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Improvement of engineering properties of pond ash based CLSM with cementless binder and artificial aggregates made of bauxite residue

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Abstract

Background: Controlled low strength material (CLSM), known as flow able fill is used as a replacement of compacted soil in cases where the application of the latter is difficult or impossible. The low mechanical requirements compared with concrete enable the use of industrial wastes for the production of CLSM.

Methods: A study was conducted to investigate the feasibility of newly developed controlled low strength material (CLSM) using industrial wastes (pond ash, artificial aggregate made by red mud) and cementless binder as a full substitute of Portland cement in mixtures. The compressive strength of pond ash based CLSM binded with Portland cement meets in the desirable range of excavatable CLSM while pond ash based CLSM binded with cementless binder, which fully replaces the cement, shows slightly lower strength than excavatable CLSM strength ranges. In order to improve engineering properties of pond ash based CLSM binded with cementless binder, artificial aggregate that was made of Bauxite residues, red mud, was mixed with pond ash. Several mixtures made with binders and aggregates were systematically tested to determine the engineering properties of controlled low strength material such as flow consistency, compressive strength and thermal conductivity.

Results: Expectedly, particle size distribution analysis result of pond ash was transformed from poorly graded sand to well graded sand mixture in USCS. After the combination of pond ash with artificial aggregate, the engineering properties of CLSM were improved.

Conclusion: A compressive strength of pond ash-artificial aggregate mixture is remarkably increased and meets the requirement of excavatable CLSM of ACI even though binded with cementless binder. Furthermore, flow consistency of all CLSM mixtures has reached highly flowable range of 200 ~ 300 mm conformed by the American Concrete Institute (ACI 229R). In addition, a significant point for flow consistency is that cementless binder can be a good component material to control the segregation separation of constituents in proposed mixtures. For the purpose of the use of proposed CLSM as a backfill material for underground boreholes and pipes, a thermal conductivity was also measured. Sufficiently high values (over 0.8W/mK) of thermal conductivity found demonstrate that the proposed mixtures are appropriate to the practical application of backfill materials for underground boreholes and pipes.

Keywords: CLSM; Pond ash; Bauxite residue; Artificial aggregate; Cementless binder

Introduction

Recently, there has been an increasing interest in the development of Controlled low strength materials (CLSM) in numerous fields such as backfill, utility bedding, void fill, pavement bases. The American Concrete Institute ACI 229 R-99 defines a CLSM as a self-compacting, cementitious material used primarily to replace conventional backfill soil and structural fillings. There are various inherent advantages of using CLSM instead of compacted fill in these applications. These benefits include reduced labor and equipment costs (due to self-leveling properties and no need for compaction), faster construction, and the ability to place material in confined spaces. The relatively low strength of CLSM is advantageous because it allows for future excavation, if required. Another advantage of CLSM is that it possibly contains by-product materials, thereby reducing the demand on landfills, where these materials may otherwise be deposited and contributing towards the sustainable development (Razak et al. 2009).

With the subject of CLSM development, several successful studies have been recently published such as beneficial reuse of foundry sands in controlled low strength material (Dingrando et al. 2004), development of controlled low strength materials using CKD (Thaha 2008), utilization of waste materials and byproduct in producing controlled low strength materials (Siddique 2009), beneficial reuse of construction surplus clay in CLSM (Wu and Lee 2011), application of CLSM with incinerated sewage sludge ash and crushed stone powder (Fujita et al. 2010), controlled low strength materials made using bottom ash and quarry dust (Naganathan and Razak 2012), engineering properties of controlled low strength material containing waste oyster shells (Kuo et al. 2013), development of controlled low-strength material derived from beneficial reuse of bottom ash and sediment for green construction (Yan et al. 2014). Most previous studies have individually focused on CLSM made with Portland cement or a partial replacement of cement.

The main interest of this study consists in the new development of excavatable controlled low strength material using wastes (pond ash, artificial aggregate made by red mud, a solid waste produced in the process of alumina production from bauxite) and cementless binder as a full replacement of cement in CLSM mixtures. Several mixtures made with binders and aggregates were tested to determine the engineering properties of controlled low strength materials such as flow consistency, compressive strength and thermal conductivity. In general, the ability to excavate CLSM at later ages is an important consideration on many projects and if future re-excavation is expected for maintenance purposes, the compressive strength should be limited less than 1.4 MPa (ACI 229 R-99, 2005; Sheen et al. 2013). The flowability conforming ASTM D6103 (2004) Standard Test Method for Flow Consistency of CLSM should be targeted between 20cm and 30cm, not so low for self-leveling, not so high that, however, excessive bleeding or aggregate segregation occurs. In addition, toward objective evaluation of CLSM used as backfill materials for underground boreholes and pipes, thermal conductivity was also measured in this study.

Experimental program

Materials

In CLSM mixtures, aggregates provide the solids to develop compressive strength, as well as load carrying capacity whereas binders, supplementary cementitious materials

and water are important ingredients in all CLSM mixtures with the hydration process that enable CLSM to be cohesive and hence harden to develop strength.

In this study, Portland cement conforming to ASTM C150 (2004) was firstly used as a cementitious material. In addition, the cementless binder, an inorganic binder made of dehydration material 50 %, Inactivator 20 %, Slag 30 %, was also employed as cement substitute in this investigation. It is a combination of fly ash concatenated irregular three dimensional structures with Ca^{2+} , Mg^{2+} , Al^{3+} and other ions.

With a generation of 3,245 MW thermal power plants every year, a large of ponded ash are being produced and stored at Gwangyang area. The disposal of pond ash will be a big challenge in the near future for Korea to decrease harmful environmental effects. Therefore, finding alternative use of this waste material and its use in construction is one of the effective methods of utilization. Increase in demand and decrease in natural resource of fine aggregate (e.g., sand) for construction have resulted in the need of identifying a new source of fine aggregate. The possibility of utilization of thermal power plant by-product pond ash as replacement to find aggregate in construction is taken into consideration (Kim et al. 2014 and Do et al. 2015). In this study, Pond ash (PA) produced from cogenerate plants was used, conformed to the ASTM C33 (2004), as a fine aggregate in a production of CLSM and its specific gravity at room temperature was 2.15.

Artificial aggregate (AA) primarily made with red mud was also used as the partial replacement of pond ash in order to improve the engineering properties of CLSM binded with cementless binder. The specific gravity and water absorption of artificial aggregate are 1.89 and 16.92 %, respectively. The chemical compositions of pond ash and artificial aggregate are detailed in Table 1. The artificial aggregate was also tested for environmental impacts before using as a construction material. As a result, the presence of hazardous substances in the artificial aggregate conformed to the Korean standard of waste fair test as shown in Table 2. The particle size distribution curves and photograph of PA and AA are shown in Fig. 1 & Fig. 2. From the particle size distribution curves, PA and AA were classified as a soil of SP (poorly graded sand) and GP (poorly graded gravel), respectively.

Interestingly, from Fig. 1, it can be found that a mixture of pond ash and artificial aggregate is classified as a well graded soil (SW) that probably provides a good pore-

Table 1 Chemical composition of pond ash and artificial aggregate

Chemical composition (%)	Ponded ash (PA)	Artificial aggregate (AA)
SiO ₂	52.84	25.8
Al ₂ O ₃	22.55	20.8
Fe ₂ O ₃	18.81	23.8
MgO	2.09	-
SO ₃	0.01	-
K ₂ O	1.04	0.09
N ₂ O	0.2	10.5
CaO	-	2.68
TiO ₂	-	5.39
MnO	-	0.06
P ₂ O ₅	-	0.03

Table 2 The presence of hazardous substances in the artificial aggregate

Analyte	Units	Results	Threshold requirements	Standards used
Lead	mg/L	0.14	<3.0	Korean waste fair test criteria :2014
Copper	mg/L	No detection	<3.0	Korean waste fair test criteria :2015
Arsenic	mg/L	No detection	< 1.5	Korean waste fair test criteria :2016
Mercury	mg/L	No detection	< 0.005	Korean waste fair test criteria :2017
Cadmium	mg/L	No detection	< 0.3	Korean waste fair test criteria :2018
Cyanogen	mg/L	No detection	< 1.0	Korean waste fair test criteria :2019
Chromium VI	mg/L	No detection	< 1.5	Korean waste fair test criteria :2020
Organophosphorus	mg/L	No detection	< 1.0	Korean waste fair test criteria :2021
Oily	%	0.3	< 5.0	Korean waste fair test criteria :2022
PCE	mg/L	No detection	0.3	Korean waste fair test criteria :2023
TCE	mg/L	No detection	0.1	Korean waste fair test criteria :2024

filling function for CLSM mixtures after the combination. Soil classification parameters based on ATSM D2487 Standard Practice for Classification of Soils for engineering purposes are summarized in Table 3.

Fly ash produced from Cogeneration plant conforming in ASTM C618 (2004) was used in CLSM to effectively improve the fluidity or flowability of mixtures with its fineness and spherical shaped particles. Its specific gravity is 2.3.

Mixture proportions and test methods

As reported by Du et al. (2002), material constituents in mixture are generally known to have strongly influence on the performance of CLSM. Thus, in order to thoroughly understand about it, two groups with fresh mixtures were prepared, namely G-PA (Pond ash based CLSM) and G-PA + AA (Pond ash-artificial aggregate mixture based CLSM) corresponding with aggregate constituents. Furthermore, a series of mixtures with various water-binder ratios (W/B) were adopted to investigate the effect of binder

Fig. 1 Particle size distribution curves of PA, AA and PA + AA mixture

Fig. 2 Artificial aggregate and its particle size

amount to the properties of CLSM in which the quantities of binders were systematically varied from 4.0 to 5.41.

Aggregates and binders were first placed in a tilting type of the mixer. And designed amount of water was added and mixed for at least 15 minutes. All mixtures of both groups G-PA and G-PA + AA given in Table 4 were evaluated for flowability, compressive strength and thermal conductivity. For flowability test, the open-ended cylinder of 75×150 mm was used to measure the diameter of spread in two perpendicular directions to determine the flow consistency. The flowability of the mixed samples was tested immediately after mixing following ASTM D6103 (2004). Compressive strength test was further performed on 55×110 mm cylindrical specimens molded in plastic molds and then stored under a saturated condition with a water bath that can maintain the temperature immediately adjacent to the cylinders until desirable testing times of 3 days, 7 days and 28 days as presented in ASTM D4832 (2004). The universal testing machine with loading rate 1.1 mm/minutes was employed for unconfined compressive strength tests. Each strength test was carried out on three cylindrical specimens and then the averages were recorded. Thermal conductivity was also measured according to the ASTM D5334 (2004) to verify the feasibility of CLSM as backfill materials for underground boreholes and pipes.

Test results and discussions

Flow consistency

As expected for all CLSM mixtures, flow consistency ranged from 22cm to 28cm satisfying the standard requirement reported in ACI 229. It can be clearly seen from Fig. 3 that the flow consistency increases with the increase of W/B ratio. This result is identical to Tripathi et al. (2004). The larger the amount of binders, the lower the flow consistency. It can be explained that mixtures containing more amount of binders probably need more mixing water for the hydration reaction. In addition, as shown in Fig. 4,

Table 3 Soil classification parameters

Soil types*	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_c	USCS	G_s
PA	0.1	0.387	2	20	0.747	SP	2.15
AA	5.12	6.09	7.55	1.48	0.96	GP	1.89
PA + AA	0.638	2.526	5.543	8.68	1.8	SW	-

Note: PA Pond ash, AA Artificial aggregate, D_{10} , D_{60} , D_{30} Particle diameter such that 10 %, 60 %, 30 % correspondingly of the soil grain are smaller than this size, C_u Coefficient of uniformity, C_c Coefficient of curvature, SP Poorly graded sand GP Poorly graded gravel, SW Well graded sand

Table 4 Mixture proportions of CLSM

Aggregate (%)	Fly ash (%)	Binders (%)	Water (%)
(56.58 ~ 57.43)	(14.89 ~ 15.11)	Cement (4.28 ~ 5.71)	(22.83 ~ 23.17)
		Cementless binder (CB)	

PA based CLSM mixtures has a remarkably higher flow consistency than (PA + AA) based CLSM. This is primarily due to the high water absorption of artificial aggregate. The replaced artificial aggregate may absorb the water and it makes the flowability of the mixture decreases.

In addition, a significant point for flow consistency is that cementless binder can be a good component material to control the segregation separation of constituents in proposed mixtures. It can be graphically visualized from Fig. 5, the segregation separation exhibited by the bleeding in the Portland cement bindered CLSM mixtures whereas there is no evidence of segregation observed from the CLSM mixtures made with cementless binder shown in Fig. 6.

Unconfined compressive strength

Figure 7 shows the increment in compressive strength due to the hydration process of cementitious materials, which gradually completed with curing ages. For pond ash based CLSM binded with Portland cement, the compressive strength at 28 days ranged from 0.5 to 0.99 MPa conforming to the strength requirement of re-excavation in ACI. However the compressive strength of pond ash based CLSM binded cementless binder ranged from 0.2 to 0.51 MPa, which was slightly lower than required strength. To improve the compressive strength of pond ash based CLSM, artificial aggregate which is made of bauxite residue was mixed with pond ash. Finally it was found that a pond ash-artificial aggregate mixture based CLSM shows huge increment in strength for both kinds of binder-cement and cementless binder.

This is primarily due to a good pore-filling function that could be made from a well graded mixture (SW) after mixing artificial aggregate with pond ash as shown in Fig. 1. In addition, as addressed by Chi and Huang (2013) and Lee et al. (2013), the compressive strength of specimens increases with an increase dosage of Na_2O because molarity of

Fig. 3 The flow consistency of CLSM mixtures made with pond ash (G-PA)

alkali solution increased more OH⁻ (hydroxide ions) hydrolyzed on the surface of fly ash. Hence, Si, Al and Ca species were dissolved to form C-S-H gel through polymerization resulting in a higher compressive strength of CLSM. From Table 1, it can be found that much higher dosage of Na₂O (10.5 %) was provided in pond ash-artificial aggregate mixture than pond ash. That is probably another reason for a dramatic increase in strength after combining artificial aggregate in mixtures. This finding plays a key role in verifying the feasibility of improvement of Engineering Properties of Pond ash based CLSM with Cementless Binder and Artificial Aggregates made of Bauxite Residue.

Thermal conductivity

Toward use of proposed CLSM as a backfill material for underground boreholes and pipes, thermal conductivity was measured at the age of 3 days, 7 days and 28 days for both groups G-PA and G-PA + AA with W/B = 4.6. Generally, the sufficiently higher

Fig. 6 Cement bindered CLSM

values than 0.8 W/mK of thermal conductivity were obtained as shown in Fig. 8 for all CLSM mixtures at any curing age.

Particularly, the first group G-PA consists of the pond ash based CLSM mixtures that have thermal conductivity of 0.85 ~ 0.89 W/mK whereas CLSM mixtures made with pond ash-artificial aggregate combination in G-PA + AA show higher values of 0.93 ~ 1.04 W/mK. Difference in thermal conductivity between both groups is remarkably observed at the age of 28 days shown in Fig. 9. This is predominantly due to the good pore-filling function that could be made from a well graded mixture after combination of pond ash and artificial aggregate as explained before. Mixing artificial aggregate with pond ash reduces the voids and provides more contact points between CLSM particles, consequently higher thermal conductivity was obtained regardless of binder.

Fig. 7 Compressive strength development of CLSM mixtures

Conclusions

The engineering properties of excavatable controlled low strength material using wastes and cementless binder as the full substitute of cement in mixtures were experimentally investigated. Based on the results, three main conclusions can be drawn as follows:

- 1) Flow consistency of all prepared mixtures has reached a desirable range of 20 ~ 30 cm conformed to the performance requirements for general flowability grade for CLSM. In addition, a significant point was found that cementless binder can control the CLSM segregation better than cement.
- 2) Using bauxite residue artificial aggregate, pond ash based controlled low strength material binded with cementless binder has reached a desirable range of 0.5 to 1.4. Main reasons of the strength increment were good pore-filling function and Pozzolanic reaction due to higher dosage of Na_2O from Bauxite residue artificial aggregate. This finding is very important when verifying the feasibility of Improvement of Engineering Properties of Pond ash based CLSM with Cementless Binder and Artificial Aggregates made of Bauxite Residue.

- 3) Toward use of proposed CLSM as a backfill material for underground boreholes and pipes, thermal conductivity was measured. Sufficiently high values (over 0.8W/mK) of thermal conductivity found demonstrate that the proposed mixtures are appropriate to the practical application of backfill materials for underground boreholes and pipes.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

TD carried out the series of experiments and drafted the manuscript. Manuscript was checked and revised by YK. BR developed the artificial aggregate using Bauxite residue.

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References

- American Concrete Institute (ACI) (2005). *Controlled Low Strength Materials (CLSM)* Aiken, South Carolina: Savannah River Site.
- ASTM C150. (2004). "Standard specification for Portland cement," *Annual book of ASTM Standards*, Vol. 04.02, PA 19428-2959, US.
- ASTM C33. (2004). "Standard Specification for Concrete Aggregates," *Annual book of ASTM Standards*, Vol. 04.02, PA 19428-2959, US.
- ASTM C618. (2004). "Standard Specification for Fly Ash And Raw Or Calcined Natural Pozzolan For Use As A Mineral Admixture In Portland Cement Concrete," *Annual book of ASTM Standards*, Vol. 04.02, PA 19428-2959, US.
- ASTM D4832. (2004). "Standard test method of preparation and testing of controlled low strength material (CLSM) test cylinders," *Annual book of ASTM Standards*, Vol. 04.02, PA 19428-2959, US.
- ASTM D5334. (2004). "Standard Test Method for determination of thermal conductivity of soil and soft rock by thermal needle probe procedure," *Annual book of ASTM Standards*, Vol. 04.02, PA 19428-2959, US.
- ASTM D6103. (2004). "Standard test method for flow consistency of controlled strength material (CLSM)," *Annual book of ASTM Standards*, Vol. 04.02, PA 19428-2959, US.
- Chi, M, & Huang, R (2013). Binding mechanism and properties of alkali-activated fly ash/slag mortars. *Journal of Construction and Building Materials*, 40, 291–298.
- Dingrando, JS, Edil, TB, & Benson, CH (2004). "Beneficial reuse of foundry sands in controlled low strength material", *Journal of ASTM international*, Vol. 1, No 6.
- Do, TM, Kim, YS, Dang, QM, Son, M, Yoo, BC (2015). "Development of excavatable controlled low strength materials made with cementless binder and partial replacement of artificial aggregate," *KSCOE National Conference 2015 / May 21-22*.
- Du, L, Kevin, JF, & David, T (2002). Effects of constituent materials and quantities on water demand and compressive strength of Controlled Low-Strength Materials. *Journal of materials in Civil Engineering*, 14, 485–495.
- Fujita, R, Horiguchi, T, Kudo, T, and Shimura, K (2010). "Application of CLSM with incinerated sewage sludge ash and crushed stone powder," *International conference on Sustainable construction materials and Technologies*, ISBN 978-1-4507.
- Kim, YS, Do, TM, Jung, SH (2014). "Recycling of ponded ash from a cogeneration plant as aggregate for excavatable controlled low strength materials," *KGS Spring National Conference 2014 / March 20-21*, pp. 408-415.
- Kuo, WT, Wang, HY, Shu, CY, & Su, DS (2013). Engineering properties of controlled low strength materials containing waste oyster shells. *Journal of Construction and Building Materials*, 46, 128–133.
- Lee, NK, Kim, HK, Park, IS, & Lee, HK (2013). "Alkali-activated. cementless, controlled low-strength materials (CLSM) utilizing industrial by-products", *Journal of Construction and Building Materials*, 49, 738–746.
- Naganathan, S, Razak, AH (2012). "Controlled low strength materials made using bottom ash and quarry dust," *M A Sc: University of Malsia, Kuala Lumpur*. ISBN 978-3-659-13681-8.
- Razak, HA, Naganathan, S, & Hamid, SN (2009). Performance appraisal of industrial waste incineration bottom ash as controlled low-strength material. *Journal of Hazardous Materials*, 172, 862–867.
- Sheen, YN, Zhang, LH, & Le, D-H (2013). Engineering properties of soil-based controlled low-strength materials as slag partially substitutes for Portland cement. *Journal of Construction and Building Materials*, 48, 822–829.
- Siddique, R (2009). "Utilization of waste materials and byproduct in producing controlled low strength materials", *Resources, Conservation and Recycling*, Vol. 54, pp. 1–8.
- Thaha, W (2008). "Development of controlled low strength materials using CKD," *M A Sc: Ryerson University. Toronto. Technical Services Engineer at St Marys Cement*. ISBN 978-3-639-06322-6.
- Tripathi, H, Pierce, CE, Gassman, SL, Brown, TW (2004). "Method for field and laboratory measurement of flowability and setting time of controlled low strength materials," *Journal of ASTM international*, Vol.1, No 6.
- Wu, JY, & Lee, M-Z (2011). "Beneficial reuse of construction surplus clay in CLSM. Int", *J. Pavement Res. Technol*, Vol. 4 No 5.
- Yan, DYS, Tang, IY, & Lo, IMC (2014). "Development of controlled low-strength material derived from beneficial reuse of bottom ash and sediment for green construction", *Journal of Construction and Building Materials*, Vol. 64, pp. 201–207.