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Engineering Properties of Flowable Fills with Various Waste Materials

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Abstract

Flowable fill is generally a mixture of sand, fly ash, a small amount of cement and water. Sand is the major component of most flowable fill with waste materials. Various materials, including two waste foundry sands(WFS), an anti-corrosive waste foundry sand and natural soil, were used as a fine aggregate in this study. Natural sea sand was used for comparison. The flow behavior, hardening characteristics, and ultimate strength behavior of flowable fill were investigated. The unconfined compression test necessary to sustain walkability as the fresh flowable fill hardens was determined and the strength at 28-days appeared to correlate well with the water-to-cement ratio. The strength parameters, like cohesion and internal friction angle, were determined for the samples prepared by different curing times. The creep test for settlement potential was conducted. The data presented show that by-product foundry sand, an anti-corrosive WFS, and natural soil can be successfully used in controlled low strength materials(CLSM), and it provides similar or better properties to that of CLSM containing natural sea sand.

Key words **:** CLSM, Flowable fill, Waste foundry sand, Anti-corrosive wfs, Unconfined compression strength, Creep test

1. Introduction

A controlled low strength material(CLSM) is a self-leveling and self-compacting cemented material used primarily as a backfill in lieu of compacted fill. Typically CLSM consists of sand as fine aggregate, fly ash, cement, and water. The typical mixture proportions of CLSM are 80 to 85% sand, 10 to 15% fly ash, and 5 to 10% cement by mass. The actual mixture proportions of these constituents vary depending on the physical properties of the materials and the intended use or requirements of the application (Ali et al., 1994; Bhat and Lovell, 1996).

In Korea, most of civil engineers have been skeptical about the use of CLSM in construction because of the lack of design properties and the perceived risks associated with any nontraditional material's performance. The objective of this research is to provide engineering properties of flowable fill containing various materials to expand the beneficial use of by-products and natural soil as backfill materials of underground structures. The specific purposes of this paper were as follows :

① Evaluation of mixing ratios, including compressive strength and flowability, of CLSM mixtures containing clay-bonded WFS, chemically bonded WFS, anti-corrosive WFS, and natural soil;

② Evaluation of the internal friction angle and cohesion for all the CLSM mixtures;

③ Evaluation of the settlement potential by static creep test and permeability test.

2. Experimental Investigation

2.1 MATIRIALS

Type I Portland Cement (ASTM-150) supplied by Sungshin Industries, Korea, was used in this research. Its specific gravity was determined to be 3.150. The fly ash used in this research was generated at Tae-An thermoelectric power plant in Tan-An peninsula that used anthracite coal as fuel. The fly ash was at the stage in the process just before refining for use cement mixing. Its chemical composition is given in Table 1 and it is classified as class-F fly ash.

The four different WFS, like green WFS, furan WFS, coated WFS and anti-corrosive WFS, and recycled in-situ soil were employed in this research. Its specific gravity measured was shown in Table 1, and the particle gradation properties of each WFSs are shown in Table 2. Table 3 shows the results of XRF (X-Ray Refraction) test of Portland cement, fly ash and each WFSs.

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Table 1. Specific Gravity of Each Material

Type	Natural Sea Sand	Waste Foundry Sand				Recycled In-Site Soil
		Green	Furan	Coated	Anti-Cor.	
Value	2.652	2.377	2.459	2.424	2.684	2.565

2.2 Mix Design Methodology (Flow Test & Determination of Mixing Ratio)

To find the point of minimum water demand (PMWD), the quantity of cement and WFS was fixed in the first stage and the points satisfying the flowability criterion set forth in previous section were connected increasing the quantity of water and fly ash shown in Fig. 1. This is done because flowability is controlled not only by water, but also by fly ash. The positive effect of fly ash on flowability is commonly believed to be the result of the spherical shape of the fly ash particles. This seems to be particularly true for mixes with low fly ash content. The fly ash particles most likely surround individual sand grains, and act as "ball bearings" during the flow, thus reducing the frictional resistance to flow, thus reducing the frictional resistance of the sand to flow. Consequently, the water demand to produce the same flowability decreases. Every point on the flow curve in Fig. 1 represents the same flowability. The most significant feature of flow curves is the Point D of Minimum Water Demand (PMWD), which gives the minimum amount of water that can produce the required flowability for a given combination of sand and fly ash. The ideal point for choosing the proportion of sand and fly ash for design purposes is the PMWD for the following reasons. The PMWD gives the minimum water-solid ratio, and therefore, should correspond to the minimum porosity. It is also important to consider, while designing a mix, the ease of handling

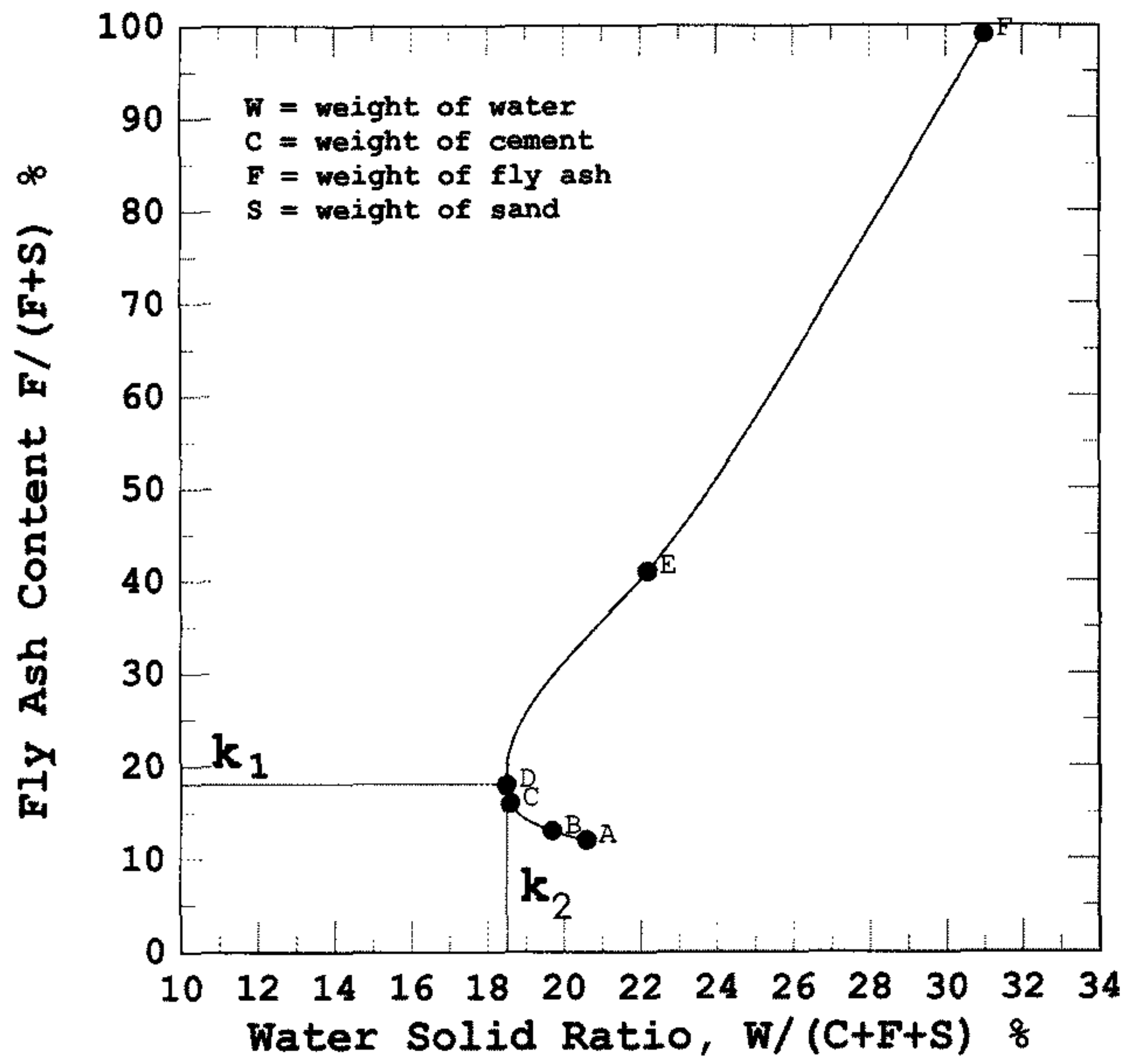

Fig 1. Decision of PMWD (Bhat & Lovell, 1966)

the flowable fill, the homogeneity of the mix, and the possibility of segregation. At high fly ash contents (above PMWD), the mix becomes highly viscous and sticky, and it takes a longer time to thoroughly mix the ingredients. This might cause delays in the field, and also may necessitate special equipment in the field to handle high fly ash content mixes (Bhat & Lovell, 1996).

From the results of flow tests, k_1, k_2, and k_3 are obtained

Table 2. Particle Distribution of Each Testing Materials

Type	Waste Foundry Sand				In-Situ Soil
	Green	Furan	Coated	Anti-Corrosion	
D_{10}, mm(in)	0.14(0.00551)	0.20(0.00787)	0.19(0.00748)	0.36(0.00142)	0.14(0.00551)
D_{30}, mm(in)	0.21(0.00827)	0.34(0.0134)	0.31(0.0122)	0.61(0.0240)	0.47(0.0185)
D_{60}, mm(in)	0.25(0.00984)	0.57(0.0224)	0.45(0.0177)	1.15(0.0452)	0.99(0.0389)
C_u*	1.79	2.85	2.36	3.19	7.29
C_c**	1.26	1.01	1.43	0.90	1.70

* : $C_u = D_{60}/D_{10}$, **$C_c = (D_{30})^2/(D_{10} \times D_{60})$

Table 3. Chemical Composition(%) of Each Material

Type	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	SO_3	CaO	MgO	K_2O	Na_2O	P_2O_5	L.O.I.
Cement	21.80	4.40	2.90	-	2.60	63.2	3.60	-	0.62	-	0.67
Fly ash	60.33	24.78	3.82	1.06	0.88	2.39	0.84	0.86	0.59	0.50	4.84
Green WFS	80.74	7.92	2.75	0.22	0.00	0.71	0.48	2.27	1.43	0.02	3.46
Furan WFS	87.04	5.45	0.91	0.19	0.00	0.19	0.04	2.67	0.66	0.01	2.85
Coated WFS	81.50	5.31	1.41	0.08	0.00	0.16	0.00	2.91	0.59	0.01	8.01

※L.O.I. : Loss On Ignition

using the following equation:

$$k_1 = \frac{F}{F+S} \quad k_2 = \frac{W}{C+F+S} \quad k_3 = \frac{W}{C} \tag{1}$$

where, F = fly ash content (kg/m^3), S = sand content (kg/m^3)
W = water content (kg/m^3), C = cement content (kg/m^3)

Assuming that the air content in the flowable fill is negligibly small, the volume of all the ingredients taken together should add to the full volume. There will be a small amount of air entrapped in the flowable fill, but in practical purposes this assumption seems to be reasonable. Therefore, unit volume of flowable fill :

$$\frac{W}{1000G_W} + \frac{F}{1000G_F} + \frac{S}{1000G_S} + \frac{C}{1000G_C} = 1.0 \tag{2}$$

where, G_W = specific gravity of water (= 1),
G_F = specific gravity of fly ash
G_S = specific gravity of sand
G_C = specific gravity of cement

The amount of fly ash, F, can be rearranged in terms of design parameters k_1, k_2, k_3 and specific gravities of the ingredients as

$$F = \frac{1000}{\frac{k_k(k_3 G_C + 1)}{k_1 G_c (k_3 - k_1)} + \frac{1}{G_F} + \frac{1-k_1}{k_1 G_s}} \tag{3}$$

From the results of flow testing and unconfined compression tests, the relationship between the W/C ratio and unconfined compressive strength is obtained. After getting the W/C ratio corresponding to unconfined compressive strength larger than 150 kPa, which is the selected strength for excavation by man or common equipments, the parameters k_1, k_2, and k_3 are obtained. Table 4 shows the parameters k_1, k_2, and k_3 for each WFS. Mixing ratio of each CLSM is shown in Table 5.

3. Testing Method and Results

3.1 Preparation of Testing Materials

For the permeability test, the unconfined compression test and triaxial test, specimens with 5 cm diameter and 15 cm length were prepared. When the mold was removed, the ends of the specimens were easily broken, and trimming was needed. Thus, the real length of the specimens was about 12.5cm. After the WFS and in-site soil were sieved by No. 10 sieve, and allowed to dry for a day, it was mixed with the other materials (water, cement, and fly ash) for sample preparation. One or two days after the mortar had been poured into the mold, it hardened enough for cure to continue without the mold. So, the comparison in various conditions was possible approximately 1 to 2 days after the mix was poured into the mold. In the case of curing in air, the temperature was 27 to 33°C and the relative humidity was 70 to 80%. In the case of curing in water, the reservoir temperature was maintained at 23 ± 2°C.

3.2 Hydraulic Conductivity Testing

A control panel and a flexible-wall cylinder were the devices used for the hydraulic conductivity tests. In the control panel, it is possible to apply pressure to the test materials, to subject vacuum at the same time, and to supply de-aired water. Therefore, saturation of materials and permeability tests are simultaneously carried out. Flexible wall testing using the falling head condition was done in a triaxial cell. The detailed test method is based upon ASTM(D 5084). The hydraulic conductivity of each CLSM obtained from the testing is shown in Table 6. Values fell within such a narrow range because the particles of the fly ash, which are very small and rounded, went through those of sand, which have large particle size, and the structures of mixtures were very similar. The mixtures of Furan WFS had slightly higher hydraulic conductivity than that of Green WFS and Coated WFS, because its

Table 4. Parameters of WFS Mixtures

WFS	Green Sand	Furan Sand	Coated Sand
Strength at 28day	$101.57(W/C)^{-1.3997}$	$164.88(W/C)^{-1.3792}$	$107.44(W/C)^{-1.4696}$
Range of W/C	$5.11 \le W/C \le 8.03$	$7.44 \le W/C \le 11.77$	$4.91 \le W/C \le 7.56$
k_1	0.111	0.216	0.209
k_2	0.319	0.240	0.281
k_3	5.11	7.44	4.91

Table 5. Mixing Ratio(%) of Each CLSM

Type	Natural Sea Sand	Waste Foundry Sand(WFS)				In-Situ Soil
		Green	Furan	Coated	Anti-Cor.	
Water	20.15	25.43	22.66	23.02	23.81	23.22
Cement	3.60	2.93	1.57	1.65	1.50	3.24
Fly Ash	20.81	7.96	16.36	17.33	28.97	20.22
Aggregate	55.45	63.68	59.40	58.00	45.72	53.22

Table 6. Hydraulic Conductivity of Each CLSM

Type	Sand	Waste Foundry Sand				In-Situ Soil
		Green	Furan	Coated	Anti-Cor.	
cm/sec	4.13×10^{-5}	3.61×10^{-5}	5.05×10^{-5}	4.30×10^{-5}	0.59×10^{-5}	8.02×10^{-5}

particles are larger than those of the other WFS's. Green WFS had the lowest hydraulic conductivity because it had the smallest particle, which were moreover coated with bentonite. It was also observed that the specimens had capability absorbing water quickly, which was seems to be due to the small fly ash particles.

3.3 Unconfined Compression Test

The unconfined compression apparatus was used in this testing. The objective of the testing program was to obtain the unconfined compressive strength versus curing time. The diameter of the test material was 5 cm, and the length was 12.5 cm. According to Head (1982), the compression velocity should be 2 mm/min for the test of which the diameter was 5cm; this velocity was equivalent to 1.6% strain per minute for the samples tested in this program. In this test, "failure" was defined at peak strength and the un-drained elastic modulus was taken as a secant modulus. Generally, the test was continued until the strain reached 20%, but for specimens cured for less than 3-day the stress beyond 6% strain fell to practically zero and so it was impossible to perform the test up to 20% strain until the strain of it was 20%. Specimen of Green WFS, to which bentonite was coated as bonding agent, could stand by themselves. All WFS specimens experienced ductile failures when cured in 2 days and brittle failures when curled in more than 2 days. All specimens were mixed to have larger than 150 kPa unconfined compressive strength at 28 days, which was achieved to within ±9%. Table 7 shows the unconfined compressive strength of each CLSM mixtures.

3.4 Triaxial Compression Test

The "Automated Triaxial Testing System (C.K.C Type)" developed by Chan(1981, 1990) was used to perform triaxial tests on WFS specimens. The testing procedure followed ASTM D 4767. The strength parameters of the specimens were obtained when the curing times of 1, 3, 7 and 28 days. Tests were consolidated un-drained(CU) tests, for they can be carried out in short times. Because the specimens had characteristics of concrete, and consolidation could be occurred almost instantaneously, the shearing test was carried outjust after specimen was mounting.

Table 7. Unconfined Compressive Strength(kPa) of Each CLSM

Curing Time	Sand	Waste Foundry Sand				In-Situ Soil
		Green	Furan	Coated	Anti-Corrosion	
1-day	108.3	119.6	50.5	52.3	174.6	121.4
3-day	172.6	238.3	125.5	128.4	328.5	153.8
7-day	308.9	241.2	170.0	169.3	424.6	238.1
28-day	321.6	311.8	224.6	220.6	551.1	305.6

Having obtained the stress-strain behavior of flowable fill at different confining pressures, its shear strength plotting the $p' = (\sigma_1' + \sigma_3') / 2$ and $q' = (\sigma_1' - \sigma_3') / 2$ corresponding to the peak shear strength of each test in a p'-q' diagram.

The slope of α, and the intercept, m, of the resulting line can be related to the shear strength parameters, c' and ϕ. The variation of c' and ϕ with curing time is shown in Table 8.

3.5 Static Creep Test

A UTM, which is shown in Fig. 2, was used for static creep

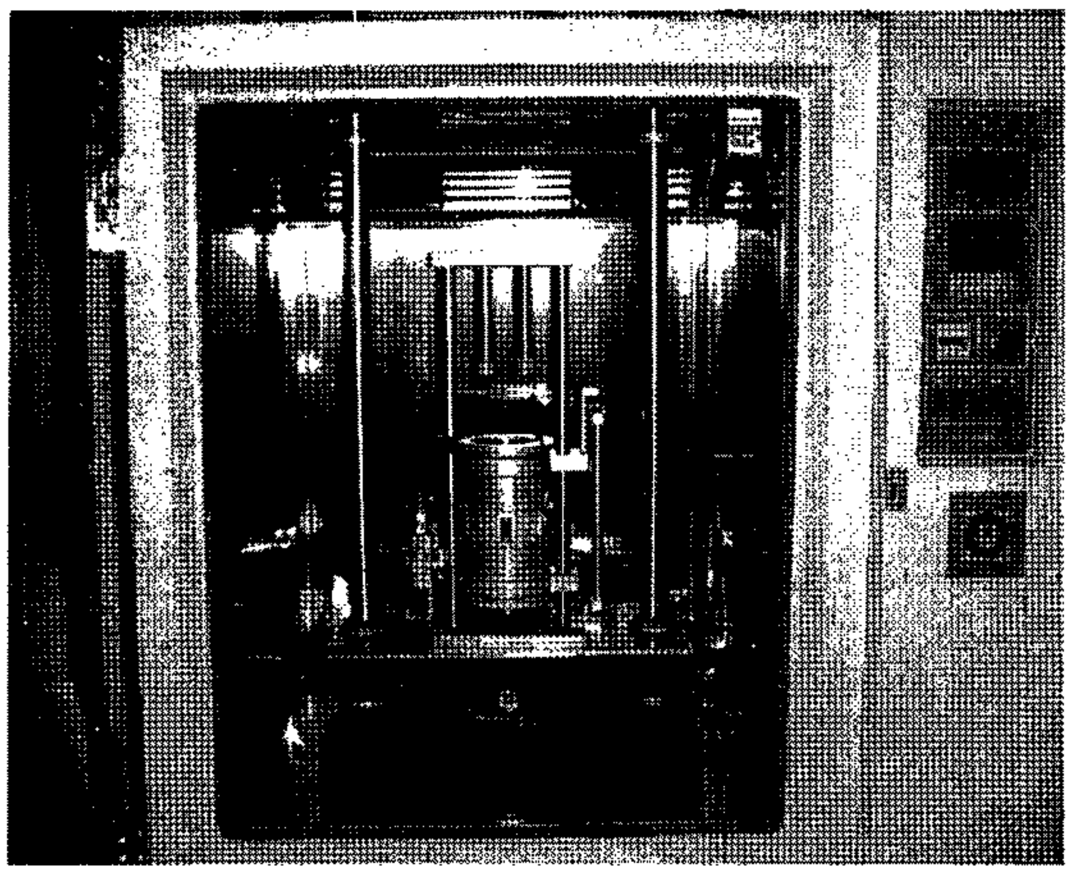

Fig 2. Testing Machine

Table 8. Strength Parameters of Each CLSM (kPa & degree)

Curing Time	Sand		Waste Foundry Sand								In-Situ Soil	
			Green		Furan		Coated		Anti-Corrosion			
	c	ϕ'	c	ϕ'	c	ϕ'	c	ϕ'	c	ϕ'	c	ϕ'
1-day	18.3	12.5	11.8	33.1	0.7	34.4	5.7	33.6	24.5	13.9	15.4	18.6
3-day	35.5	26.4	49.0	34.9	1.4	35.7	18.6	34.7	38.2	17.3	33.6	27.8
7-day	46.2	28.3	51.6	35.8	29.5	38.3	42.0	36.9	54.6	22.4	55.1	34.5
28-day	53.7	31.5	54.8	35.5	49.3	41.8	56.0	38.7	71.7	27.3	62.1	35.3

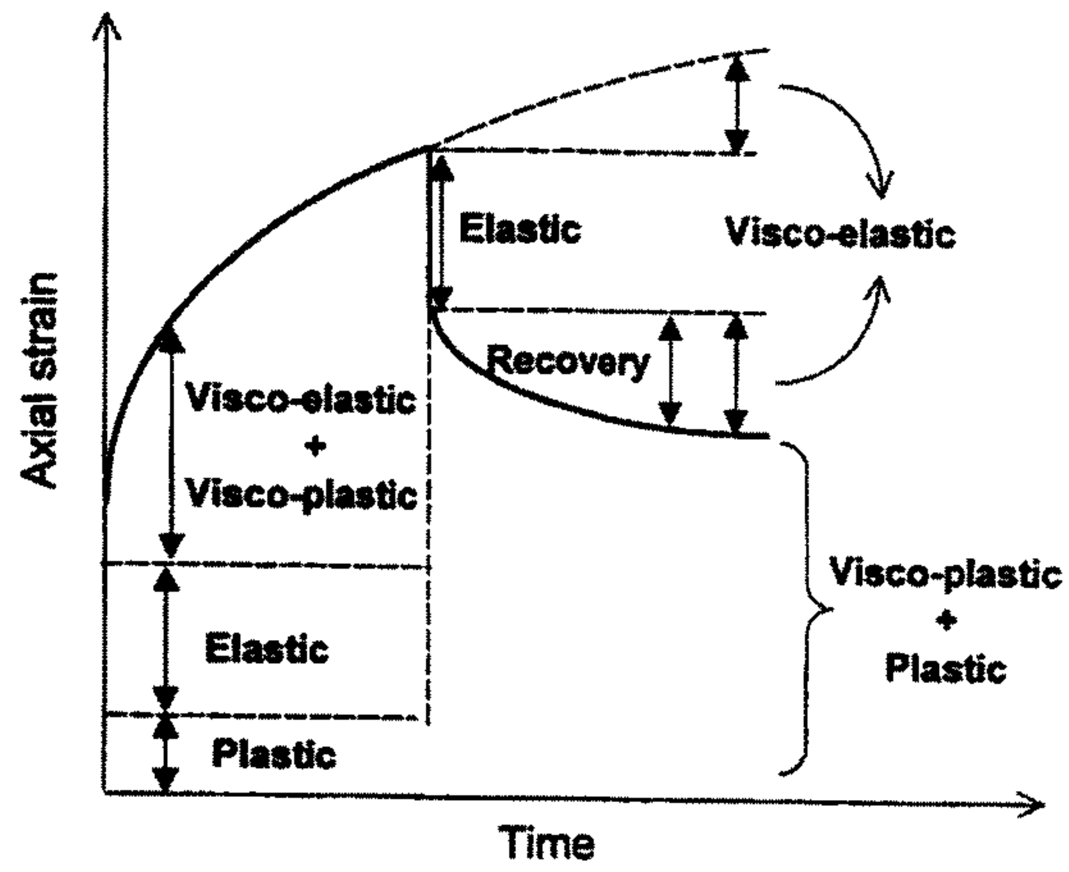

Fig 3. Concept of Visco-elastic Material Behavior

test on each CLSM mixtures. Fig. 3 shows the basic concept of visco-elastic materials behaviors and the analysis method of strain with testing time, including elastic strain, plastic strain, visco-elastic strain and visco-plastic strain. Creep tests were carried out for each mixture with 3600 sec of loading and 900 sec of unloading process. The deformations (μm) were measured with testing time. Table 9 shows the measured deformation with curing time at 1 day, 3 day, 7 day and 28 day curing, for each CLSM mixtures. The permanent deformations of each sample decreased as curing time increased.

3.6 Leaching Test

A common leaching test was carried out for these WFS mixtures. The goal of the test was to determine the concentration of a number of chemicals in the leaching liquid from WFS mixtures. Test results are shown in Table 10. Considering the leaching test results, the presence of heavy metal in the WFS CLSM mixtures is very small which means within the criteria.

4. Conclusion

The research presented in this paper aimed to characterize the engineering properties of fly ash and WFS mixtures to be used as backfill. A testing program was carried out to evaluate the hydraulic conductivity, shear strength, and creep strain of WFS mixtures. Within the limited laboratory test, following conclusion can be drawn.

The hydraulic conductivity of all the mixtures was about 4×10^{-5} cm/s. This value of hydraulic conductivity is equivalent to that of residual soil of granite. The results of unconfined compression tests showed that the strength of the 7-day cured specimens composed of Green WFS was 94% of that of 28-day cured specimens, but that of the 7-day cured specimens composed of Furan WFS and Coated WFS were only 64% and 66% of the 28-day cured specimens, respectively. This difference was due to the bentonite used as bonding agent in Green WFS mixtures. All specimens had a ductile response when cured in less than 2 days, and a brittle response for longer curing periods. Specimens cured in more than 7-days had characteristics similar to those of concrete, failing just after the peak in shear strength. The results of the CIU tests showed that the friction angle of specimens composed of

Table 9. Deformation Analysis of Creep Tests for Each Mixture (unit : μm)

Mix Type	curing days	Loading Time				Analysis of Deformation		
		Just after loading	at 3600 sec	just after unloading	at 4500 sec	elastic	viscoelastic	plastic+ viscoplastic
Green WFS	1	37.0	609.2	597.4	585.0	11.8	12.4	585.0
	3	30.7	187.8	180.2	177.3	7.6	2.9	177.3
	7	21.8	121.0	112.3	109.1	8.7	3.2	109.1
	28	11.9	178.9	168.9	167.8	10.0	1.1	167.8
Furan WFS	1	42.1	1920.3	1898.2	1891.9	22.1	6.3	1891.9
	3	37.1	402.1	384.3	377.3	17.8	7.0	377.3
	7	22.5	367.1	345.2	342.9	21.9	2.3	342.9
	28	20.9	282.5	269.5	268.7	13.0	0.8	268.7
Anti Corrosion WFS	1	133.6	740.9	735.6	732.2	5.3	3.4	732.2
	3	14.0	306.9	299.3	293.3	7.6	6.0	293.3
	7	43.2	280.6	273.0	254.0	7.6	19.0	254.0
	28	26.7	260.4	251.2	248.0	9.2	3.2	248.0
Natural Sand	1	201.0	1443.8	1432.6	1408.6	11.2	24.0	1408.6
	3	15.5	110.5	106.0	103.7	4.5	2.3	103.7
	7	15.5	98.2	95.7	94.3	2.5	1.4	94.3
	28	12.2	82.1	71.7	71.0	10.4	0.7	71.0
In-Situ Soil	7	17.5	212.6	204.5	203.0	8.1	1.5	203.0

Table 10. Specification & Test Results for Leaching Test (mg/l)

	Specification		Test Results			
	Korea	Japan	Green	Furan	Coated	Anticorrosion
Cd or Compound	0.3	0.3	ND	0.014	0.014	0.014
Pb or Compound	3	3	ND	ND	ND	ND
Cu or Compound	3	ND	0.099	0.029	0.099	0.029
As or Compound	1.5	1.5	ND	0.005	ND	0.005
Hg or Compound	0.005	0.005	ND	ND	ND	ND
Hg or Compound	ND	ND	ND	ND	ND	ND
Cr^{+6} or Compound	1.5	1.5	ND	ND	ND	ND
CN Compound	1	1	ND	ND	ND	ND
P Compound	1	1	ND	ND	ND	ND
PCB Compound	50	30	ND	ND	ND	ND
Trichloroethylene	0.3	0.3	ND	ND	ND	ND
Tetrachloroethylene	0.1	0.1	ND	ND	ND	ND

Furan WFS increased moderately with curing time, but in the other two WFS°Øs the friction angle increased significantly with curing time. The cohesion of the WFS mixtures increased sharply with curing time and then stabilized between approximately 10-15 days and 28 days. There is little evidence of expansion due to soaking and of coming out of heavy metal.

Acknowledgement

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Appendix 1. List of Notations, Definitions, and Symbols

C : Cohesion of soil mixtures

C_c : coefficient of curvature

C_u : coefficient of uniformity

D_{10} : Grain diameter in mm corresponding to 10% passing by weight

D_{30} : Grain diameter in mm corresponding to 30% passing by weight

D_{60} : Grain diameter in mm corresponding to 60% passing by weight

G_C : Specific gravity of cement

G_F : Specific gravity of fly ash

G_S : Specific gravity of sand

G_w : Specific gravity of water

Φ : Internal friction angle of soil mixtures

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