 and M5 are appropriate for structural filling works, for instance filling of abandoned structures, bridge abutment and foundation opening. Other mixtures having strength of less than 2.1 MPa are suitable for non-structural uses like backfilling, utility bedding and void filling (ACI 229R-99, 1999).

CONCLUSIONS

This paper explored the performance of CLSM made using coal ashes, lime and NaOH. All the mixtures exhibited good flowability and segregation resistance. Mixtures with higher quantity of bottom ash required more water content to maintain the flowability. Higher FA/binder ratio contributed to reduction in flowability of CLSM mixtures. Addition of bottom ash and use of NaOH contributed to increase in hardened density. Using higher amount of NaOH led to a lower water absorption rate in most of the CLSM mixtures**.** Major cause of strength development in specimens is due to proper reaction between lime and NaOH. Excess amount of NaOH extracted to the surface and did not react with lime. Hence, addition of lime and NaOH did not lead to increase in compressive strength for all mixtures. In terms of ratio, M2 with strength of 3.35 MPa and M5 with strength of 2.44 MPa exhibited increase in strength which emphasizes the ideal ratios wherein better reaction between lime and NaOH takes place. CLSM can successfully be developed using NaOH as cement replacement and coal ashes as an alternative to aggregates.

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