WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2024.150992

ARCHIVES OF CIVIL ENGINEERING

Vol. LXX ISSUE 3 2024

pp. 419 –430

Research paper

The influence of slag content on the mechanical properties of high-strength concrete

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Abstract: In light of the current situation where excessive amounts of excavated earth from subway tunnel construction are being stacked with low utilization and value, this study used residue as a mineral admixture to investigate the effects of different proportions of residue content (0%, 2.5%, 5.0%, 7.5%, and 10.0%) on the workability and mechanical properties of C50 concrete. The results indicate that: (1) The initial slump and slump loss of C50 concrete decrease gradually as the residue content increases. (2) The compressive strength of C50 concrete with varying residue contents is lower than the control group at early stages (3d, 7d), while it is higher than the control group at 28d. There exists an optimal content of residue for improving C50 concrete compressive strength, and it is found that the highest compressive strength at 28d is achieved when the residue content is 7.5% of the cement content. (3) The microscopic structure of C50 concrete with different residue contents at 28d shows that as the residue content increases, the microscopic structure of C50 concrete gradually becomes more compact and the porosity decreases.

Keywords: consistency, compressive strength, microstructure, residue, slump

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1. Introduction

With the rapid development of urbanization and underground space construction in China, underground structures such as basements, municipal pipelines, and subway lines have become an indispensable part of urban life. The shield tunneling method is commonly used in subway tunnel construction, which has advantages such as safety, efficiency, and economy [2, 3]. However, it will also lead to an increasing amount of shielding residues [4]. According to relevant statistics, building a 1-kilometer subway tunnel with a diameter of 6 meters can generate 68000 cubic meters of soil, approximately 100000 tons [5–8]. Improper management of transportation vehicles during transportation not only pollutes urban roads, but also affects urban landscapes. Dust in residues can be carried away by the wind, leading to a decrease in air quality. In addition, disposing of such a large amount of residue requires a lot of space, and traditional disposal sites in the suburbs not only damage farmland, but also have a negative impact on the local ecology. At present, the main methods of waste disposal both domestically and internationally are pile driving, landfill, and use as roadbed filling [10, 11].

Li et al. [12] used Ningbo shield tunneling slag as the main raw material and soil solidifying agent with volcanic ash reaction cementation hardening mechanism as the cementitious material to successfully prepare unburned ceramic particle samples, and verified that their performance indicators meet the requirements of national standards. Xie et al. [13] used the assistance of straw and magnesium oxide to prepare composite ceramic particles from shield tunneling slag through sintering method, and obtained the optimal raw material ratio and sintering temperature for phosphorus removal performance of ceramic particles. Jiang and Yi [14] successfully prepared sintered bricks using slag from the shield tunneling section of Guangzhou Metro as raw material through a roasting test at 1040° and proposed a complete process plan. Guo et al. [15] added a certain proportion of cement, lime, and reinforcing agent to engineering waste soil and prepared unburned bricks from waste soil through compression molding. However, compared to the conservative estimate of over 119 million tons [16, 17] of slag production per year, relying on replacing ceramic pellets to prepare raw materials to treat slag can be a drop in the bucket.

The solidification and reuse technology, which has a simple process and can dispose of a large amount and on a large scale, has reached a development climax [18]. Song and Zhu [19] used fly ash and slag as the main raw materials, combined with quartz sand and alkali silicate activators, to prepare geological polymer materials with certain strength and environmental friendliness. Zhang et al. [20] achieved the solidification of clay and sand using slag cementitious materials. The results showed that when the curing age was 28 days, the unconfined compressive strength of 9% slag cementitious soil was higher than that of 15% cement cementitious soil. Wang et al. [21] only used cement to solidify soil and compact it, and found that the strength of solidified soil is positively correlated with curing time, and attributed this phenomenon to the hydration reaction of cement. Liang et al. [22] used cement to solidify abandoned silt soil and found that the strength of silt soil increases with the increase of cement mass fraction and compaction degree. As the cement mass fraction and age increase, the improvement effect of compaction degree on water stability tends to be gentle or even weakened. Zhang et al. [23] mixed a certain proportion of slag, silica fume, and cement to produce a new type of CG-SF curing agent, which not only meets the requirements of clay reinforcement, but also achieves energy conservation and environmental protection. Woyciechowski P. [24] conducted a corresponding study on the post curing performance of polymer cement concrete. Zych M. [25] proposed a new theory for the constraint coefficient of reinforced concrete components after cracking.

The research aims to study the relationship between the content of shield residue and water-cement ratio and the influence of these factors on the workability and mechanical properties of concrete, in order to determine the optimal mix ratio for residue concrete used in shield tunneling projects. Moreover, the study explores the effect of shield residue on the working performance and mechanical properties of geopolymer, and compares its effect with that of ordinary geopolymer. With this as a foundation, the paper investigates the impact of shield residue on the anti-permeability and anti-freezing performance of concrete and geopolymer, in an attempt to provide new ways for the recycling and utilization of shield residue in subway shield tunneling projects.

2. Classification of shield residue

The types of residual materials generated by shield tunneling vary depending on geological conditions and excavation equipment used, and can mainly be divided into plasticity, soft plasticity, and fluidity. There are two commonly used shield tunneling methods: mud shield tunneling and earth pressure balance shield tunneling. The former produces flowable residues, while the latter typically produces plastic or soft plastic residues, occasionally producing flowable forms of residues under certain conditions. The proportion of slurry shield tunneling in subway construction is very small, and most of the residual shield tunneling materials are generated through the earth pressure balance shield tunneling method.

In order to improve the efficiency of shield tunneling and reduce the wear and tear of the shield machine during soil cutting, special equipment installed in the shield machine is usually used to inject soil stabilizer into the surface of the cutter, soil chamber, or screw conveyor. Then mix the soil stabilizer with the shield residue through rotation and stirring to ensure uninterrupted excavation. Generally speaking, shielding residues containing residual soil stabilizers have the characteristics of high water content, large porosity, and uneven permeability, making their recovery challenging.

The current methods for handling shield tunneling residues, such as backfilling, only transfer soil without producing substantial value-added products. Sintering is highly energy consuming, highly polluting, and prone to producing toxic gas emissions. The non calcination method for producing bricks and ceramic particles has limited production capacity and low added value. Adding shield tunneling slag to concrete can not only avoid pollution but also improve the high value-added utilization rate of slag soil. This measure can also effectively alleviate the shortage of additive production in recent years. In addition, using shield tunnel slag as a raw material for producing geological polymers can also help solve the problem of low utilization rate of slag in the construction field.

3. Test

3.1. Raw materials

The selected material is shield tunneling waste generated by a subway line in Shanghai. In addition, there are cement, river sand, crushed stone, and crushed stone additives produced by Hebei Institute of Building Science.

Grind the dried raw materials in a ball mill for 30 minutes to obtain a specific surface area of 19000 m^2/kg and 11 μ. The average particle size of m and dry density are 1810 kg/m^3. The chemical and mineral components of the residue are shown in Figure 1, respectively. In addition, the microstructure of the residue is shown in the Figure 2.

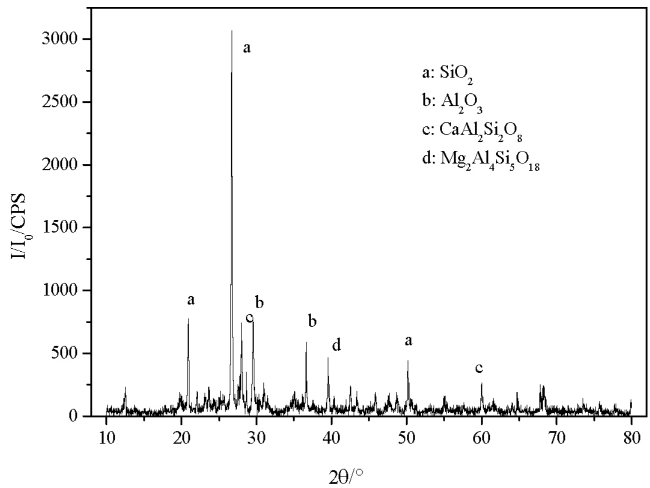

Fig. 1. Mineral composition of residue

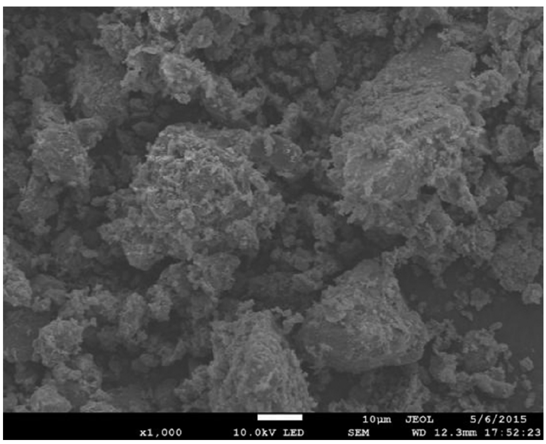

Fig. 2. Microstructure of residue

3.2. Mix proportion design of concrete

The present study investigates the impact of varying levels of residue content (2.5%, 5.0%, 7.5%, and 10.0%) on the workability and compressive strength of C50 concrete.

3.3. Pre-treatment plan for shield residue

The shield residue used in this study was sourced from a certain section of Suzhou Rail Transit Line 3. To meet the experimental requirements, appropriate methods were applied to pre-treat the shield residue. The residue was classified by particle size into 200-mesh, 0–5 mm, 5–10 mm, and 10–15 mm in accordance with the experimental needs.

1. The residue was subsequently sieved using mesh screens, where the particle sizes ranging from 0–5 mm, 5–10 mm, and 10–15 mm were obtained.
2. The moisture content of the 0–5 mm, 5–10 mm, and 10–15 mm particles from the naturally air-dried shield residue was measured separately.
3. The air-dried shield residue was placed in an oven and dried for 5 ± 0.5 h at a temperature of $105° \pm 0.5$. The residue was then sieved using mesh screens to obtain particles with particle sizes ranging from 0–5 mm, 5–10 mm, and 10–15 mm for further use.
4. The 0–5 mm residue obtained after crushing was placed in a ball mill and powdered for 120 minutes. The shield residue obtained after grinding was then passed through a 200-mesh sieve and used as raw material for the experiment.

3.4. Test methods

By employing the method of controlled variables, this study investigated the effects of the preparation method of the soil slurry, the content of shield residue, and the water-cement ratio on the mechanical properties of concrete, in order to determine the optimal mix proportion for concrete made with shield residue from subway construction sites. The results of this study will serve as a preparation for subsequent durability tests. The slump and compression strength test methods for concrete were conducted in accordance with the *Standard Test Methods for Trial Mixtures of Normal Concrete* (GB/T 50080-2002) and *Standard Test Methods for Mechanical Properties of Concrete* (GB/T 50081-2002) and *GB/T 50081-2019 for testing the mechanical properties of ordinary concrete*, respectively, for sample molding, preparation, and inspection. The microstructure of the concrete at 28 days, with different levels of shield residue content, was analyzed using a JMS-7800F scanning electron microscope, to investigate the mechanism of the effect of the varying levels of shield residue content on the mechanical properties of the resultant concrete.

4. Test results and analysis

4.1. Volcanic ash activity of residue

Table 1 presents the results of the volcanic ash test conducted on the ground residue. It can be observed from Table 1 that ground residue does not exhibit any volcanic ash activity.

Table 1. Volcanic ash activity of residue

	First test		Second test	
	OH-1	**CaO**	**OH-1**	**CaO**
V Before titration (mL)	0.3	0.3	0.5	1.0
V After titration (mL)	15.8	25.0	13.4	25.1
V Consumed after titration (mL)	15.5	24.7	12.9	24.1
C (mmol/L)	58.3	12.4	48.5	12.1
Test results	Unqualified (no volcanic ash activity)		Unqualified (no volcanic ash activity)	

4.2. Influence of residue on workability of concrete

The influence of different residue contents on the initial and 0.5-hour slump loss of C50 concrete is illustrated in Fig. 3, as the residue content increased, the initial slump of the concrete gradually decreased from the control level of 160 mm to 60 mm (with 5.0% content), 35 mm (with 7.5% content), and 28mm (with 10.0% content). The underlying reasons for these observations may be attributed, on the one hand, to the much larger specific surface area of the residue compared to that of the cement particles, resulting in a higher level of water absorption after the equivalent substitution of cement by residue. On the other hand, the strong adsorption ability of the polycarboxylates (PC) molecules in the superplasticizer on the residue and the intercalation effect of the PC molecules in the residue layers may result in a significant depletion of the PC molecules in the residue, thereby reducing the amount of PC molecules acting on the cement and ultimately leading to a decline in the concrete slump [15].

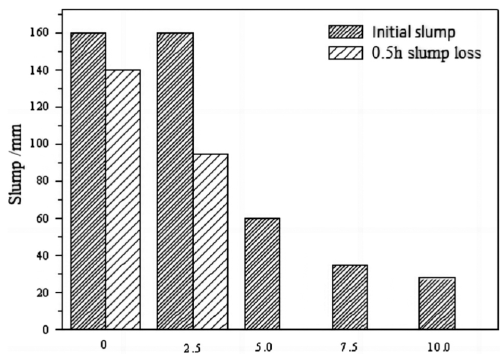

Fig. 3. Influence of residue content on workability of C50concrete

At a residue content of 2.5%, the concrete experienced severe slump loss, with a slump reduction from the initial 160 mm to 95 mm after 0.5 hours, representing a loss of 65 mm. As the residue content increased to 5.0%, the concrete became too stiff and lost its slump completely after 0.5 hours, resulting in a dry and rigid concrete. These phenomena can be attributed to the strong water-absorbing capacity of the residue.

In other testing experiments, when the water seepage pressure is high and the water cement ratio remains constant at 0.5, the water seepage height of the concrete gradually increases with the increase of shield tunneling slag content, that is, the impermeability of shield tunneling slag concrete gradually deteriorates. When the content of shield tunneling slag soil increases from 0 to 10%, the water seepage height of shield tunneling slag concrete increases rapidly, with an increase of 28.69%; When the content of shield tunneling slag soil is increased to 20% and 30%, the increase in water seepage height of shield tunneling slag concrete is relatively gentle, reaching 6.94% and 9.20%, respectively. Mechanism analysis: Although the addition of shield tunneling slag can have a micro aggregate filling effect and fill the pores of concrete to a certain extent, the workability of concrete decreases sharply after the addition of shield tunneling slag, making it difficult to compact and resulting in more and larger pores. Therefore, the impermeability of shield tunneling slag is reduced after its addition.

4.3. Influence of residue on mechanical properties of concrete

The impact of different residue contents on the compressive strength of C50 concrete is illustrated in Fig. 4. The addition of residue can potentially affect the early strength of C50 concrete, as the compressive strength after 3 days and 7 days is lower than that of the control group, owing to the reduced amount of cement resulting from the substitution of residue. However, it is noteworthy that the addition of residue can improve the compressive strength of C50 concrete after 28 days. This phenomenon can be attributed to the smaller particle size of the residue, which can effectively fill the inter-particle voids between the cement particles and improve the grading and compactness of these particles, leading to improvements in the microscopic structure of the concrete during the later stages of curing.

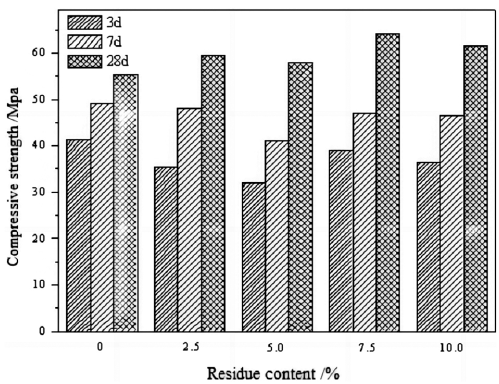

Fig. 4. Influence of residue content on compressive strength of C50 concrete

Furthermore, Fig. 5 reveals a trend where the early-age compressive strength (at 3 and 7 days) of C50 concrete with varying residue contents initially decreases and then increases, while the 28-day compressive strength follows a trend of initially increasing before eventually decreasing. Specifically, at residue contents of 2.5%, 5.0%, 7.5% and 10%, the 3-day compressive strength of the slag-residue-added concretes decreased by 14.5%, 22.5%, 5.6%, and 11.6%, respectively, compared to the control concrete; and the 7-day compressive strength reduced by 2.2%, 16.5%, 4.5%, and 5.3%, respectively. However, at a later stage of 28 days, the compressive strengths of the concrete with varying residue contents were found to increase by 7.4%, 4.3%, 15.7%, and 11.0%, respectively, compared to the control concrete. These results suggest that the addition of residue at a content of 7.5% can most effectively balance the reduction in early compressive strength resulting from the decreased cement content, while harnessing the micro-aggregate filling effect of residue, leading to the development of a more compact microstructure with fewer pores and enhanced compressive strength in the later stages.

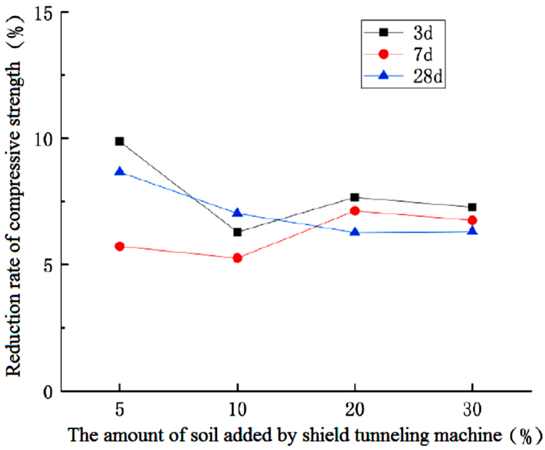

Fig. 5. The relation diagram between shield residue content and compressive strength decline rate of concrete when water-binder ratio is 0.5

Upon exceeding a residue content of 10% in shield residue concrete, a significant decrease in strength is observed. When the residue content is below 10%, despite a reduction in cement content, the micro-aggregate filling effect of the shield residue slurry improves the interfacial transition zone, thus partially compensating for the loss of strength due to the decrease in cement content. Furthermore, in the shell-making process, the water added to the first half of the shield residue slurry is absorbed by the coarse and fine aggregates, forming a thin layer of shield residue on the surface. This layer not only reduces the further absorption of water by the aggregates but also lowers their porosity. The cement and the remaining shield residue slurry added later form a layer of cement coating and cement-residue coating on the surface of the aggregates. Together, these three layers of coatings create a compact and strongly connected structure that mitigates the decrease in strength. However, as the residual content continues to increase, the precipitate formed by the shielding residue is first absorbed by the aggregates, which may aggregate and form clusters, forming weak areas that have an adverse impact on compression performance. Furthermore, due to poor flowability, concrete is difficult to densify when vibrated, and issues such as voids and honeycombs often arise, negatively affecting concrete strength. Therefore, the overall compressive strength of high-slag-residue-content shield residue concrete is low. When the water cement ratio is 0.5, with the increase of shield tunneling slag content, the early compressive strength of shield tunneling slag concrete decreases first and then increases.

In order to further elucidate the influence of residue on the compressive strength of C50 concrete, the microstructure of concrete with different residue contents at 28 days was investigated, as shown in Fig. 6.

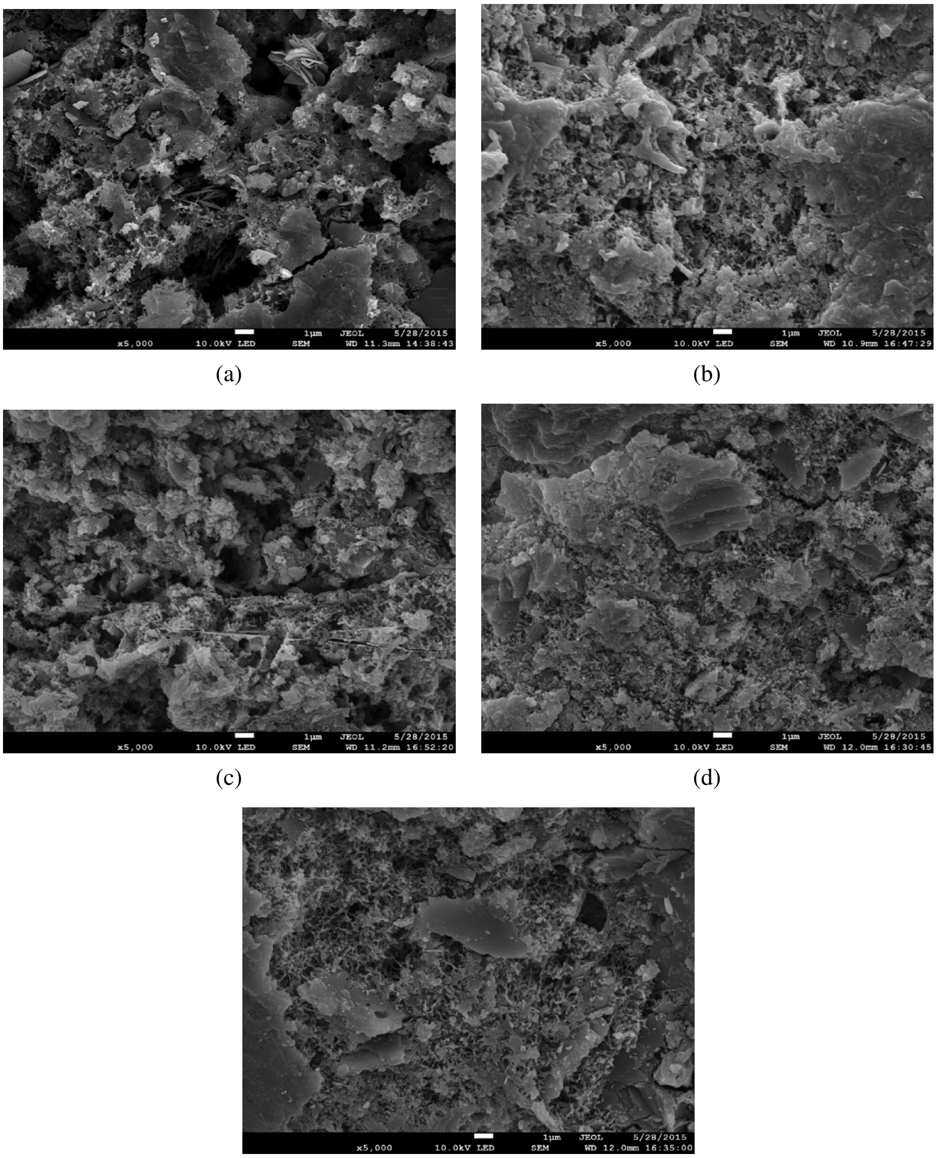

Fig. 6. Influence of residue content on microstructure of concrete for C50; (a) 0%, (b) 2.5%, (c) 5.0%, (d) 7.5%, (e) 10.0%

Based on the findings presented in Fig. 6, the microstructure of concrete exhibits several features in the absence of residue (control group), including an abundance of pores, as well as the presence of C–S–H and AFt material with a needle-like morphology. Conversely, when the residue content is 2.5%, a notable reduction in pore density is observed, coupled with a decrease in the occurrence of needle and rod-shaped structures. This may be attributed to a decline in AFt content due to reduced cement usage, as well as the filling effect of residue particles in the interstices between cement particles. Significantly, at a residue content of 7.5%, the microstructure of the concrete displays the least pore density and exhibits the most compact and densely-packed architecture, relative to the control, as well as the groups with residue contents of 2.5%, 5.0%, and 10.0%. This phenomenon may be attributed to the combined effects of the propensity of residue to reduce cement content – consequently leading to a reduction of hydration products – and the filling effect of residue.

5. Conclusions

The influence of different contents of residue on the workability and mechanical performance of C50 concrete were researched, and the regularity of the effect of residue on the workability and mechanical performance of C50 concrete were determined. The main conclusions drawn from this research are as follows:

1. The initial slump and slump loss of C50 concrete gradually decrease with the increase of residue content. Considering the constant usage of water and admixtures, the amount of residue added to the concrete should not exceed 10%.
2. The effect of different contents of residue on the compressive strength of C50 concrete at different ages varies. With an increase in residue content (2.5%, 5.0%, 7.5%, and 10.0%), the early compressive strength (3d, 7d) of C50 concrete is lower than that of the control group. However, at a residue content of 7.5%, the reduction rate of early compressive strength (3d, 7d) is the lowest, i.e., 5.6% and 4.5%, respectively. Further, with an increase in residue content (2.5%, 5.0%, 7.5%, and 10.0%), the compressive strength of C50 concrete at 28d is higher than that of the control group. At a residue content of 7.5%, the improvement rate of compressive strength is the highest, i.e., 11.7%.

In terms of cost, in practical engineering, considering cost reduction, there is not much difference in the strength values of different shield tunneling slag particles at different times. In actual engineering, the shield tunneling slag soil blocks can be preliminarily crushed to below 15mm for the preparation of slag slurry. Shield tunneling slag soil that has only been air dried can also be preliminarily crushed and mixed for a long time to prepare shield tunneling slag concrete.

Availability of data and materials: The data used and analysed during the current study are available from the corresponding author on reasonable request.

Competing interests: The authors declare that they have no competing interests.

Funding: No funding supports.

References

[1] J. Xiao, J. Shen, Q Gao, et al., "The current situation of engineering abandoned soil and innovative technologies for resource utilization", *Journal of Building Science and Engineering*, vol. 37, no. 4, pp. 1–13, 2020, doi: 10.19815/j.jace.2019.11038.

[2] S, Lin, "Environmental protection technology for subway shield tunneling engineering", *China Equipment Engineering*, no. 19, pp. 208–209, 2018.

[3] C. Wang and G. Wang, "Research and application of a new type of dual fluid grouting material for synchronous grouting in shield tunnels", *Tunnel Construction*, vol. 37, no. 4, pp. 416–420, 2017, doi: 10.3973/j.issn.1672-741X.2017.04.005.

[4] S. Liu, "Overview of comprehensive utilization of construction waste", *New Materials Industry*, no. 4, pp. 41–46, 2008, doi: 10.3969/j.issn.1008-892X.2008.04.012.

[5] J. Chen, "Understanding and hope for the resource utilization technology of construction waste in China", *Construction Technology*, no. 23, pp. 15–17, 2016, doi: 10.16116/j.cnki.jskj.2016.23.001.

[6] Y. Li and Z. Li, "Research on the application of construction waste soil in urban roads", *Highway*, no. 7, pp. 235–240, 2013.

[7] K. Zhu, Y. Zhang, Z. Xue, et al., "Environmental issues and green treatment of shield tunneling waste soil", *Urban Architecture*, no. 29, pp. 108–110, 2018, doi: 10.19892/j.cnki.csjz.2018.29.032.

[8] C. Shen and Y. Feng, "11 Bayi Square can be pushed by the muck of Metro Line 1". [Online]. Available: http://jiangxi.jxnews.com.cn/system/2013/05/24/012435387.shtml. [Accessed: 24 May 2013].

[9] R. Yao, "Main problems and improvement measures of construction waste soil management in Hangzhou", *Environment and Sustainable Development*, vol. 5, pp. 160–163, 2014, doi: 10.3969/j.issn.1673-288X.2014.05.047.

[10] J. He, "Research on improvement technology of bentonite slurry residue in loess shield tunnels", *Tunnel Construction*, no. 4, pp. 448–453, 2012.

[11] W. Liu, "Improvement technology of composite shield soil in Nanchang", *Tunnel Construction*, no. 5, pp. 455–462, 2015.

[12] J. Li, X. Chen, Y. Don, et al., "Preparation of non-fired haydite from shield muck and its properties", *Journal of Anhui University of Technology (Natural Science Edition)*, vol. 38, no. 3, pp. 250–254, 2021, doi: 10.3969/j.issn.1671-7872.2021.03.003.

[13] F. Xie, H. Li, G. Li, et al., "Phosphate removal by using shield residues/carbon composite ceramsite", *Chinese Journal of Applied Chemistry*, vol. 34, no. 2, pp. 211–219, 2017.

[14] J. Jiang and B. Yi, "Research on development of new wall materials by shield muck", *Brick and Tile Magazine*, no. 3, pp. 45–48, 2019, doi: 10.16001/j.cnki.1001-6945.2019.03.016.

[15] A. Guo, X. Wei, Y. Wang, et al., "Study on preparation and properties of unburned brick by building waste", *Non-Metallic Minerals*, no. 3, pp. 45–48, 2019.

[16] W. Guo, B. Wang, Y. Li, et al., "Status quo and prospect of harmless disposal and reclamation of shield muck in China", *Tunnel Construction*, vol. 40, no. 8, pp. 1101–1112, 2020, doi: 10.3973/j.issn.2096-4498.2020.08.001.

[17] X. Chen, T. Xu, K. Li, et al., "Present Situation and countermeasures of waste soil management of development and construction projects in Shenzhen", *Soil and Water Conservation in China*, no. 12, pp. 22–24, 2014, doi: 10.14123/j.cnki.swcc.2014.12.011.

[18] Q. Guo, "Experimental study on solidification and utilization of muck in underground excavation engineering in Nanjing area", *Nanjing: Southeast University*, 2019, doi: 10.27014/d.cnki.gdnau.2019.004570.

[19] X. Song and J. Zhu, "Influencing factors of mechanical properties of slag composite base geopolymer", *Journal of Xian University of Architecture and Technology (Natural Science Edition)*, vol. 48, no. 1, pp. 128–132, 2016, doi: 10.15986/j.1006-7930.2016.01.021.

[20] D. Zhang, X. Tian, H. Hou, et al., "Mechanical properties and mechanism of slag cementitious material solidifying soft soil", *Rock and Soil Mechanics*, vol. 28, no. 9, pp. 1987–1991, 2007, doi: 10.16285/j.rsm.2007.09.042.

[21] B. Wang, W. Yang, and Z. Li, "Micromechanism of strength increase with curing time for compacted cement-soil", *Journal of University of Science & Technology Beijing*, vol. 30, no. 3, pp. 233–238, 2008, doi: 10.3321/j.issn:1001-053X.2008.03.003.

[22] S. Liang, J. Chen, H. Lin, et al., "Experimental study on cement solidified sludge waste soil as filling material", *Journal of Guangdong University of Technology*, vol. 37, no. 2, pp. 102–106, 2020, doi: 10.12052/gdutxb.190085.

[23] W. Zhang, X. Du, F. Xu, et al., "Research on mechanical properties of new CG-SF solidified soil", *Journal of Chongqing University of Science and Technology (Natural Science Edition)*, vol. 24, no. 3, pp. 84–89, 94, 2022, doi: 10.19406/j.cnki.cqkjxyxbzkb.2022.03.004.

[24] P. Woyciechowski, "Effect of curing regime on polymer-cement concrete properties", *Archives of Civil Engineering*, vol. 66, no. 1, pp. 144–160, 2020, doi: 10.24425/ace.2020.131780.

[25] M. Zych, "Application of a new theory of restraint factor after cracking of reinforced concrete members", *Archives of Civil Engineering*, vol. 69, no. 1, pp. 198–212, 2023, doi: 10.24425/ace.2023.144168.

Received: 2023-09-12, Revised: 2024-01-23