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Efficient recycling strategies for slurry TBM excavated soil

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Abstract. In downtown subway project most of excavated soil is discarded externally, whereas in road construction excavated soil is used as filling material and management of surplus soil becomes important factor for success of the project. Excavated materials from slurry shield TBM are discharged through discharge pipe to slurry treatment plant and excavated soil mixed with bentonite are separated in separation plant by grain size. Fine material has been discarded together in filter cake without recycling. Its volume can vary according to geologic condition but statistically fine material as filter cake is about 5%~30% out of overall excavated volume. However, filter cake is non-toxic and can be recycled when mixed in the appropriate proportions with coarse aggregate. Therefore, in this study, utilization of excavated soil from a slurry shield TBM were examined and lab tests were conducted to find the proper way for mixing filter cake and aggregate to be recycled as fill material for road construction.

Keywords: bentonite recycling; fill material for road construction; filter cake recycling; slurry TBM

1. Introduction

The Slurry Shield TBM is the safest method to excavate under high porewater pressure condition. Slurry and excavated soil is transported through a discharge pipe to the slurry treatment plant, and the mixed material is separated by grain sizes in the separation plant. The filter cake separated from filter press is a mixture of bentonite and fine excavated soil, and is generally treated as waste material. However, filter cake is non-toxic material mixed of fine excavated soil and bentonite which is basically clay composed of montmorillonite. The excavated soil mixed with bentonite from tunnels is used as fill material in road construction projects, and the use of such a vast amount of excavated soil is an important factor for saving construction cost.

Barbieri *et al.* (2022) studied for using calcium bentonite and sodium bentonite as road stabilizers and found that the use of bentonite clay is an effective solution to stabilize unbound granular materials by significantly increasing the resilient modulus. Cui *et al.* (2023) studied the properties of the soil dregs from shield TBM, and reused shield TBM soil dregs as synchronous grouting material based on the special treating agent. Gueddouda *et al.* (2010) present a study on the valorization of local materials such as dune sand and mined bentonite from the Laghouat region to implement the liner base layer of the insulating barrier concept of a hazardous waste center. Zhang (2020) presented a guideline for classifying and recycling the discharged soil from EPB shield tunnel and its feasibility was examined by a series of laboratory tests. In addition, a method of using the GP technique to obtain the optimal formulation of raw materials is proposed to achieve an optimal performance for the synchronous grouting.

In this study, laboratory tests were conducted to determine the appropriate mixing ratio of filter cake and coarse aggregate to recycle the filter cake from a slurry shield TBM to be used in the road construction.

2. Slurry treatment method of slurry shield TBM

The outline of the slurry treatment plant of the slurry shield TBM was summarized in Fig. 1. When fresh bentonite is transported into a slurry shield TBM equipment through the feed pipe, it is mixed with the soil and rock excavated by the cutter head and mixed material is discharged through a pipe back to the ground. The excavated soil mixed in slurry is separated into bentonite and excavated soil, and the bentonite is transported back to the TBM in the tunnel. The excavated soil is separated and discharged to the ground through the slurry treatment plant (Fig. 2). The excavated soil discharged through the slurry treatment plant is separated into coarse aggregates and fine aggregates, and can be adjusted according to the screen net size and the size of the cyclone centrifuge. Fig. 3 shows conceptual drawing of slurry treatment plant showing a system in which coarse aggregates are discharged through

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Table 1 Risk assessment for soil contamination

Material	Contamination criteria (Unit: mg/kg,For PCDD/Fs: pg-TEQ/g)		
	District 1	District 2	District 3
1. Cadmium (Cd)	4	10	60
2. Copper (Cu)	150	500	2,000
3. Arsenic (As)	25	50	200
4. Mercury (Hg)	4	10	20
5. Lead (Pb)	200	400	700
6. Chromium(+6)	5	15	40
7. Zinc (Zn)	300	600	2,000
8. Nickel (Ni)	100	200	500
9. Fluorine (F)	400	400	800
10. Organic P Complex	10	10	30
11. PCB (polychlorinated biphenyl)	1	4	12
12. Cyanide	2	2	120
13. Phenol	4	4	20
14. Benzene	1	1	3
15. Toluene	20	20	60
16. Ethyl benzene	50	50	340
17. Xylene	15	15	45
18. TPH (Total Petroleum Hydrocarbon)	500	800	2,000
19. TCE (Trichloroethylene)	8	8	40
20. PCE (Tetrachloroethylene)	4	4	25
21. Benzo[a]pyrene	0.7	2	7
22. 1,2-Dichloroethane	5	7	70
23. Dioxin(Include Purin)	160	340	1,000

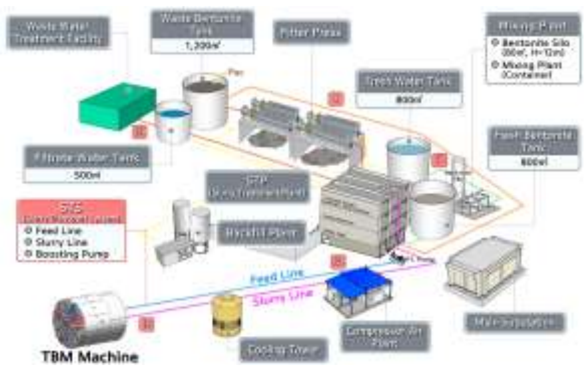

Fig. 1 Conceptual lay-out of slurry treatment plant for slurry shield TBM

Fig. 2 Excavated materials after separation plant

the central outlet and fine aggregates are discharged through both outlets.

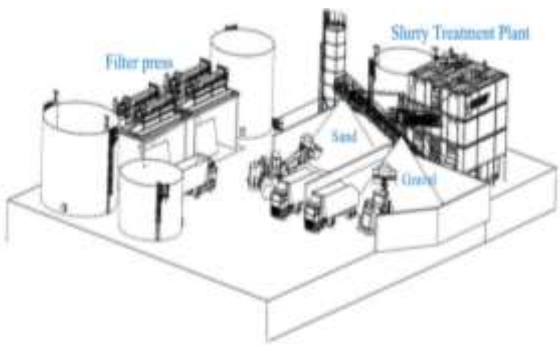

Fig. 3 Conceptual Drawing of Slurry Treatment Plant

The fine material, which is smaller than 0.03mm is not filtered and remains in the slurry. However, if the fine contents accumulate above a certain concentration, the quality of slurry deteriorates, and the slurry is replaced with new one because the slurry cannot function properly in TBM. The discarded slurry consists of bentonite, fine particles, and water, and water is removed through a filter press. The dehydrated bentonite and fine particles are discharged in the form of filter cake in shown in Fig. 4.

3. Study for required quality of recycling of filter cake

In order to recycle waste bentonite discharged in the form of a filter cake, it must be free of toxic substances according to the pollution-related quality test standards, risk

Table 2 Hazardous chemicals standard in designated waste

Category	Unit	Criteria for containing	Remark
Lead (Pb)	mg/L	more than 3	-
Copper (Cu)	mg/L	more than 3	-
Arsenic (As)	mg/L	more than 1.5	-
Mercury (Hg)	mg/L	more than 0.005	-
Cadmium (Cd)	mg/L	more than 0.3	-
Chromium(+6)	mg/L	more than 1.5	-
Cyanide	mg/L	more than 1	-
Total Oil	%(wt/wt)	more than 5	-
TCE	mg/L	more than 0.3	Trichloroethylene
PCE	mg/L	more than 0.1	Tetrachloroethylene
Organic P Complex	mg/L	more than 1	-

Fig. 4 Filter cake in filter press

assessment for soil contamination which is specified in the enforcement regulations of the Soil Environment Conservation Act by districts. District 1 is defined as the area where the land in accordance with the Act on the Establishment and Management of Spatial Information is used for residential purposes, school grounds, gourds, fish farms, parks, historical sites, graveyards and children's play facilities. District 2 refers to the area where is forest land, salt pond, warehouse, river, maintenance, water supply, sports, amusement park and religious area. District 3 is the area where is factory site, parking lot, gas station site, road site, railway site and embankment. Depending on the classification, each District's pollution standards are different and only materials that meet the pollution standard can be recycled. The relevant examination must be requested to an accredited institution of authority, and the test results must be submitted to the local government for approval. Recycled materials are prohibited from being taken out to other areas and should be utilized within those areas. Standard values of risk assessment for soil contamination are shown as Table 1.

Road construction belongs to district 3 and contamination criteria should be below standard value. Also, hazardous substances are listed in designated wastes by Wastes Control Act. Heavy metals such as copper, arsenic, mercury, cadmium, hexavalent chromium compounds, oil, radioactive materials and asbestos should be less than hazardous chemicals standard in designated wastes values as described in Table 2.

The standard values for fill materials according to the highway construction material quality standard are as shown in Table 3.

4. Required quality for recycling of filter cake and aggregates

Samples of filter cakes and excavated soil were collected at the site of Kimpo-Paju Expressway slurry shield TBM tunnel project (Fig. 5). The ground condition was found to be banded gneiss with uniaxial compressive strength of about 100MPa and slaking durability of 0.06%. Kimpo-Paju Expressway project is the first river crossing road tunnel project using a slurry shield TBM with the largest diameter(14.01 m) in Korea. The two tunnels are 2.8 km long and the total volume of excavated ground is about one-million cubic meter. To cope with the high porewater pressure conditions in the riverbed, a slurry shield TBM tunneling method has been chosen, and significant amount of bentonite is also used. The test results according to Risk assessment for soil contamination are summarized in Table 4, and both filter cake and aggregate were found to meet all risk level of District 3.

The tests were conducted at the Korea Environment Institute of Water and Environment, and the tests were performed according to the soil contamination process testing standard (Notice No. 2022-38 of the National Institute of Environmental Research) under the condition of indoor temperature of 20°C to 23°C and humidity of 18% to 40%.

Table 5 shows the test results to confirm whether the hazardous substances contained in designated wastes are

Table 3 Expressway construction materials quality standard

Description			Unit	Sub grade: Rock fill	Sub grade: Soil	Sub grade	Backfill: SB-1 (H3.5 m below)	Backfill: Good Earth (H3.5 m Above)
Material Standard	Maximum Size		㎜	600 below	300 below	100 below	75 below	100 below
	modified CBR		%	-	2.5 above	10 above	50 above	10 above
	Sieve analysis (5 mm)		%	-	-	25 ~ 100	30 ~ 65	25 ~ 100
	Sieve analysis (0.08 mm)		%	-	-	0 ~ 25	0 ~ 8	0 ~ 15
	Plasticity Index		%	-	-	10 below	6 below	10 below
	Liquid limit		%	-	-	-	25 below	-
	Abrasion loss		%	-	-	-	50 below	-
	Sand Equivalent		%	-	-	-	25 above	-
Construction Standard	1st bed Thickness after compaction		cm	60 below	30 below	20 below	20 below	20 below
	Method of Compaction lab test		-	-	A,B method	C,D,E method	D,E method	D,E method
	Compaction ratio		%	-	90 above	95 above	95 above	95 above
	Field density test	Relative Density (Dr)	%	70 above	-	-	-	-
	Grain size distribution	Coefficient of Uniformity (Cu)	-	G : Cu≥4 S : Cu≥6	-	-	-	-
	Grain size distribution	Coefficient of curvature (Cg)	-	1<Cg<3	-	-	-	-
	PBT – APP	Settlement	cm	0.125	0.25	0.25	0.25	0.25
	PBT – APP	Bearing Capacity Factor (K30)	kgf/cm3	20 above	15 above	20 above	30 above	15 above
	PBT – APP	Bearing Capacity Factor (K30)	MN/m3	200 above	150 above	200 above	300 above	150 above
	PBT – CEM	Settlement	cm	0.125	0.125	0.125	0.25	0.25
	PBT – CEM	Bearing Capacity Factor (K30)	kgf/cm3	20 above	10 above	15 above	30 above	15 above
	PBT – CEM	Bearing Capacity Factor (K30)	MN/m3	200 above	100 above	150 above	300 above	150 above
General Standard for Filling materials			LL : < 50% , Dry Density > 1.5t/m3, PL < 25% , Porosity < 42%					

*APP: AP Pavement

*CEM: Cement Pavement

below the standard value for aggregate and filter cake obtained from Kimpo-Paju Expressway tunnel project, and no hazardous substances were detected in samples. The test was conducted at the Korea Environment Institute of Water Environment. The test environment was conducted according to the waste process test standard (Notification No. 2022-83 of the National Institute of Environmental Research) with an indoor temperature of 20°C to 23°C and a humidity of 15% to 24%

The mixing ratio of aggregates and filter cake was determined considering field mock up test based on Expressway quality standard as shown in Table 6. The volume of the filter cake varies depending on the geological conditions of excavation. In the case of rock excavation, the quantity is minimal, whereas for soil excavation, the volume can increase significantly. In this study, the ratio of filter cake was fixed, but further parametric study for various ratios will be required to understand the behavior of

Fig. 5 Sample collection of filter cake and aggregate from filter press and slurry treatment plant

Table 4 Test results by risk assessment for soil contamination

Description	Unit	Risk level	Test Result		Remark
		District 3	STP aggregate	Filter Cake	
Cadmium (Cd)	mg/kg	60	0.15	0.27	
Copper (Cu)	mg/kg	2000	19.8	182.6	
Arsenic (As)	mg/kg	200	Not Found	Not Found	
Mercury (Hg)	mg/kg	20	0.11	0.32	
Lead (Pb)	mg/kg	700	6.9	12.5	
Chromium(+6)	mg/kg	40	Not Found	Not Found	
Zinc (Zn)	mg/kg	2000	113.5	144	
Nickel (Ni)	mg/kg	500	14.2	35.5	
Fluorine (F)	mg/kg	800	196	248	
Organic P Complex	mg/kg	30	Not Found	Not Found	
PCB (polychlorinated biphenyl)	mg/kg	12	Not Found	Not Found	
Cyanide	mg/kg	120	Not Found	Not Found	
Phenol	mg/kg	20	Not Found	Not Found	
Benzene	mg/kg	3	Not Found	Not Found	
Toluene	mg/kg	60	Not Found	Not Found	
Ethyl benzene	mg/kg	340	Not Found	Not Found	
Xylene	mg/kg	45	Not Found	Not Found	
TPH (Total Petroleum Hydrocarbon)	mg/kg	2000	Not Found	Not Found	
TCE (Trichloroethylene)	mg/kg	40	Not Found	Not Found	
PCE (Tetrachloroethylene)	mg/kg	25	Not Found	Not Found	
1,2-Dichloroethane	mg/kg	70	Not Found	Not Found	
Benzo[a]pyrene	mg/kg	7	Not Found	Not Found	

Table 5 Test results by Hazardous chemicals standard in designated wastes

Category	Unit	Criteria for containing	Test Result		Remarks
			STP Aggregates	Filter cake	
Cadmium (Cd)	mg/L	more than 3	Not Found	Not Found	
Copper (Cu)	mg/L	more than 3	0.015	Not Found	
Arsenic (As)	mg/L	more than 1.5	Not Found	Not Found	
Mercury (Hg)	mg/L	more than 0.005	Not Found	Not Found	
Cadmium (Cd)	mg/L	more than 0.3	Not Found	Not Found	
Chromium(+6)	mg/L	more than 1.5	Not Found	Not Found	
Cyanide	mg/L	more than 1	Not Found	Not Found	
Oil	%	more than 5	Not Found	Not Found	
TCE	mg/L	more than 0.3	Not Found	Not Found	
PCE	mg/L	more than 0.1	Not Found	Not Found	
Organic P Complex	mg/L	more than 1	Not Found	Not Found	

Table 6 Mixing ratio with STP aggregates and filter cake

Description	Slurry Treatment Plant		Filter press	Remark
	Gravel	Sand	Filter cake	
Mixing Ratio	60%	30%	10%	

mixed material for various road-bed fill conditions. The tests were carried out in a testing lab accredited by the authorities. According to the test results the mixed material of filter cake and aggregates meets the Korean Expressway road subgrade quality standards as shown in Table 7.

The field mock-up tests were carried out at the Kimpo-Paju expressway project site to confirm the suitability andcompactness of the mixed material for expressway subgrade. The test area was 200m2 with a width of 10 m and length of 20 m, and a 10.5-ton roller and a backhoe were mobilized for the plate bearing tests (Fig. 6).

Table 7 Test Result for Expressway construction materials quality standard

Description		Unit	Sub grade		Remark
			Standard	Test Result	
Material Standard	Maximum Size	㎜	100 below	53.0	
	modified CBR	%	10 above	30.4	
	Sieve analysis(5 mm)	%	25 ~ 100	34.2	
	Sieve analysis(0.08 mm)	%	0 ~ 25	10.3	
	Plasticity Index	%	10 below	N.P	
General Standard	Density	g/㎤	1.5 above	2.653	
	Liquid Limit	%	50 below	N.P	
	Plastic Limit	%	25 below	N.P	

Table 8 Load Results when the settlement reaches 2.5 mm

Number of compaction	Load, q (KN/㎡)	Settlement, s (mm)	Test Result, K30 (MN/m3)
6 times	515.4	2.5	206.1
8 times	586.4	2.5	234.6
10 times	725.5	2.5	299.9

Fig. 6 Plate bearing test

The plate bearing tests was carried out to determine the ultimate bearing capacity of the soil and the probable settlement under a given load, and load cells and dial gauges was installed. Roller compaction was done 6, 8 and 10 times for each test. Fig. 7 shows load-settlement relationship from the plate bearing tests. The load can be obtained corresponding to the settlement up to 2.5 mm, and the loads when the settlement reaches 2.5 mm are summarized in Table 8.

The modulus of subgrade reaction, K30 for mixed soil of filter cake and aggregate is calculated using Eq. (1). The required modulus of subgrade reaction is 150 MN/m3 for subgrade of expressway, and it was found that the mixed soil of filter cake and aggregate meet the required criteria if compacted more than 6 times of compaction.

$$\boldsymbol{K_{30}} = \frac{\boldsymbol{q\ (kN/m^2)}}{\boldsymbol{s\ (mm)}} \tag{1}$$

5. Conclusions

In this study, the technical analysis of the recycling method of excavated soil and filter cake from slurry shield TBM was examined through lab and field tests. As a result of technical considerations, it was found that recycled mixed soil with filter cake and aggregate satisfied the relevant legal regulations and quality standards as subgrade material for expressway projects. However, this study performed tests with only one mixing ratio of filter cake (waste bentonite) and excavated soil, and further research is needed to find the optimal mixing ratio for various ground conditions. Also, it is necessary to verify the long-term stability of the fill using this mixed soil with filter cake and excavated aggregate. This study results can be used as a basis for recycling excavated soil and bentonite from slurry shield TBM in the future. Recycling of construction waste is expected to help reduce construction and social costs due to environmental improvement.

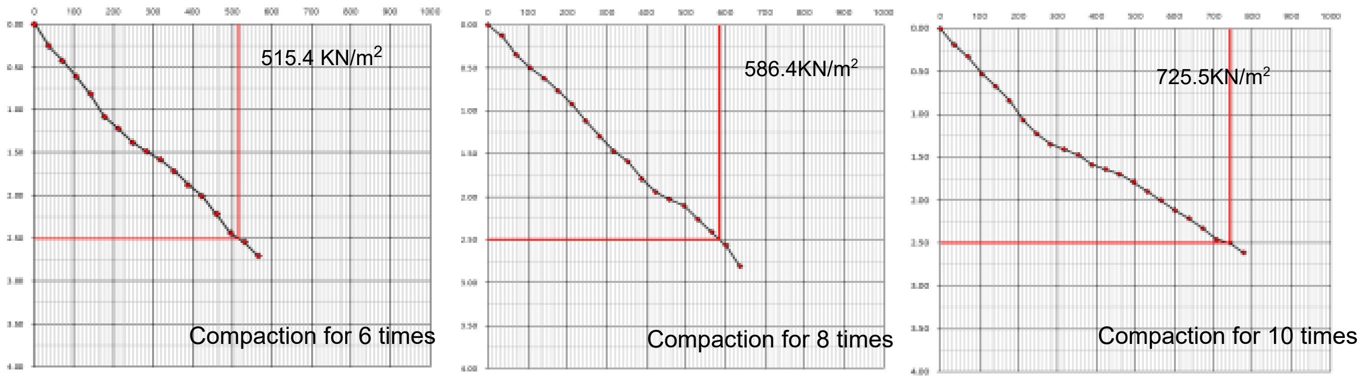

Fig. 7 Load-settlement relationship for various number of roller compactions

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