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Controlled Low-Strength Materials Containing Bottom Ash from Circulating Fluidized Bed Combustion

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Abstract: This paper develops controlled low strength materials (CLSM) incorporating bottom ash from Circulating Fluidized Bed Combustion (CFBC). This work conducted a preliminary study to understand bottom ash influence on fresh and strength properties of eleven selected CLSM mixtures where bottom ash, fly ash, and ground granulated blast furnace slag (GGBS) contents varied from 10 to 20%, 10 to 30%, and 20 to 60% of total mass, respectively. This study conducted laboratory tests of mixture proportions for various properties, such as flowability, setting time, bleeding, length change, unit weight, compressive strength, and water absorption. Results indicated that the setting time for the 20% bottom ash of CFBC-sand replacement is the shortest, while that for the 0% replacement is the longest. Following 28-day curing, the compressive strength of CLSM was 3.71-6.29*MPa*. Mixing fly ash and GGBS with cement and sand produced higher strength and lower water absorption than using bottom ash of CFBC alone due to its low pozzolanic activity. Observations show that by-product materials such as bottom ash of CFBC, fly ash, and GGBS can be successfully used in CLSM. This successful utilization of by-product materials is important to sustainable development and is the focus of this research.

***Key words**: Bottom ash; Circulating fluidized bed combustion; Controlled low strength materials; Fly ash; GGBS.*

Introduction

Correct waste material disposal from various industries is an important problem in Taiwan. Construction manufacturing is an area where safely using materials has a promising future. Recent research in many countries has led to a better understanding of the chemical-physical characteristics of concrete incorporation fly ash, silica fume, pulverized-fuel ash, and ground granulated blast furnace slag (GGBS) [1-4]. This is well recorded in various codes of practice. Cement and Concrete Terminology (ACI 229R) defines Controlled Low Strength Material (CLSM) as "a material resulting in compressive strength of 8.3*Mpa* (1,200*psi*) or less." CLSM is a self compacted, cementitious material which after hardening, allows future excavation with properties similar to stabilized soils [5]. CLSM is basically a mixture of cement, a by-product material, fine aggregate, and water that can be used as backfill material in place of compacted soils with its self compacting property. Recycling waste material for use in CLSM is also helpful in environmental conservation. Researches have also investigated using various by-products in CLSM mixtures such as acid mine drainage (AMD) sludge, quicklime (QL), and fly ash (FA) [6-7]. Bouzalakos et al. studied using waste precipitates derived from neutralizing effluents from CLSM mineral processing [8]. Circulating fluidized bed combustion (CFBC) is a clear technology for coal burning that achieves in suit SO_2 removed by injecting calcium-based absorbent into the combustor [9]. Approximately eight hundred thousand tons of CFBC ashes are produced annually by the Taiwan petroleum industry. When limestone calcines, it produces a porous CaO matrix which then sulphates. Studies have shown that the environmental impact from CFB ashes is less than that from petroleum coke (p.c.) ashes and should be used as by-products [10]. Using of CFBC fly ash includes soil stabilization, road base, structural fills, and synthetic aggregate. Research presented in this paper focuses on evaluating CLSM mixture properties contained in waste materials. The current work investigates CLSM mixtures, including FA, GGBS, bottom ash of CFBC, and Portland cement (PC). The experimental study determines the compressive strength, flowability, bleeding, length change, and setting time of various CLSM mixtures. This investigation uses the initial surface absorption test (ISAT) to measure water absorption by capillary suction to study the permeation properties of CLSM mixtures.

Experimental Details

Material Properties

Typical CLSM mix components include FA, GGBS, aggregate, cement, accelerator, and water. The experiment used Type I Portland cement conforming to ASTM C150 [11] in all mixes. The fineness of cement was 345m^2/kg. GGBS, a nonmetallic product consisting of silicates and alumino-silicates of calcium, derive from the blast furnace production of iron ore through water jetting and water-immersing the molten blast-furnace GGBS for granulation. The large-size granules are then ground to at least cement particle size, named as GGBS. The experiment used GGBS with specific gravity of 2.90 (±0.01) and fineness of 383m^2/kg and FA with specific

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Table 1. Chemical Composition (%) and Specific Gravity of Portland Cement, Bottom Ash of CFBC, FA, and GGBS.

	Portland Cement	CFBC Bottom Ash	FA	GGBS
Specific Gravity	3.15	2.83	2.24	2.90
SiO_2	20.6	5.24	56.66	34.4
Al_2O_3	4.0	1.31	23.97	9.0
Fe_2O_3	6.1	1.14	7.56	2.58
CaO	62.8	49.76	1.94	44.8
MgO	2.6	1.81	1.34	4.43
SO_3	3.1	38.95	0.57	2.26
Na_2O	-	0.25	0.30	0.62
K_2O	-	0.08	0.60	0.5
LOI*	1.8	0.75	3.64	1.32

* Loss of ignition

gravity of 2.20 (±0.01). The U.S. produces two main types of FA; Class F, commonly described as non-cementitious and Class C, possessing cementitious characteristics (as described in ASTM C618). The current study used Class F in all mixes. For all CLSM mixtures, the dosage of the air-entraining admixture (AEA) was kept constant at 0.15kg/m^3.

This study used CFBC bottom ash with specific gravity of 2.83. Bottom ash of CFBC is a fine, highly alkaline powder with fineness of 232m^2/kg. Table 1 lists the chemical composition of cement, GGBS, FA, and CFBC ash as determined by X-ray fluorescence. Total lime (CaO) is about 50% of CFBC bottom ash. The maximum size of coarse aggregate was 9*mm* and the fineness modulus of fine aggregate was 2.69. Pan mixer was used in this study. Three different mixtures were prepared using 0, 10, and 20% bottom ash of CFBC replacement to total fine aggregate and designated as A, B, and C, respectively. The percentages of GGBS in cementitious materials were 0, 20, 40, and 60% by cement weight and designated as N, S20, S40, and S60, respectively. FA was added to mortar mixtures to replace 10, 20, and 30% of Portland cement by weight and designated as F10, F20, and F30, respectively. $CaCl_2$ was used as an accelerator, and dosages of 3, 5, and 7% by cementitious material weight were tested. Table 2 presents eleven mix designs in this study.

Preparation and Testing Procedure

The procedure evaluated workability using an open-ended cylinder in accordance with ASTM D6103 [12]. The same water/cementitous ratio of 1.28 was used for all mixes. Table 3 presents mix properties and unit weights of test specimens for every CLSM mixture. Air content tests were conducted in accordance with ASTM C231 [13] to evaluate the air content of freshly mixed concrete. Bleeding tests were conducted in accordance with ASTM C232 [14]. For measurement of length change, the prismatic specimens with 25.3×25.3×284.6*mm* were prepared. After de-molding, the specimen was cured in water for three days and then placed in a humidity cabinet at 23°C and 70% relative humidity (RH) for 28 days. Initial length of specimens was measured before placing them into the humidity cabinet.

Compressive strength tests were conducted in accordance with ASTM C109 [15] to evaluate the strength development of concrete containing various CFBC bottom ash contents at the age of 12hrs, 7, 28, and 56 days. In the study, river sand was partially replaced by CFBC bottom ash. Twenty 100×200*mm* (diameter × height) cylindrical specimens were cast for each batch following ASTM C109 specifications. After 24-hr curing, the experiment de-molded the specimens and placed them into a water tank at room temperature until testing.

The initial surface absorption test (ISAT) was carried out according to BS 1881 [16]. Fig. 1 illustrates the ISAT set-up. The test specimen was a 100*mm* (in diameter) and 50*mm* (in length) cylinder. The tests determined the rate of water absorption by the surface zone of mortar samples during a prescribed period under a head of 200*mm* of water. The rates of absorption of water at 10, 30,

Table 2. Properties of Fresh CLSM.

Mix No.	Unit Weight (kg/m^3)	Flow (*mm*)	Air Content (%)
AN-3	1,971	15.4	18.5
AN-5	1,973	15.6	17.2
AN-7	1,980	15.1	17.5
BN-7	1,999	12.0	16.9
CN-7	2,015	11.6	17.1
BF10-7	1,987	12.1	16.2
BF20-7	1,960	13.0	17.9
BF30-7	1,942	13.1	18.5
BS20-7	1,962	12.1	16.3
BS40-7	1,956	12.4	16.9
BS60-7	1,955	12.6	17.1

Table 3. Mix Design for CLSM (kg/m^3).

Mix No.	Water	Cement	Fine Aggregate	CFBC Bottom Ash	Fly Ash	GGBS	Accelerator	Air-Entraining Admixture
AN-3	250	195	1500	0	0	0	5.85	0.15
AN-5	250	195	1500	0	0	0	9.75	0.15
AN-7	250	195	1500	0	0	0	13.65	0.15
BN-7	250	195	1350	150	0	0	13.65	0.15
CN-7	250	195	1200	300	0	0	13.65	0.15
BF10-7	250	175.5	1350	150	19.5	0	13.65	0.15
BF20-7	250	156	1350	150	39	0	13.65	0.15
BF30-7	250	136.5	1350	150	58.5	0	13.65	0.15
BS20-7	250	156	1350	150	0	39	13.65	0.15
BS40-7	250	117	1350	150	0	78	13.65	0.15
BS60-7	250	78	1350	150	0	117	13.65	0.15

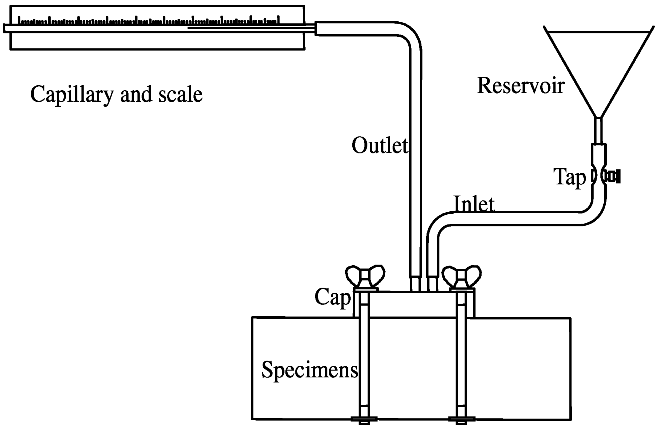

Fig. 1. Schematic Diagram of ISAT.

and 60mins from the start of test were recorded. The rate of initial surface absorption is expressed in *ml/m*^{2}*s*.

Results and Discussion

Properties of Fresh CLSM

Table 3 gives the fresh properties of the CLSM, including the flow, air content and unit weight. The current measured unit weight of CLSM mixtures was between 1,942 to 2,015*kg/m*^{3} by ASTM D854. Specific gravity valued for CFBC bottom ash was 2.83, compared with specific gravity for sand of 2.69. A slight increase in unit weight occurred, with an increase in CFBC replacement for sand. The ACI 229R recommends a normal CLSM unit weight between 1,840 to 2,320*kg/m*^{3}. The AEA dosage for all mixtures was 0.15*kg/m*^{3}. Table 3 shows that the air content for all mixes was relatively high (between 16.3-18.5%), irrespective of cementitious materials used.

Flow values are also listed in Table 3 for all mixtures. A decrease in flow generally results with an increase in CFBC bottom ash replacement for sand. This is due to increased cohesiveness of the mixtures caused by the very fine bottom ash particle size. Table 3 also presents that in order to achieve a constant flow above 120*mm*, the FA and GGBS replacement for cement ranged from 10 to 30% and 20 to 60%, respectively.

Setting Time

The current work considered the amount of time each test specimen needed to reach a penetration resistance, which measured by the pocket penetrometer, equal to 25 and 200*kPa* as the initial and finial setting time, respectively. Fig. 2 shows that the initial and finial setting time of CLSM mixtures ranged from 96 to 340mins and from 208 to 643mins, respectively. A major observation from Fig. 2 is a general decrease in the initial and finial setting time with an increase in CFBC replacement for sand. The setting time of CLSM made with CFBC bottom ash is short because of the quick hydration reaction of lime and calcium sulfate.

$CaO + H_2O \rightarrow Ca(OH)_2$ calcium hydroxide

$CaSO_4 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O$ gypsum

The initial and finial setting time of CLSM made with fly ash ranged from 112 to 167mins and from 318 to 359mins, respectively. The initial and finial setting time of CLSM made with GGBS ranged from 156 to 248mins and from 362 to 722mins, respectively. The reference specimens (BN-7) were set much slower, with the initial and finial settings of 154 and 435mins, respectively. The fast setting of CLSM made with fly ash was due to higher fineness of the FA. The slow setting of CLSM with CCBG was due to the low cement content of this type of specimen. However, the initial and finial setting time of all mixtures containing CFBC bottom ash, FA, and GGBS were less than 300 and 1440mins, respectively. A rapid-setting concrete or asphalt pavement is placed, resulting in total traffic-bearing repair in about 180-300mins [5]. The finial setting time of 1,440mins or less allows the CLSM as a substitute material for compacted fill in quick-construction projects like pavement bases, backfills, and structural fills [6]. The setting times for CLSM containing FA and GGBS specimens in this investigation

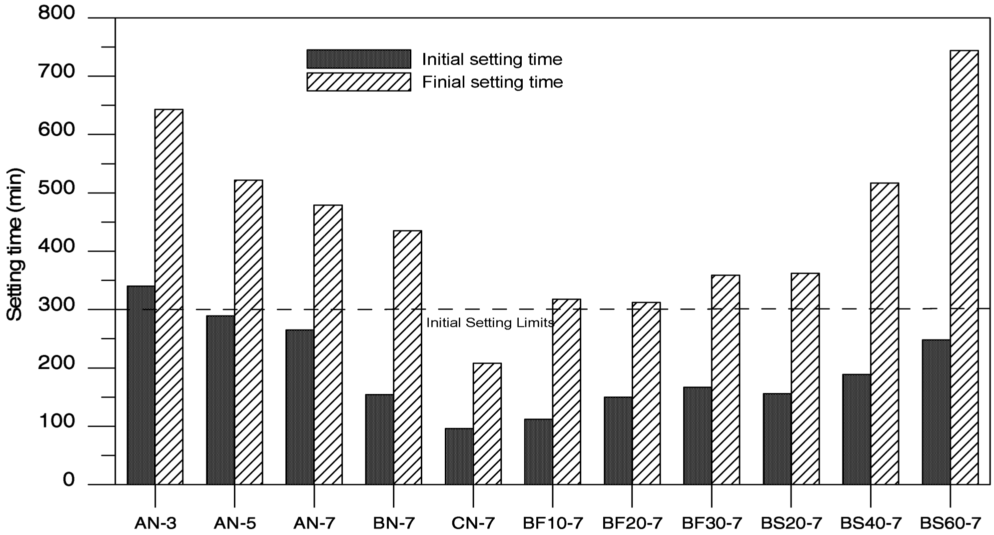

Fig. 2. Setting Time of Various CLSM Mixes.

probably will not cause any practical problems in the field applications.

Bleeding of CLSM

Fig. 3 gives bleeding results for fresh CLSM. Using CFBC bottom ash apparently decreased CLSM bleeding compared to CLSM bleeding without CFBC bottom ash added to the mixtures. The total amount of water bleeding was negligible for all CLSM specimens containing FA. The data indicate that FA is very effective in reducing bleeding. The total amount of water bleeding was very low for all the CLSM with GGBS, ranging from 0.0127 to 0.0361*ml/cm*^{2}. This is probably due to higher fineness of GGBS.

Length Changes of CLSM

Figs. 4 to 7 present the results of length changes of the CLSM sample. Shrinkage for the CLSM mixtures investigated was low, and did not exceed 0.14% at 28 days. The highest value of 0.138% was for CLSM made with 60% GGBS, and the lowest value of 0.089% was for CLSM made with fly ash. Fig. 5 shows a general decrease in drying shrinkage with an increase in CFBC replacement for sand. This may, however, be due to free lime and higher SO_3 content of CFBC bottom ash. Expansion often occurs with curing of the CFBC ash-water system [17]. Since the CFBC bottom ash has a large influence on shrinkage, evidently expansion caused by CFBC bottom ash is compensated by lower cement content. The phenomenon may not cause any foundation settlement problems in the field utilization.

Compressive Strength

Table 4 gives the compressive strength data of CLSM. These mixtures were designed to produce a CLSM with higher compressive strength that can be re-constructed in the field. Results show that all mixtures have compressive strength higher than 0.7*MPa* except the mix BS60-7 at 12hrs. The 12hrs compressive

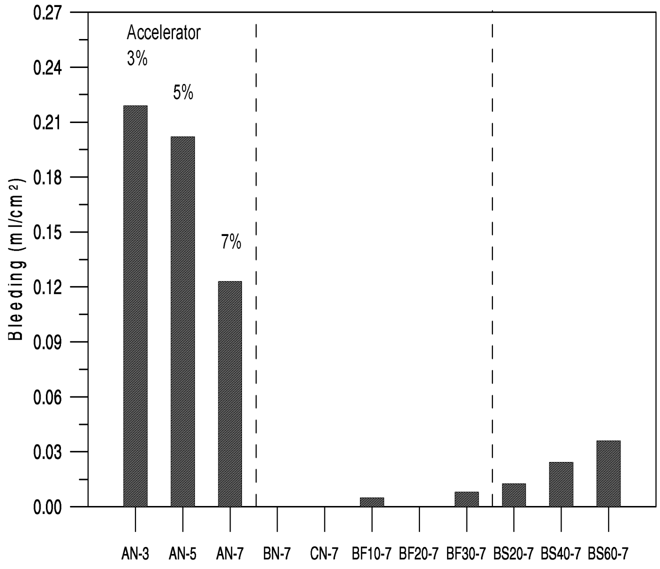

Fig. 3. Bleeding of Various CLSM Mixes.

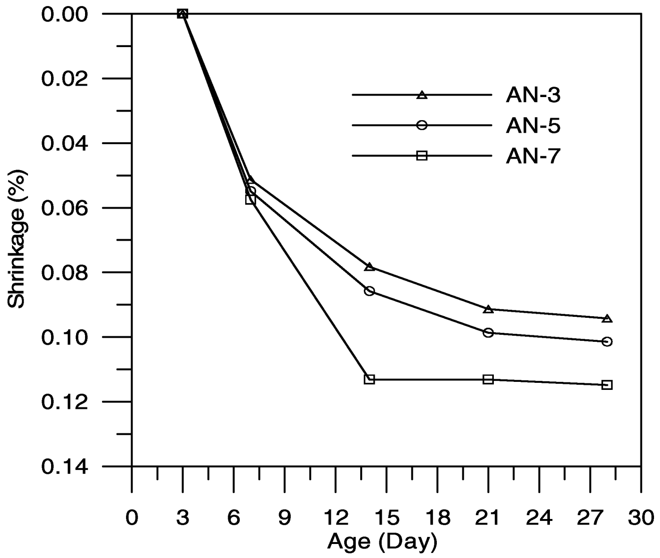

Fig. 4. Shrinkage of CLSM Produced versus Curing Time.

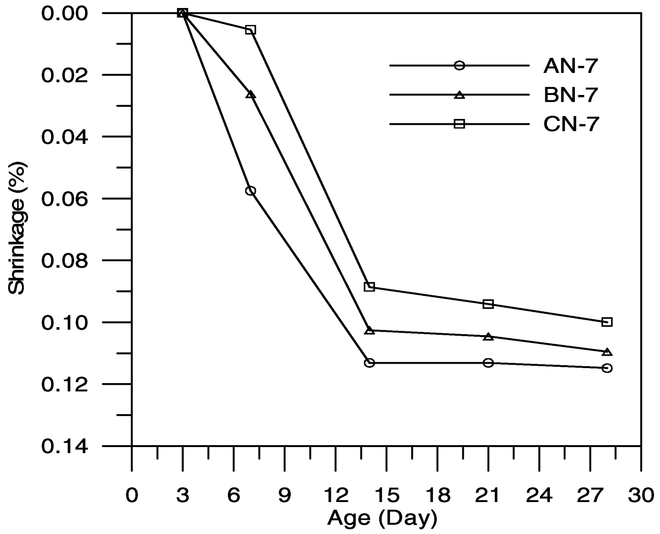

Fig. 5. Shrinkage of CLSM Produced versus Curing Time.

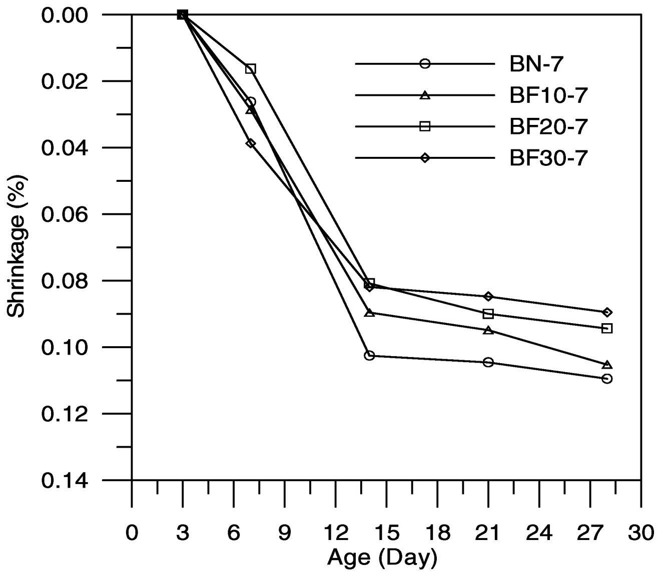

Fig. 6. Shrinkage of CLSM Produced versus Curing Time.

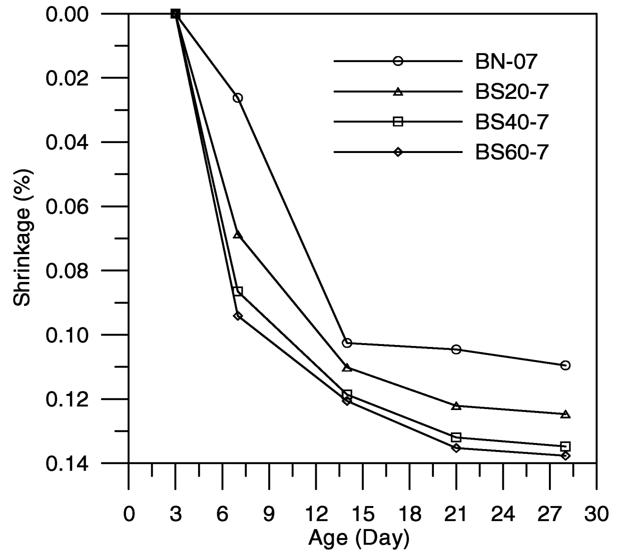

Fig. 7. Shrinkage of CLSM Produced versus Curing Time.

Table 4. Compressive Strength of Various Type of CLSM.

Mix No.	Compressive Strength, *MPa*			
	12 hrs	7 Days	28 Days	56 Days
AN-3	0.71	2.57	3.71	4.92
AN-5	0.70	3.16	4.09	5.09
AN-7	0.74	3.33	4.12	5.19
BN-7	1.05	3.08	4.17	5.66
CN-7	1.21	3.15	5.25	6.21
BF10-7	0.70	2.56	4.53	5.90
BF20-7	1.02	2.58	4.87	7.04
BF30-7	1.15	2.23	4.68	7.07
BS20-7	1.03	3.92	5.62	6.62
BS40-7	0.71	3.93	6.00	7.74
BS60-7	0.56	3.88	6.29	7.76

strength of the reference specimens (BN-7) was noticeably lower than that of the CLSM made with fly ash specimens ranging from 0.71 to 1.15*Mpa*. Strength development of the reference specimens was slower than that of the CLSM made with fly ash specimens in the early age. The higher compressive strength at 56 days obtained by the mixes containing fly ash is probably due to the pozzolanic activity of this material. Table 4 also shows a general increase in compressive strength with an increase in CFBC bottom ash replacement for sand, affected by gypsum generated from anhydrite hydration that increases early strength development. Cement paste hydration with higher SO_3 and f-CaO content produces more C-S-H and AFt in hydration products, and self-cementitious properties of CFBC ash with curing age [18]. Ettringite forms from soluble calcium hydroxide, alumina, and gypsum. This is the reason why compressive strength increases with an increase in added CFBC. Average strength development of the control mixture was slightly slower at 28 days than that of CLSM made with fly ash and GGBS. The average 12hrs compressive strength of CLSM made with GGBS was about 0.56 to 1.03*MPa*, lower than that of the control mixtures. As the curing period increased, the strength value of GGBS specimens increased more than the control mixtures. Compressive strength development depends upon the GGBS replacement percentage and mortar age. The glassy compounds in GGBS react slowly with water and it takes time to obtain hydroxyl ions from the hydration product of Portland cement to break down the glassy GGBS parcels at an early age. The GGBS mixes that have no cementing or pozzolanic properties exhibited the lowest strength of all at the early age. Some studies show GGBS as slowly reactive [19], and adding GGBS retarded concrete setting time [20]. However, BS60-7 has highest compressive strength than other specimens at 56 days due to the nearly accomplished hydration and pozzolanic reaction. Higher GGBS replacement percentage has higher ultimate strength within the range of this study as Table 4 indicates.

Property of Permeability

Fig. 8 shows the initial surface absorption test results at intervals of 10, 30, and 60mins. This study uses the permeation indices for classifying concrete durability quality in terms of low, medium, or high permeation. According to Kumar [21], when initial surface

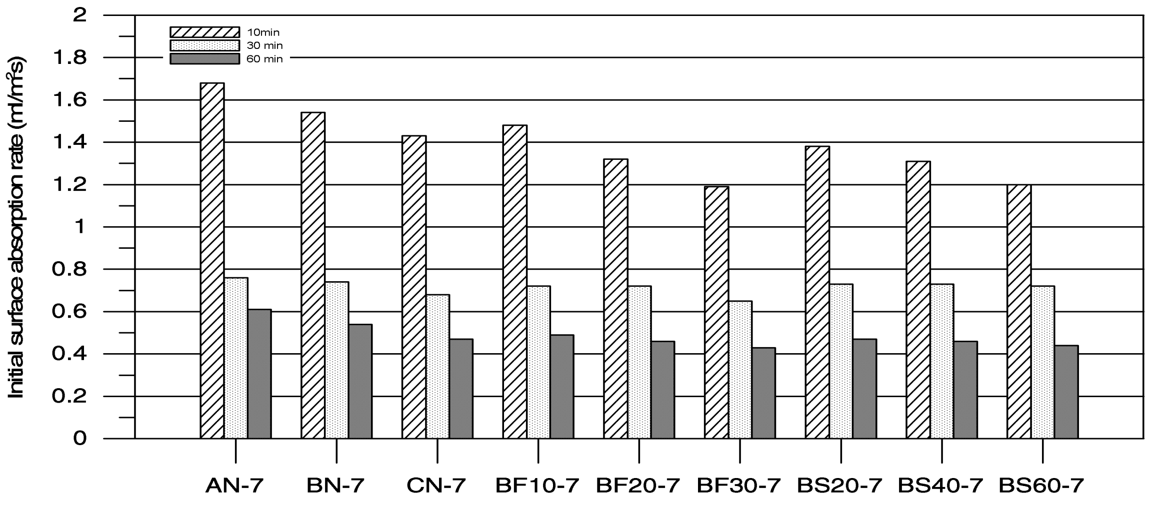

Fig. 8. ISAT Plot for Various CLSM Mixes.

absorption (ISA) rate at 60mins is higher than 0.2*ml/m*^{2}*s*, concrete permeation is high. When ISA rate at 60mins is between 0.1 to 0.2*ml/m*^{2}*s*, concrete permeation is average. Owing to the high water content of CLSM specimens, permeation values in Fig. 8 were high, in the range of 0.43-0.61*ml/m*^{2}*s* which is acceptable for construction proposes. However, permeation values slightly decreased for all mix designs with GGBS and fly ash addition. This result indicates reduced pore sizes since binder hydration is pozzolanic material dependent. Nevertheless, the differences in these values are very small and can be regarded as negligible.

Conclusions

This study illustrates the influence of CFBC bottom ash on CLSM properties and behavior. The conclusions are drawn as follows:

1. Replacing sand with CFBC bottom ash increased concrete unit weight value.
2. CLSM mixtures containing CFBC bottom ash as a replacement for sand produced lower flow values. At 20% CFBC bottom ash replacement, the flow dropped to 11.6*mm*. On the other hand, CLSM mixtures containing fly ash and GGBS as a replacement for cement, exhibited a slight increase in flow values with the increase of the fly ash and GGBS content.
3. Replacing sand with CFBC bottom ash up to 20% exhibited a higher compressive strength than specimens without CFBC bottom ash for 28 days of curing. The maximum compressive strength of 7.76*MPa* was achieved using 60% GGBS as a replacement for cement after 56 days of curing, when compared to 5.66*MPa* for the reference mixture.
4. The increased amounts of CFBC bottom ash may reduce mixture bleeding. Larger bleeding values are expected for GGBS mixes, due to their delayed setting.
5. Increasing CFBC bottom ash and fly ash contents reduced shrinkage in all mixes; increasing GGBS as binder replacement significantly increased shrinkage.
6. The ISA rate increased with an increase in CFBC replacement for sand. At 10 and 20% CFBC substitution for sand, the reductions in ISA rate value were 11.5 to 23.0%, respectively. Decreased ISA rate resulted in an increase in FA and GGBS replacement for cement in this study.

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