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A study on the mixed properties of green controlled low strength cementitious

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In this study, two industrial wastes – circulating fluidized bed combustion co-fired fly ash (CFA) and ground granulated blast-furnace slag (GGBS) – were used as green materials instead of cementitious materials in controllable low strength material (CLSM). CLSM was used to backfill the pavement. CLSM should meet the compressive strength requirements of the CLSM specification (under 8.24 MPa), and it had the self-consolidating characteristics of fluidized concrete. In order to comply with the characteristics of self-consolidation, a mix design including superplasticizers, adhesives, and accelerators were used to ensure that the proportion could meet the requirements of both CLSM and the self-consolidating properties. The test methods included the slump flow test, ball drop test, strength activity index, compressive strength, mercury intrusion porosimetry, chloride migration test, and scanning electron microscope. A water/cement ratio of 0.85 was used as the mix design for the CLSM requirements. The CFA and GGBS used in CLSM could replace 78 wt.% of the cement, and CLSM could effectively meet the requirements of the workability, strength and microscopic properties.

Keywords: *Co-fired fly ash; ground granulated blast-furnace slag; controlled low strength materials; self-consolidating concrete; green materials*

1. Introduction

Environmental awareness has begun to rise for all walks of life, and the concept of creating buildings with sustainable development and green building materials has emerged in the civil engineering community, with the hope of creating a pollution-free society for future generations. Taiwan has a narrow landmass and a dense population, and environmental pollution has had a considerable impact. People should cherish the land that they have. While enjoying these social resources, people can also improve their thinking about environmental protection. One must not forget where natural resources come from so that future generations can have land with a clean quality of life.

According to *Ellen* Macarthur's analysis report in the World Economic Forum [1], the circular economy can create output values that include a net income of 500 million US dollars for 5 years, 100,000 job opportunities, and avoid 100 million tons of material waste. Besides, it potentially saves 1 trillion US dollars in material costs every year and creates 1 million potential jobs in the renewable manufacturing and recycling industries. In addition, greenhouse gas emissions and global demand for cement are increasing. Carbon dioxide emissions from the cement industry are the major sources of greenhouse gas emissions [2]. In the circular economy, recycled green construction materials have diversified engineering applications, including research on the substitution of pozzolanic materials as a substitute for cement, and research on the replacement of aggregates with materials that do not contain the attributes of pozzolanic materials. According to the 2019 Global Carbon Bud-

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get Survey, China is one of the four largest carbon dioxide emitters in the world. As shown in Fig. 1, the world's six largest emitters include China (28%), the United States (15%), the EU 28 (9%), India (7%), Russia (5%), and Japan (3%). China's growth rate is about 2%. From Fig. 2, it can be seen that cement emissions temporarily rank third [3].

In the construction industry, controlled low strength material (CLSM) [4–10] is a construction material that can effectively reuse industrial waste in large quantities. We tried to deal with sustainable development issues as by-products that had been recommended in the production of CLSM with the characteristics of high workability and low strength materials, and it could be seen that the direction of use was relatively unique from that of other materials, and the self-condensing properties could replace the earthwork backfilled after a pipeline operation [11–14]. The design compressive strength of the backfill material reference source is shown in Table 1. When the CLSM replaced conventional backfilling soil, its relatively low strength can avoid the scope of the pipeline damage. CLSM could also be used in temporary works that required short excavations, making the CLSM a concept for which the improvements of time, construction, and the reduction of engineering costs had substantial and direct help. It could also help create the real target of recycling, reuse, and sustainable development goals [15, 16].

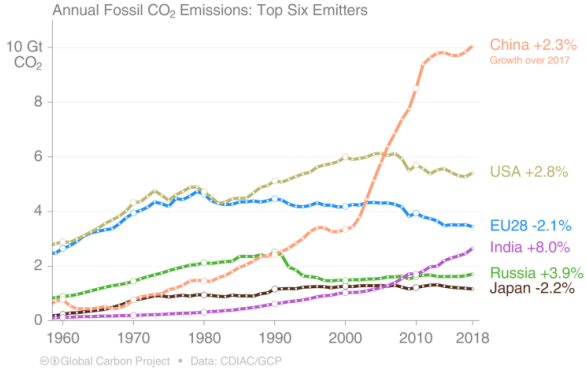


Fig. 1. Results of the 2019 Global Carbon Budget Survey (by country) [3].

Many research works have been initiated and developed worldwide with the intention of replacing the virgin ingredients of CLSM with different waste materials and/or by-products, such as fly ash and other materials [17, 18]. By-products or waste materials containing reasonable CaO content have been used to replace cement as a binder in CLSM, whereas materials with less or no cementing properties and coarser sizes have been used as aggregates in CLSM [19, 20]. Due to its comparatively low-strength requirements for ingredients, CLSM has been heavily targeted for high-volume waste recycling [21]. Industrial wastes in CLSM were mainly used as a large replacement by cement or cementitious material, and the application of CLSM was made to achieve the waste reuse in geotechnical applications such as structural backfill, pavement bases or pipeline beddings [21–24]. In this study, industrial wastes have been successfully used to replace the cement by the combination of co-fired fly ash (CFA) and ground granulated blast-furnace slag (GGBS). CFA is a new by-product from circulating fluidized bed combustion (CFBC). CFBC technology has high efficiency, low pollution, good coal adaptability, strong load regulation ability, relatively low cost, and relatively easy to master technology [25–27]. For CFA [28], CaO (35.00%) is the largest amount of fly ash product, followed by SiO_2 (29.46%) and the Al_2O_3 (19.00%), and with a higher amount of SO_3 (7.00%) than cement. CFA contains a large amount of free CaO and performs great pozzolanic behaviour. CFA can be used to activate GGBS and its advantage is that it helps to form hydration

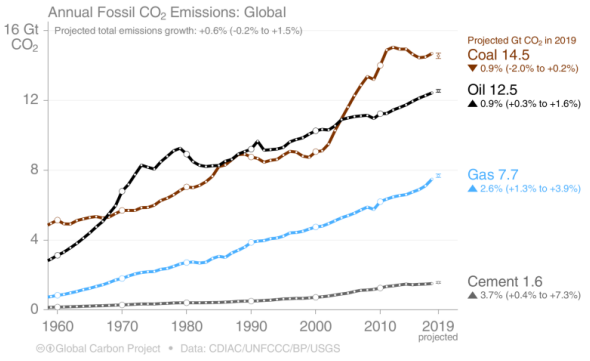


Fig. 2. 2019 Global Carbon Budget Survey Results (by Industry) [3].

products [29–31]. GGBS [32–34] is obtained by quenching molten iron slag (a by-product of iron and steel-making) from a blast furnace in water or steam, to produce a glassy, granular product that is then dried and ground into a fine powder. GGBS is highly cementitious and high in CSH (calcium silicate hydrates), which is a strength enhancing compound that improves the strength, durability and appearance of the concrete. The chemical composition of the GGBS after production is similar to that of cement. For this aspect, the reuse of GGBS and CFA as a substitute for cement in CLSM is promising. In addition, CFA can be usually accompanied as cement substitutes in CLSM due to industrial development especially in Taiwan and China. No particular restrictions exist for CLSM, so it can contain CFA to alleviate the problem of inadequate landfill space and reduce secondary pollution. Also, the combination of CFA and GGBS can keep the strength and applicability requirement of CLSM.

The aim of this study was to develop a low cement dosage in CLSM using CFA and GGBS as a cement replacement. This is because CFA is one kind of waste material with an extremely low reuse rate in Taiwan. Various experiments involving the strength activity index, fresh properties, compressive strength, chloride migration test, scanning electron microscope (SEM) energy-dispersive analysis (EDS) analysis, and mercury intrusion porosimetry (MIP) were performed on the fresh properties, mechanical properties, and microscopic properties of the developed green CLSM. The study also confirmed the feasibility of CFA and GGBS to replace large quantities of cement in CLSM.

2. Materials and methods

2.1. Material

In this study, by-products with CFA and GGBS were used to replace cement (53–100 wt.%) and (50–100 vol.%), respectively. Two types of superplasticizers, one type of accelerator, two types of methylcellulose, and one type of adhesives were used to adjust the properties of the fresh mix to meet the self-consolidating properties. For the cementing material, CFA and GGBS were used to replace the cement with high content, with the hope of achieving the recycling economic benefits of waste reuse and replacing the cementing of up to 78% by volume in the concrete.

The coarse aggregates were mined from the Lanyang River. After taking into account the requirements of fluidity, a gradation with a maximum particle size of 13 mm was selected. The specific gravity of the coarse aggregates was 2.84 and the water absorption was 1.24%. The cement used in this study was Portland Type I cement from Taiwan Cement Co., Ltd. The main ingredients of the cement were 61.96% CaO and 20.42% SiO_2. The specific gravity of the cement was 3.15 and the specific surface area was 345 m^2/kg.

The composition of the cement met the requirements of the American Society for Testing and Materials (ASTM) C150. According to the chemical properties of the CFA in Table 2, the main chemical components were CaO, Al_2O_3, SiO_2, and a small amount of SO_3. The scanning electron microscope (SEM) photo is shown in Fig. 3, and the X-ray Diffraction (XRD) component analysis is shown in Fig. 4. The CFA that was studied in this experiment was introduced by Yongfengyu Group's Shinwu Plant, and it was produced by the combustion of a CFBC at Ahlstrom Company. The specific gravity of the CFA was 2.73 and the specific surface area was 280 m^2/kg.

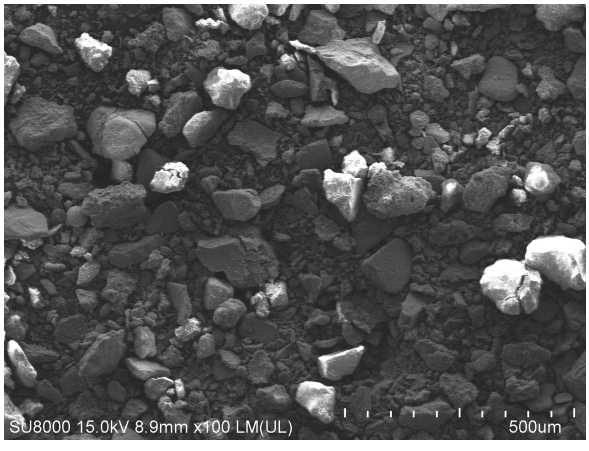


Fig. 3. SEM image of the CFA (100×).

Table 1. Designed compressive strength for various backfill materials [35–37].

Items	Backfill material	Compressive strength
1	Specification requirements	8.3 MPa (1200 psi)
2	Recommended strength	2.1 MPa (300 psi)
3	CLSM long-term compressive strength	0.3 MPa–2.1 MPa (50 psi–300 psi)
4	Equivalent to good compaction	0.35 MPa–0.7 MPa (50 psi–100 psi)
5	Foundation support	0.7 MPa–8.3 MPa (100 psi–1200 psi)
6	Subgrade	2.8 MPa–8.3 MPa (400 psi–1200 psi)
7	Can be manually mined	0.3 MPa (50 psi)
8	Reliable mechanical digging	0.7 MPa–1.4 MPa (100 psi–200 psi)
9	The strength that can be excavated only when using fine sand or fly ash as the granular material	2.1 MPa (300 psi)

Table 2. Chemical compositions of CFA.

Composition	Value (%)		Composition	Value (%)	
	Sample I	Sample II		Sample I	Sample II
Na_2O	0.75	0.00	Fe_2O_3	3.49	3.34
MgO	1.82	2.15	NiO	0.00	0.00
Al_2O_3	19.27	12.21	Co_2O_3	0.00	0.05
SiO_2	29.47	26.21	CuO	0.00	0.04
P_2O_5	0.47	0.67	ZnO	0.08	3.11
SO_3	7.36	10.35	As_2O_3	0.00	0.00
Cl	0.07	0.14	Br	0.01	0.04
K_2O	1.02	0.90	Rb_2O	0.00	0.00
CaO	35.54	40.24	SrO	0.05	0.04
TiO_2	0.55	0.49	ZnO_2	0.00	0.00
Cr_2O_3	0.00	0.00	Y_2O_3	0.00	0.00
MnO	0.05	0.05	ZrO_2	0.02	0.03

Table 3. Chemical compositions of CFA and GGBS.

Composition	CFA	GGBS
	Content, wt. (%)	
Silicon dioxide (SiO_2)	29.47	33.68
Aluminium oxide (Al_2O_3)	19.27	14.37
Ferric oxide (Fe_2O_3)	3.49	0.29
Calcium oxide (CaO)	35.54	40.24
Magnesium oxide (MgO)	1.82	7.83
Sulphur trioxide (SO_3)	7.36	0.66
Others	3.05	2.93

The GGBS was selected by following ASTM C989 [38], and it was made by smelting molten iron in the steelmaking plant of CHC Resources Co., Ltd. The molten slag produced with iron ore, limestone, coke, and flux was produced by high pressure. The water quenching blast furnace grate was produced by the water quenching process, the main chemical components of which were CaO, SiO_2, and Al_2O_3. Its properties are shown in Table 3. It had the properties of hydration and cementation that were caused by the reaction of the pozzolans. The surface area was 419 m^2/kg and the activity was 112% in 28 days. The SEM micrograph is shown in Fig. 5.

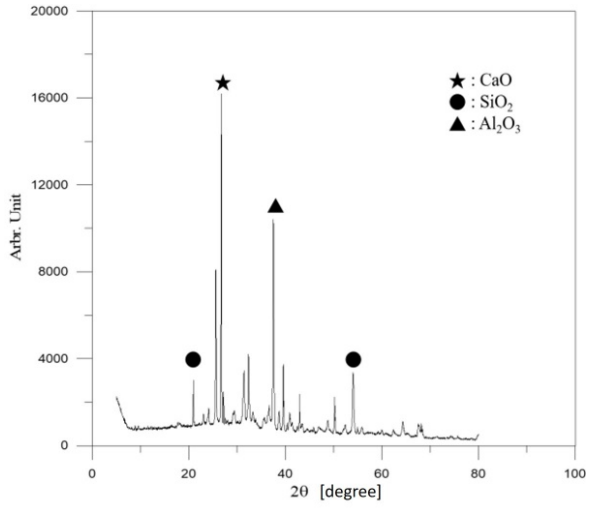


Fig. 4. XRD composition analysis of the CFA.

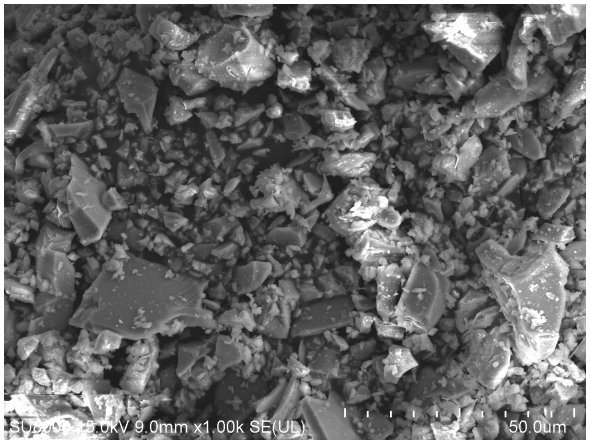


Fig. 5. SEM observation of the GGBS (1000).

2.2. Test methods and specimens

In this study, the reference specification American Concrete Institute (ACI) 229 [39] was used for the CLSM proportioning design. First, it was necessary to confirm whether the characteristics of the pozzolans were taken as the priority consideration and whether to replace the cementitious or aggregates. The materials were selected to reach the standard workability and compressive strength. Table 4 shows the mix design of the activity index test in cementation material. Besides, three specimens were tested for each mixture in our test, and then the results were averaged and compared. A standard deviation was controlled less than 5% for the tested results.

Table 4. Mix design for the activity index test (kg/m^3).

Specimen No.	Cement	Standard sand	CFA	GGBS	Water
A-C	500	1375			242
A-F	400	1375	100		252
A-S	400	1375		100	240

The recommended dosage of the CLSM according to the recommendations of ACI 229R is shown in Table 5. The recommended dosage of the cement was in the range of 30–120 kg/m^3. In the CLSM, the cement content was very small compared with that of ordinary concrete. However, the reason why the recommended dosage did not use cement was that cement replaced materials would have affected the material in terms of the cementing ability and the setting time. Therefore, the addition of a small amount of cement was an irreplaceable factor in the construction control of the proportioning design, followed by water. In terms of volume, the cement replaced materials were used in large quantities. If certain workability was required, more water was used than in ordinary cement concrete. Therefore, the water consumption was as high as 193 kg/m^3 to 344 kg/m^3, which accounted for 20%–35% by volume of CLSM. If a finer material was used, a higher content of water was used due to the effect of a specific surface area.

Table 5. ACI 229 recommended dosage for the CLSM.

Material	Recommended dosage (kg/m^3)
Cement	30–120
Class F fly ash (when used instead of fine particles)	0–1200
Class C fly ash	0–210
Fine aggregate	1500–1800
Water	193–344
Water (when using Class F fly ash)	590

For the CLSM, the trial and error method was mainly adopted when carrying out the proportioning design. The recommended amount of CFA as

Table 6. Proportioning design of the CLSM pastes.

Numbering	CFA (%)	GGBS (%)
F100	100	0
F75	75	25
F50	50	50
F25	25	75
F0	0	100

cement-replaced material was used in a large range. The design was based on fluidity requirements. The amount of fine aggregate filled after the cement, CFA, water, and air content were determined. For the filling, the general dosage was about 1500–1800 kg/m^3, explained in Appendix A.4 of the National Standards of the Republic of China (CNS) 15865 in Taiwan. A typical CLSM contains about 5%–10% of Portland cement, and soil containing an upper limit of 20% can be used. In total, three batches of CFA and six mixing series were used to test the materials before and after the use of CFA and GGBS. The compression values that were obtained after mixing were too high to meet the compression value requirements of the CLSM specification.

In the proportioning design and concrete trial mixing, the proportioning design research that complied with the CLSM and self-consolidating concrete (SCC) regulations was completed. The proportioning design is shown in Table 6 and Table 7. Methylcellulose was used as the adhesive and the aluminate-based accelerators and carboxylic acid-based superplasticizer were used in the mixtures. SCC was defined according to ACI 237 [40] as highly self-consolidating ability with non-segregation. Without any mechanical tamping, the concrete can be filled into the formwork and wrapped with reinforcement in the filling pouring area. Table 8 is the evaluated properties of SCC self-consolidating capacity grade, which is the evaluation of CLSM performance in this study.

3. Test results and discussion

3.1. Strength activity index

The fluidities for the strength activity index testing of the Ordinary Portland Cement (OPC), CFA, and GGBS specimens are shown in Table 9. According to the standard of ASTM C311 [41], the fluidity of the OPC was 17 cm and the water amount was 242 g, as marked in Table 5. The CFA and GGBS had the same fluidity as the OPC group. The final amounts of water used were 252 and 240 g, respectively. It could be known that when the proportion of CFA was used, if the same fluidity needed to be maintained, either the water consumption had to be increased or a water reducing agent had to be added at the same time.

The results of the compressive test of the strength activity index at 7 and 28 days are shown in Table 10. It is worth knowing that the compressive strength of the CFA at 7 days was the same as that of the OPC group, but the compressive strength of the CFA was only 29% at 28 days. The improvement showed that the strength could be maintained in the early stage, and it had lower strength in the later age, which could meet the requirement of CLSM containing CFA.

As shown in Table 10, the calculated strength activity index of the GGBS was similar to the results of the CFA test at seven days, but it increased slightly to 112% at the age of 28 days. Considering the increase in the amount of GGBS for fluidity, it should be noted that the compressive strength was increased at the same time to avoid exceeding the upper limit of the CLSM requirements. The strength activity index of CFA decreases as the number of days increases may be because the sulphide of CFA has a micro-expansion effect on cement hydrates [42], resulting in a slight decrease in compressive strength, but it is still 75% higher than the ASTM C311 requirement [41].

3.2. Fresh properties

The freshly mixed properties according to Table 7 are shown in Table 11. These properties indicated that the T10 specimens could meet the requirements of the fresh properties of the CLSM.

Table 7. Mix design of CLSM (kg/m^3).

Mix No.	w/c	Cement	CFA	GGBS	Coarse Aggregates	Fine Aggregates	Water	Superplasticizer	Accelerator	Adhesive
T1	0.85	31.5	94.7	155.5	400.5	1304.0	242.5	22.1	3.2	0.060
T2		47.3	142.0	233.3		806.8	376.4		3.2	0.060
T3		34.7	104.2	171.1		1204.5	269.3		3.2	0.090
T4		69.3	136.9	101.4		1204.3	269.3		3.2	0.320
T5		69.3	162.0	76.0		1204.2	268.9		3.2	0.410
T6		104.0	121.5	88.7		1204.2	267.4		5.0	0.473
T7		69.3	162.0	76.0		1204.2	262.0		10.0	0.473
T8		69.3	162.0	76.0		1204.2	262.0		10.0	0.410
T9		69.3	162.0	76.0		1204.2	268.0		4.0	0.410
T10		69.3	162.0	76.0		1204.2	268.4		3.6	0.410

Table 8. SCC grading table.

Grade Type	1	2	3
Box test (mm)	Over 300 (R1 disorder)	Over 300 (R2 disorder)	Over 300 (Accessibility)
Flowability (mm)	650∼750	600∼700	500∼650
V type test (sec)	10∼25	7∼20	7∼20

Table 9. Fluidities for the strength activity index testing.

Type	Flowability (cm)	Water (g)
GGBS	16.0–21.0	230–260
CFA	11.5–22.4	230–270

Table 10. Pozzolanic strength activity index results.

Mix no.	Compressive Strength (MPa)	
	7 days	28 days
A-C	32.16	44.80
A-F	31.96	41.18
A-S	31.27	50.20
Material	Strength Activity Index	
	7 days	28 days
CFA	99%	92%
GGBS	97%	112%

The T10 specimens could meet the requirements of flowability (50.0 cm) and tube fluidity (20.0 cm). In addition, the mixture of T10 specimens had higher CFA to replace large quantities of cement in the CLSM. According to the strength of each recommended load in Table 1, the recommended lower limit of the compressive strength was 0.35 MPa, which showed good compaction for the CLSM. The suitability for the load application of the T10 specimens using a ball drop test could reach its performance 7.6 cm. After the actual measurement, the material could withstand the weight of a 75 kg heavy plate without deformation after 21 hours of mixing. According to the standard penetration tests, the cemented material could reach its recommended value of 50 psi. Therefore, mould removal and curing could be performed within 24 hours without damage to the concrete. According to the results of the compressive strength at seven days, the strengths in the indoor dry curing, saturated lime water curing, and atmospheric exposure curing methods were about 2.45–3.92 MPa. This showed that the standard penetration test resistance of the cementitious material in accordance with ASTM C403 met the CLSM requirement, as shown in Fig. 6. According to Table 8, T5 and T10 specimens meet the requirements of SCC grade 3 of V type test, box test and flowability. The best mix proportion of CLSM is 11% cement, 34% CFA and 55% GGBS, which can achieve the self-

consolidating ability.

Table 11. Fresh properties of the CLSM.

Mix no.	V type test (sec)	Box test	Flowability (cm)	Tube fluidity (cm)
T1	6	Pass	59.5	20.0
T2		Severe bleeding		
T3	4	Severe bleeding		
T4	6	Did not pass	57.5	23.0
T5	7	Pass	64.0	21.5
T6	6	Did not pass	49.5	19.5
T7	17	Did not pass	38.0	15.0
T8		Rapid hardening		
T9	11	Pass	46.5	18.5
T10	7	Pass	50.0	20.0

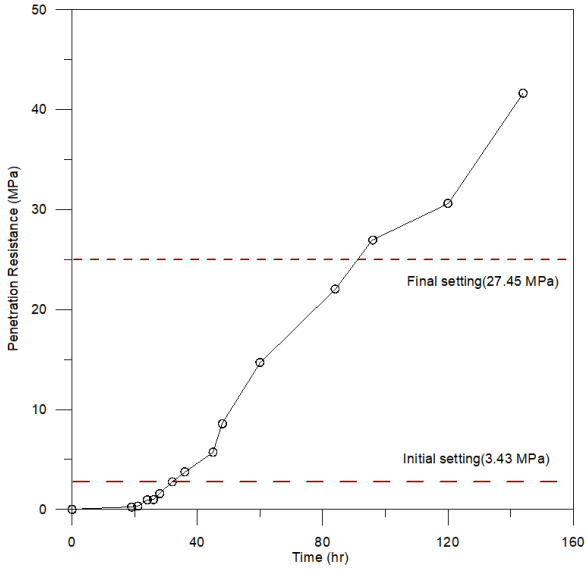


Fig. 6. Penetration Resistance vs. Time Curve.

3.3. Compressive strength for the pastes of the CLSM

In this test, a 100% replacement of the cement in the paste specimens was used to confirm the feasibility of the cementing materials in the CLSM. The mixing design is shown in Table 6. A water/cement ratio of 0.70 and five proportions were used for the paste specimens. After mixing, the specimens were demoulded for four days (as shown in Fig. 7) and then cured in the saturated lime water for seven days. This indicated that the F100 specimens could be demoulded, but the strength was extremely low, and the F100 specimens became a loose structure after being placed in the curing tank.

The demoulding of the F0 specimens (100% GGBS replacement of cement), as shown in Fig. 8, failed to have the ability to coagulate. The compressive strength at seven days was as illustrated in Table 12. The results showed that the compressive strength increased with the increase of the GGBS and the compressive strength of the F25 specimens increased by up to 9.80 MPa. This suggested that the CLSM specimens should use the higher water/cement ratio or the higher amount of CFA to meet the requirements of the CLSM standard.

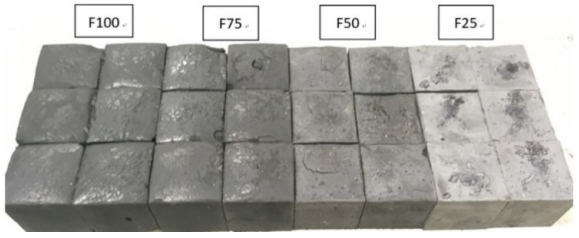


Fig. 7. Paste specimens for various CFA inclusion.



Fig. 8. F0 specimens demoulded at four days.

3.4. Compressive strength of the CLSM

The compressive strength results are summarized in Table 13 and Fig. 9. The compressive strength was between 2.84–6.18 MPa, which was

Table 12. Compressive strength of the paste specimens at seven days (MPa).

Paste specimens Value	F100	F75	F50	F25	F0
1	–	4.71	8.14	10.00	–
2	–	4.51	6.76	9.80	–
3	–	4.61	7.84	9.71	–
Average	–	4.61	7.58	9.84	–

the compressive strength of the CLSM. The compressive strength at 7 days was about 2.94 MPa. There were between 4.41–4.90 MPa at 14 days and between 5.39–5.88 MPa at 28 days. The curing methods were mainly divided into indoor dry curing (E), water curing (W), and atmospheric exposure (A). For indoor dry curing conditions, the test specimen was mainly placed in a dry indoor space to prevent water and gas intrusion. For atmospheric exposure, the site was mainly simulated after the grouting is completed, and the site was put directly into the atmosphere for curing operations. For saturated lime water curing, the test specimen was mainly placed in a lime-filled area. For different curing methods, the maximum differences between the testing and control groups were 1.78 MPa for 7 days, 2.16 MPa for 14 says, and 1.27 MPa for 28 days. At the age of 28 days, the strength growth tended to slow down and all three curing approaches neared 5.88 MPa.

The specimens at 7 days had the highest indoor dry curing and the lowest curing was in the atmospheric exposure group. Compared with the weather observation data (Table 14), the precipitation was large during the 1-day to 10-day curing age period. Although the temperature was high, the specimen was in a humid state for a long time. From 11 to 28 days, the test specimens were in a dry and high-temperature state. In the atmospheric exposure group, the values were lower than the other two groups at 7 days, and they had slowed down at fourteen days. It was inferred that the test specimens may have been dry and they may have had high temperatures. This made the intensity increase more quickly.

Table 13. Compressive strength (MPa).

Method	7-day	14-day	28-day
Atmospheric exposure (A)	2.84	5.20	5.78
Water curing (W)	2.94	4.51	5.39
Indoor dry curing (E)	3.43	4.31	5.59

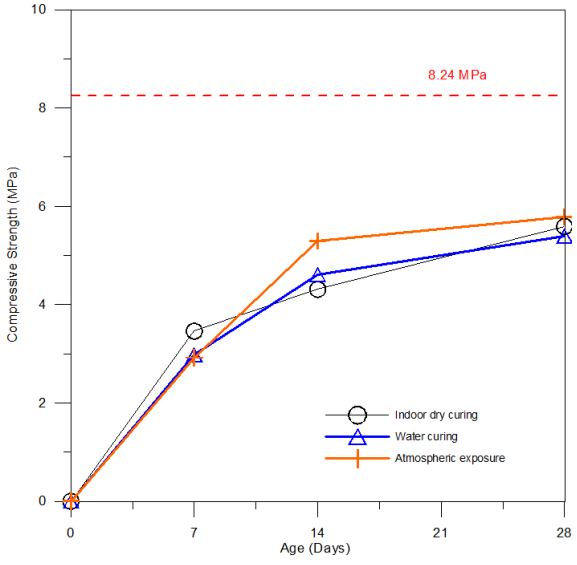


Fig. 9. Compressive strength development curves.

3.5. Accelerated chloride migration test (ACMT)

The accelerated chloride migration test (ACMT) according to the results of the initial current generated using 30 V is shown in Table 15. The current value generated by the 14-day age was about 70–140 mA, which was low when compared with the current value generated by the 7-day age (150–220 mA). The results showed that there was a downward trend in the diffusion coefficient at 7 days for atmospheric exposure, and the chloride ion diffusion coefficient of the specimens for indoor dry curing at 28 days was the highest than the other curing methods. The chloride diffusion coefficient decreased as the increase of curing age increased, which was consistent with the compressive strength. For indoor dry curing at the age of 28 days, the chloride diffusion coefficient was the lowest of the three curing methods, which was in line with the trend of higher compressive strength.

Table 14. Weather observation data.

Age	Temperature (°C)	Max. temperature (°C)	Min. temperature (°C)	Relative humidity (%)	Precipitation (mm)	Precipitation hours (hr)	Maximum hourly precipitation (mm)	Sunshine hours (hr)	Sunshine rate (%)
1	28.4	32.8	24.4	84	T	0.3	T	8.9	65.4
2	28.5	33.6	25.5	83	0.7	3.1	0.5	8.7	63.9
3	27.8	32.5	25.0	85	13.6	4.7	6.2	1.6	11.7
4	28.3	32.5	25.0	88	0.0	0.0	0.0	6.7	49.2
5	25.9	28.6	23.8	93	28.6	12.8	5.5	0.0	0.0
6	23.4	24.7	22.6	94	31.0	22.5	6.5	0.0	0.0
7	24.9	28.7	22.9	92	6.5	8.1	2.5	0.7	5.1
8	24.6	27.4	23.5	94	20.9	16.0	5.6	0.0	0.0
9	24.9	27.5	23.2	94	11.0	21.2	4.0	0.0	0.0
10	26.2	29.8	24.1	89	T	1.9	T	0.1	0.7
11	27.3	31.2	24.2	80	0.0	0.0	0.0	0.8	5.9
12	28.1	32.2	25.5	81	0.5	2.0	0.5	0.3	2.2
13	28.7	33.3	24.1	79	0.0	0.0	0.0	7.4	54.3
14	28.7	33.6	25.5	84	0.8	1.7	0.8	8.1	59.4
15	28.9	33.8	25.6	85	0.0	0.0	0.0	8.5	62.4
16	29.6	34.1	26.2	82	0.0	0.0	0.0	8.6	63.1
17	29.7	33.2	26.3	81	0.0	0.0	0.0	6.7	49.2
18	28.7	33.4	25.8	89	26.5	3.5	26.0	4.7	34.5
19	29.0	33.0	25.1	87	T	1.0	T	9.5	69.8
20	29.6	33.0	26.1	82	0.0	0.0	0.0	10.2	74.9
21	29.6	33.2	27.1	83	0.0	0.0	0.0	6.9	50.7
22	29.3	34.5	26.1	82	9.1	2.1	7.5	8.3	61.0
23	29.1	33.0	25.1	84	0.1	0.2	0.1	11.4	83.8
24	29.1	33.7	26.2	83	0.4	0.8	0.3	5.6	41.2
25	28.9	32.6	25.9	82	0.0	0.0	0.0	5.7	41.9
26	29.7	34.4	26.0	76	0.0	0.0	0.0	8.0	58.9
27	29.7	33.5	26.5	80	0.0	0.0	0.0	10.3	75.8
28	28.4	33.3	24.7	83	34.4	3.0	31.5	0.5	3.7

Remarks *T: rain (less than 0.1 mm), x: fault, V: Wind direction, /: unknown.

The specimens that were cured in water could be reflected in the better growth of the capillary pores, resulting in a lower diffusion coefficient. The specimens in atmospheric exposure conditions were also reflected in the low diffusion coefficient due to the random environmental dry and wet exposure. To keep the durability and to protect the infrastructures, the curing condition of CLSM in site construction should be considered.

Table 15. Chloride diffusion coefficient from the accelerated chloride migration test (10^{-12} m^2/s).

Method	7-day	14-day	28-day
Atmospheric exposure (A)	2.62	2.21	0.51
Water curing (W)	3.02	1.43	0.14
Indoor dry curing (E)	3.90	1.89	1.75

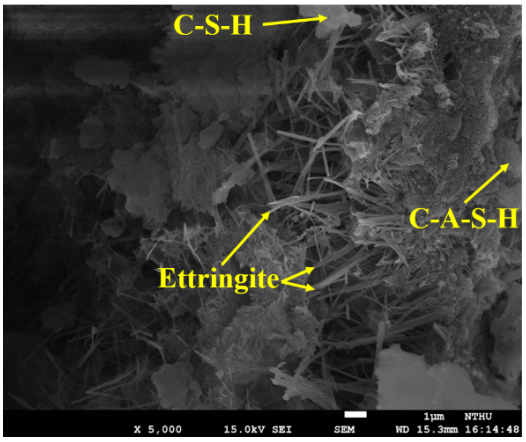
3.6. Scanning electron microscope (SEM)

The microscopic property observations and EDS analysis at 7 days for the atmospheric exposure are shown in Figs. 10 and 11. In the test results, the size of the main hydrated products was 2 µm. The characteristics could be judged to be those of ettringite based on the length and shape of the needle, and a small amount of C-S-H or C-A-S-H colloid could be observed, which as verified by EDS analysis. For 5000 magnification observations, the fracture of 1–5 µm could still be observed due to the random environmental dry and wet exposure. The EDS test results were mainly composed of oxygen, carbon, silicon, calcium, and aluminium. It was confirmed that the hydrated products might be C-S-H, C-A-S-H, ettringite, and monosulfoaluminate.

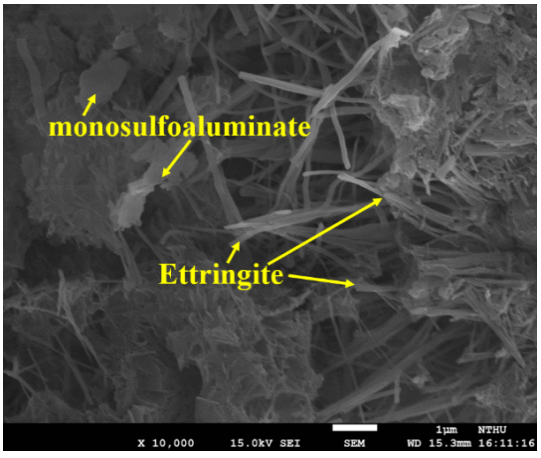
The microscopic property observations and EDS analysis at 28 days under atmospheric exposure are shown in Figs. 12 and 13. The observations and the analysis indicated that the filled hydrated products made the surface of the specimen denser, which was consistent with the results of the compressive strength and diffusion coefficients. The SEM photos at 28 days under the water curing and indoor dry curing are shown in Fig. 14. These photos indicated that there was evidence of further hydration with the pronounced formation of ettringite with needle-shaped structures and that a smooth surface was observed in the microstructures, especially for the specimens under the water curing conditions. The surface of the specimens with indoor dry curing could be seen to have more failure surfaces, an interfacial transition zone, and larger pores. It was also confirmed that the use of CFA and GGBS to replace large quantities of cement in the CLSM could be cemented and hydrated at a 28 day curing age under various curing conditions.

3.7. Mercury intrusion porosimetry (MIP)

MIP is an analytical index for capillary pores and gel pores. The distributions of the cumulative pore size diagrams are shown in Fig. 15. According to the experimental results, the pores sizes of the specimens at all ages were mainly distributed



(a) 5000 magnification



(b) 10000 magnification

Fig. 10. SEM photo of the T10 specimens under atmospheric exposure at 7 days.

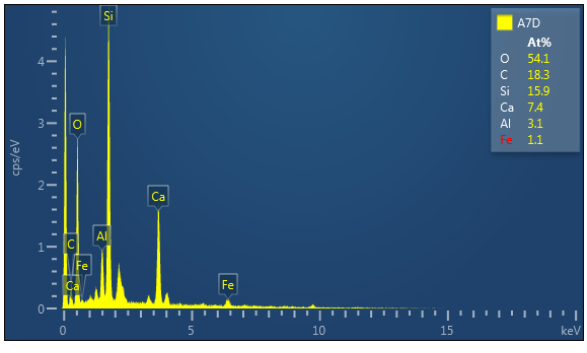


Fig. 11. EDS analysis of the T10 specimens under atmospheric exposure at 7 days.

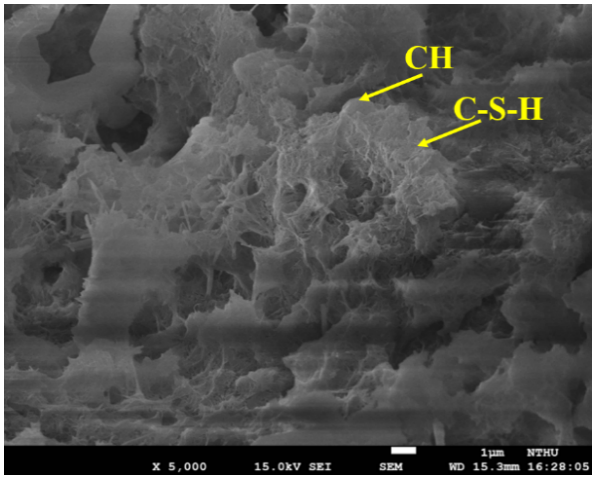


Fig. 12. SEM photo of the 5h3 T10 specimens under atmospheric exposure at 28 days (5000).

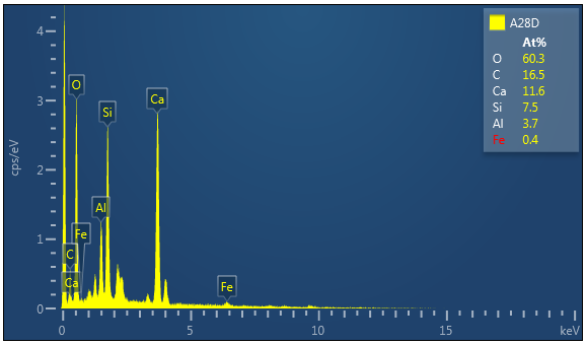
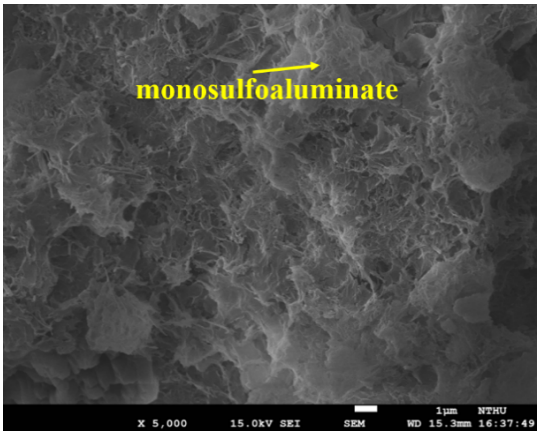
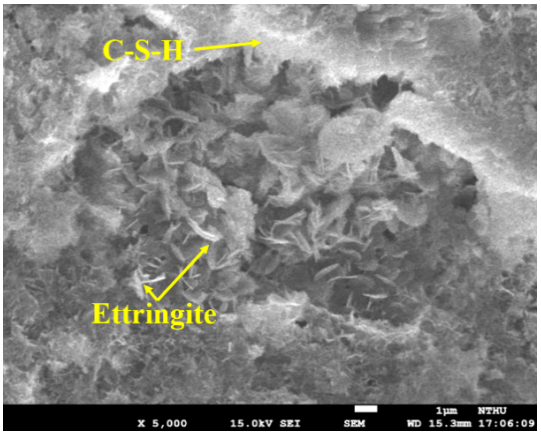


Fig. 13. EDS analysis of the 5h3 T10 specimens under atmospheric exposure at 28 days.



(a) water curing



(b) indoor dry curing

Fig. 14. SEM photo of the 5h3 T10 specimens for water curing and indoor dry curing at 28 days (5000 magnification).

between 10 nm and 4000 nm. The pore size distribution curves for three conditions were similar and the cumulative intrusions of the specimens were approximate between 0.13 ml/g and 0.15 ml/g. Fig. 16 demonstrates the relationship between a gel pore and a capillary pore for three curing conditions. The pores in hydrated cement paste could be categorized as either capillary (10–10000 nm diameter) or gel pores (3–10 nm diameter). Capillary pores are usually determined in cement-based composites using their compressive strength, permeability, and diffusivity. Gel pores are considered an intrinsic part of calcium-silicate-hydrate (C-S-H), which mainly affects concrete shrinkage and creep. A capillary pore system consists of many interconnected large pores, through which water, ions, carbon dioxide, and oxygen penetrate or diffuse into a rebar surface, deteriorate protective passive films, and cause corrosion. The capillary pores significantly increased in wet conditions. This may have been due to the leaching of calcium ions. For both the air and environmental conditions, the specimens had much fewer capillary pores than that for wet conditions. However, the specimens for three conditions still had a lower amount of gel pores due to the higher w/c ratio of 0.85.

3.8. Comprehensive comparison

The effects of the fresh properties in this study are summarized in Table 16. The CFA could effectively reduce and maintain a specific strength for

Table 16. Fresh properties for the mixing materials of the CLSM.

Material	Advantage	Disadvantage
CFA	Improve the consistency of the V type	Minimum slump Reduce the possibility of a box-type passage Reduce stress resistance
GGBS	Improve fluidity and slump Improve stress resistance	Increase compression value
Methylcellulose	Improve consistency Extend V-type test time	Reduce the possibility of a box-type passage Retard
Superplasticizers	Increase fluidity	Expensive
Accelerators	Offset time	Reduce slump

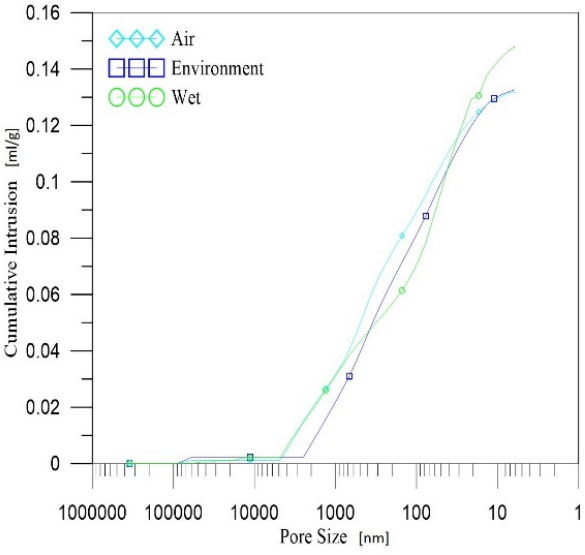


Fig. 15. Cumulative intrusion vs. pore size curves (28 days).

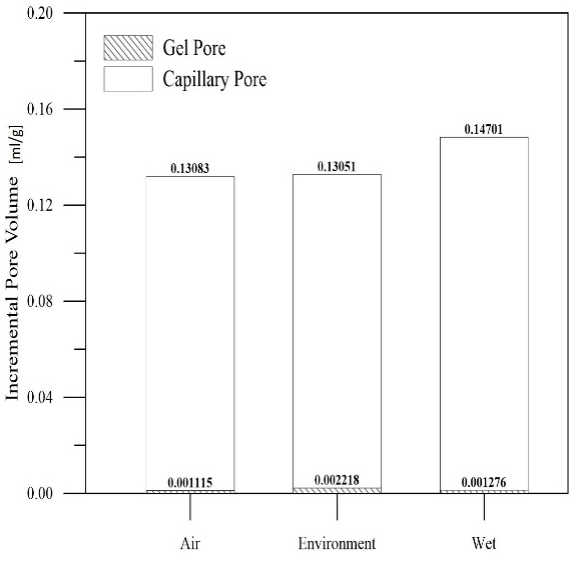


Fig. 16. Relationship between a gel pore and a capillary pore (28 days).

the CLSM and meet the compressive performance requirements of the CLSM.

The optimal mixtures that were obtained through the test results are summarized in Table 17. Table 15 shows that the mechanical properties had the lowest strength at 7 days from the environmental simulation. Through chloride ion diffusion tests and microscopic property observations, it was determined that the water absorption capacity was higher than the water absorption capacities of the water curing and indoor dry curing were, the group was high, and the chloride ion transmission rate was high. According to the observation of the microscopic properties, the width of pore cracks was about 5 μm, which is 1 to 2 times that of the other groups.

4. Conclusion

(1) High-volume CFA could provide material consistency, but if the same fluidity as that of other materials was required, higher water consumption was required due to its irregular particles.

(2) The pastes of the fully replaced cement could still be solidified and demoulded within four days, which proved that the research for the fully

Table 17. Optimal mix design of the CLSM using a higher amount of cement replacement.

Material	Value
Water–cement ratio	0.85
Cement	69.3 kg/m^3
CFA	162.0 kg/m^3
GGBS	76.0 kg/m^3
Coarse aggregate	400.5 kg/m^3
Fine aggregate	1204.2 kg/m^3
water	268.4 kg/m^3
Superplasticizers	22.5 kg/m^3
Adhesives	0.410 kg/m^3
Accelerators	3.6 kg/m^3
Unit weight	2527 kg/m^3

replaced cement still contained potential possibilities, and the fully replaced cement could be used as a special material.

(3) The test results showed that the suitable specific compressive strength of this study was in the range of 2.94 to 4.90 MPa. The compressive strength recommended by the literature review is between 2.10 MPa and 8.30 MPa, and the result in this study meets the requirements. This was the preferred range of compressive strength of the CLSM, which could be used as a CLSM backfill material with SCC performance. The optimal mix proportion of CLSM is 11% cement, 34% CFA, and 55% GGBS.

(4) The chloride ion diffusion coefficient was between $0.4\text{x}10^{-12}$ m^2/s and $1.75\text{x}10^{-12}$ m^2/s at 28 days for each curing condition. Water curing can improve the hydration of the specimens and make the microstructures more compact. The early hydration reaction of atmospheric exposure is faster and tends to slow down with the increase of curing age.

(5) It could be determined that there was no large difference between the water curing and the indoor dry curing by compressive strength test, microscopic properties, and chloride diffusion test. CLSM could cooperate with the grouting of the pavement for immediacy traffic flow or the surface layer construction with no maintenance.

(6) The use of CFA and GGBS to replace large quantities of cement (up to 78% wt. %) in CLSM could create cementation and hydration at 28 days under various curing conditions. The CLSM consisted of the combination of CFA, GGBS and cement had better performances in terms of fresh properties, mechanical properties, and microscopic properties.

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References

[1] Ellen Macarthur Foundation. (2014). Economic and business rationale. Toward the circular economy, (p. 98).

[2] K. Winans, A. Kendall, H. Deng, The history and current applications of the circular economy concept, Renew. Sustain. Energy Rev. 68 (2017) 825–83, https://doi.org/10.1016/j.rser.2016.09.123.

[3] Global Carbon Budget 2019, Global Carbon Project, https://www.globalcarbonproject.org/carbonbudget/19/files/GCP_CarbonBudget_2019.pptx.

[4] V. Alizadeh, S. Helwany, A. Ghorbanpoor, M. Oliva, R. Ghaderi, CLSM bridge abutments – Finite element modeling and parametric study, Comput. Geotech. 64 (2015) 61–71, https://doi.org/10.1016/j.compgeo.2014.10.015.

[5] V. Alizadeh, New approach for proportioning of controlled low strength materials, Constr. Build. Mater. 201 (2019) 871–878. https://doi.org/10.1016/j.conbuildmat.2018.12.041.

[6] T. Manh Do, G.O. Kang, Y. sang Kim, Development of a new cementless binder for controlled low strength material (CLSM) using entirely by-products, Constr. Build. Mater. 206 (2019) 576–589. https://doi.org/10.1016/j.conbuildmat.2019.02.088.

[7] S.K. Kaliyavaradhan, T.C. Ling, M.Z. Guo, K.H. Mo, Waste resources recycling in controlled low-strength material (CLSM): A critical review on plastic properties, J. Environ. Manage. 241 (2019) 383–396. https://doi.org/10.1016/j.jenvman.2019.03.017.

[8] J.G. Jang, S.M. Park, S. Chung, J.W. Ahn, H.K. Kim, Utilization of circulating fluidized bed combustion ash in producing controlled low-strength materials with cement or sodium carbonate as activator, Constr. Build. Mater. 159 (2018) 642–651. https://doi.org/10.1016/j.conbuildmat.2017.08.158.

[9] S.M. Park, N.K. Lee, H.K. Lee, Circulating fluidized bed combustion ash as controlled low-strength material (CLSM) by alkaline activation, Constr. Build. Mater.

156 (2017) 728–738. https://doi.org/10.1016/j.conbuildmat.2017.09.001.

[10] C.L. Hwang, C.H. Chiang, T.P. Huynh, D.H. Vo, B.J. Jhang, S.H. Ngo, Properties of alkali-activated controlled low-strength material produced with waste water treatment sludge, fly ash, and slag, Constr. Build. Mater. 135 (2017) 459–471. https://doi.org/10.1016/j.conbuildmat.2017.01.014.

[11] T.R. Naik, R.N. Kraus, R. Siddique, Controlled Low-Strength Materials Containing Mixtures of Coal Ash and New Pozzolanic Material, ACI Mater. J. 100 (2003) 208–215, https://doi.org/10.14359/12621.

[12] N. K. Lee, H. K. Kim, I. S. Park, H. K. Lee, Alkali-activated, cementless, controlled low-strength materials (CLSM) utilizing industrial by-products, Constr. Build. Mater. 49 (2013) 738–746, https://doi.org/10.1016/j.conbuildmat.2013.09.002.

[13] V. Alizadeh, S. Helwany, A. Ghorbanpoor, K. Sobolev, Design and application of controlled low strength materials as a structural fill, Constr. Build. Mater. 53 (2014) 425–431, https://doi.org/10.1016/j.conbuildmat.2013.12.006.

[14] R. Siddique, Utilization of waste materials and by-products in producing controlled low-strength materials, Resour. Conserv. Recycl. 54 (2009) 1–8, https://doi.org/10.1016/j.resconrec.2009.06.001.

[15] M. Etxeberria, J. Ainchil, M.E. Pérez, A. González, Use of recycled fine aggregates for Control Low Strength Materials (CLSMs) production, Constr. Build. Mater. 44 (2013) 142–148, https://doi.org/10.1016/j.conbuildmat.2013.02.059.

[16] M. C. Nataraja, Y. Nalanda, Performance of industrial by-products in controlled low-strength materials (CLSM), Waste Manag. 28 (2008) 1168–1181, https://doi.org/10.1016/j.wasman.2007.03.030.

[17] V. Alizadeh, Analytical study for allowable bearing pressures of CLSM bridge abutments, Transp. Geotech. 21 (2019) 100271, https://doi.org/10.1016/j.trgeo.2019.100271.

[18] T.M. Do, G.O. Kang, Y.S. Kim, Thermal conductivity of controlled low strength material (CLSM) under various degrees of saturation using a modified pressure plate extractor apparatus – a case study for geothermal systems, Appl. Therm. Eng. 143 (2018) 607–613, https://doi.org/10.1016/j.applthermaleng.2018.07.116.

[19] T.M. Do, A.N. Do, G.O. Kang, Y.S. Kim, Utilization of marine dredged soil in controlled low-strength material used as a thermal grout in geothermal systems, Constr. Build. Mater. 215 (2019) 613–622, https://doi.org/10.1016/j.conbuildmat.2019.04.255.

[20] E. Miren, A. Javier, P.M. Eugenia, G. Alain, Use of recycled fine aggregates for control low strength materials (CLSMs) production, Constr. Build. Mater., 44 (2013), pp. 142–148.

[21] Development of a Recommended Practice for Use of Controlled Low-Strength Material in Highway Construction, Dev. a Recomm. Pract. Use Control. Low-Strength Mater. Highw. Constr. (2008), https://doi.org/10.17226/13900.

[22] T.C. Ling, S.K. Kaliyavaradhan, C.S. Poon, Global perspective on application of controlled low-strength material (CLSM) for trench backfilling - an overview, Constr. Build. Mater., 158 (2018), 535–548, https://doi.org/10.1016/j.conbuildmat.2017.10.050.

[23] M. Lachemi, M. Şahmaran, K. M. A. Hossain, A. Lotfy, M. Shehata, Properties of controlled low-strength materials incorporating cement kiln dust and slag, Cem. Concr. Compos. 32 (2010) 623–629, https://doi.org/10.1016/j.cemconcomp.2010.07.011.

[24] Shulin Li, The Research on Quantitative Evaluation of Circular Economy Based on Waste Input-Output Analysis, Procedia Environ. Sci. 12 (2012) 65–71, https://doi.org/10.1016/j.proenv.2012.01.248.

[25] G. Sheng, J. Zhai, Q. Li, F. Li, Utilization of fly ash coming from a CFBC boiler co-firing coal and petroleum coke in Portland cement, Fuel. 86 (2007) 2625–2631, https://doi.org/10.1016/j.fuel.2007.02.018.

[26] R. Conn, K. Sellakumar, A. Bland, Utilization of CFB fly ash for construction applications, Proc. 15th Int. Conf. Fluid. Bed Combust. (1999).

[27] Formosa Petrochemical Corp, Promotional Report of Reuse Technology and Applications of By-Product Gypsum Mixed with Fly Ash; Annu. Rep. (2005).

[28] H.D. Weng, Circulating fluidized bed boiler technology. Chem. Technol. 6 (1998) 180–193.

[29] N.M. Jackson, R. Mack, S. Schultz, M. Malek, Pavement Subgrade Stabilization and Construction Using Bed and Fly Ash, Proc. Word Coal Ash. (2007) 1–12.

[30] C.. Lin, G.; Wu, Study on comprehensive utilization of high-sulphidation ash from CFB boiler. Environ, Sci. Technol. 26 (2003) 62–63.

[31] Han, X.; Li, Q.; Niu, M.; Huang, Y.; Jiang, X, Combined fluidized bed retorting and circulating fluidized bed combustion system of oil shale: 1. system and key issues, Oil Shale 31 (2014) 42–53.

[32] Weilong Song, Zhiduo Zhu, Shaoyun Pu, Yu Wan, Wangwen Huo,Shigong Song, Jun Zhang, Kai Yao, Lele Hu, efficient use of steel slag in alkali-activated fly ash-steel slag-ground granulated blast furnace slag ternary blends, Construction and Building Materials, 259(2020), 1–13, https://doi.org/10.1016/j.conbuildmat.2020.119814.

[33] Suman Saha, C. Rajasekaran, Enhancement of the properties of fly ash based geopolymer paste by incorporating ground granulated blast furnace slag, Construction and Building Materials, 146 (2017), 615–620, http://dx.doi.org/10.1016/j.conbuildmat.2017.04.139

[34] Xiaobin Wei, Dongqing Li, Feng Ming, Chengsong Yang, Lei Chen, Yuhang Liu, Influence of low-temperature curing on the mechanical strength,hydration process, and microstructure of alkali-activated fly ash and ground granulated blast furnace slag mortar, Cement

and Concrete Composites, 269(2021), 1–14, https://doi.org/10.1016/j.conbuildmat.2020.121811

[35] B.W. Ramme, C.F. Scholer, ACI 229R-99 Controlled Low-Strength Materials Reported by ACI Committee 229, Concrete. (n.d.), 1–15.

[36] A. Katz, K. Kovler, Utilization of industrial by-products for the production of controlled low strength (CLSM), Waste Manag. 24 (2004), 501–512, https://doi.org/10.1016/S0956-053X(03)00134-X.

[37] C.S. Shon, A.K. Mukhopadhyay, D. Saylak, D.G. Zollinger, G.G. Mejeoumov, Potential use of stockpiled circulating fluidized bed combustion ashes in controlled low strength material (CLSM) mixture, Constr. Build. Mater. 24 (2010), 839–847, https://doi.org/10.1016/j.conbuildmat.2009.10.022.

[38] ASTM, Standard Specification for Slag Cement for Use in Concrete and Mortars, ASTM Stand. 44 (2013) 1–8, https://doi.org/10.1520/C0989.

[39] ACI Committee 229, Report on Controlled Low-Strength Materials, (2013) 22.

[40] ACI 237R, Self-Consolidating Concrete, American Concrete Institute, (2007).

[41] ASTM C 311-04, Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete., Annu. B. ASTM Stand. 04.02 (2005), 204–212.

[42] K. Chen, W.T. Lin, W. Liu. Microstructures and mechanical properties of sodium-silicate-activated slag/co-fired fly ash cementless composites, J. Clean. Prod. 277 (2020) Article 124025, https://doi.org/10.1016/j.jclepro.2020.124025.

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