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BOTTOM ASH FROM MUNICIPAL SOLID WASTE INCINERATION AS A SUBGRADE GROUTING MATERIAL

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Bottom ash from municipal solid waste incineration (MSWI BA), as a product of waste incineration and power generation, is attracting the increasing attention of researchers due to its particular reactivity. In this paper, by studying the performance of MSWI BA itself and the modification of MSWI BA by GBFS, fly ash, steel slag, cement, etc., the feasibility of using MSWI BA as a foundation grout material is elucidated upon. The results show that MSWI BA has some reactivity, but more is needed to meet the sealing material requirements. However, adding cement and GBFS in MSWI BA can meet the grouting requirements of base repairs. It should be noted that when the dosage of cement, MSWIBA, and GBFS is 30, 135, and 15 g, respectively, the microstructure of the sealing material is the densest.

INTRODUCTION

With the explosive growth of the global population and social economy, municipal solid waste landfills are accordingly rapidly expanding [1-3]. Waste incineration plants have become a new rational recycling method of dealing with municipal solid waste by converting the waste into heat energy [4, 5]. Bottom ash from municipal solid waste incineration (MSWI BA) is generally the product of municipal solid waste incineration power generation at 850 – 900 °C, and its output is usually 5 – 20 % of the mass of the primary waste [6, 7]. MSWI BA has some potential to replace Portland cement due to its pozzolanic activity [8]. At present, a large number of scholars have studied and investigated MSWI BA to partially replace cement [9, 10]; However, the customary use of considerable amounts of MSWI BA seriously deteriorates the resulting mechanical properties of the concrete/mortar [11, 12]. The addition of MSWI BA may also have a negative effect on the hydration rate. Indeed, with 20 % cement partially replaced by MSWI BA, the hydration of the mixture can take up to 10 hours [13, 14].

Cement and concrete are still commonly used as subgrade repair materials [15]. However, the development of geopolymers has brought new enlightenment to roadbed repair materials. Temuujin et al. [16] reported the preparation of geopolymers at ambient temperatures by introducing slag or a high calcium source to slightly alter the composition. Saludung et al. [17] reported the mechanical and microstructural evolution of a fly ash/slag-based geopolymer at high temperatures. Saha and Rajasekaran reported that incorporating slag from 10 % to 50 % into the fly ash geopolymer resulted in a significant reduction in the initial and final setting times of 73 to 74 % and 77 to 92 %, respectively [18]. The study of geopolymers not only attracts many researchers, but due to their low cost and high initial compressive strength, they are increasingly being used to replace cement.

However, geopolymers are rarely studied as foundation repair materials. At the same time, research on the use of MSWI BA as a cementitious material slurry to reinforce the subsoil is scarce and needs further investigation. Hence, this article will explore the feasibility of using MSWIBA as a deck grout material using indicators, such as the compressive strength, flowability, setting time, SEM, and structure pores.

EXPERIMENTAL

Materials

Granulated blast furnace slag (GBFS), steel slag, fly ash, MSWI BA and P·O 42.5 are the main raw materials used in this paper, and their chemical components are shown in Table 1. The Na_2SiO_3 with a modulus of 3.2 was provided by Suzhou Youchuang Chemical Environmental Protection Technology Co., Ltd, China. Figure 1 shows the particle morphology of the MSWI BA after crushing. Figure 2 shows the mineral composition of the MSWI BA, which is mainly composed of SiO_2, calcium salt and some calcium-aluminosilicates, which shows that it theoretically has a certain gelling activity and has the possibility of a resource that is reusable.

Table 1. Chemical composition of the GBFS, steel slag, fly ash, MSWI BA, and P·O 42.5 (wt. %).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Others
GBFS	28.6	14.3	4.68	38	9.36	0	0	1.76	3.3
Steel slag	14.09	5.03	19	45.19	6.53	0.04	0.11	1.21	8.8
Fly ash	48.5	26.8	3.89	8.72	0.98	1.1	0	1.72	8.28
MSWI BA	34.11	7.86	20.88	25.71	3.52	1	0	0.81	6.11
P·O 42.5	24.98	8.29	3.19	49.55	3.61	0.21	0.55	3.98	5.64

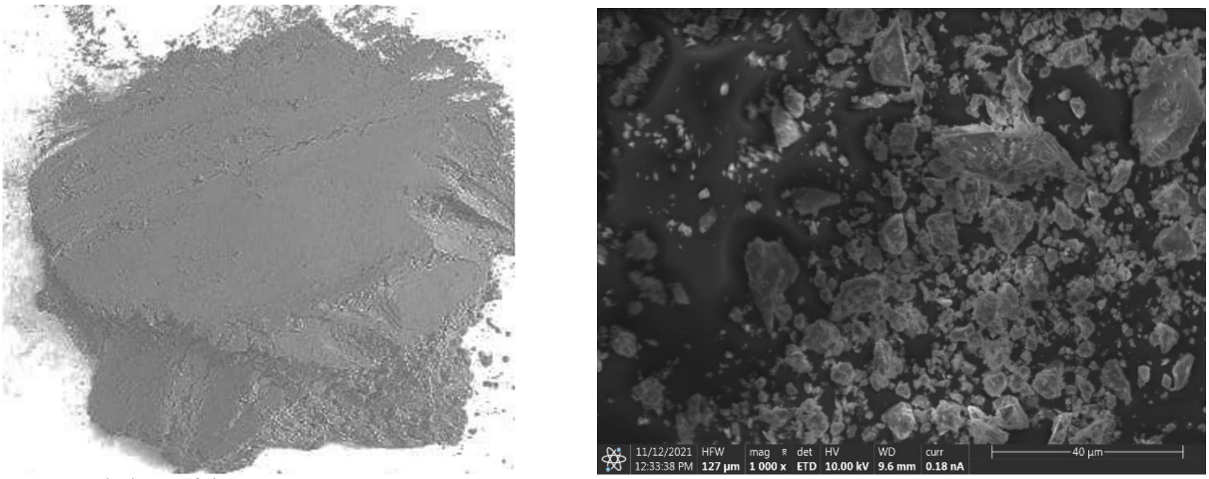


Figure 1. Morphology of the MSWI BA.

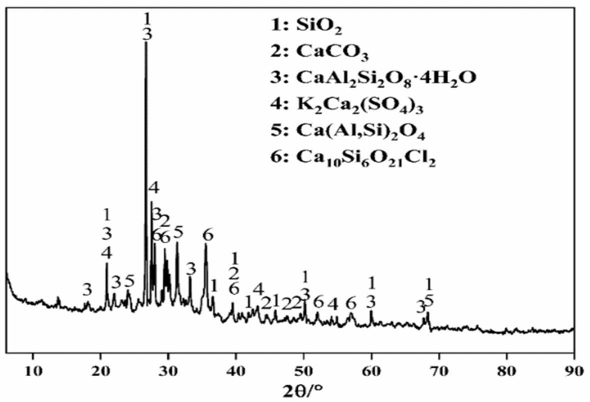


Figure 2. Mineral composition of the MSWI BA.

Methods

GB 175-2007 (General Portland Cement), GB/T50448-2015 (Technical Specification for Application of Cement-based Grouting Materials), and GB/T 1346-2011 (Testing Methods for Water Consumption, Setting Time, and Stability of Cement Standard Consistency) are referred to in order to test the strength, setting time, flowability and other technical indicators of grouting materials.

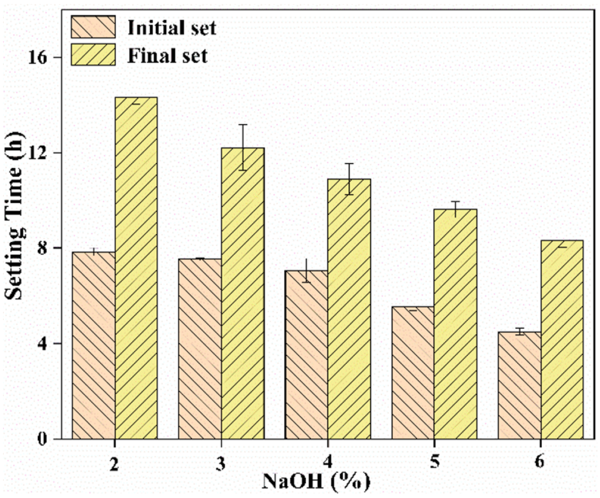
In addition, a thermal Field-Emission Scanning Electron Microscope (FESEM, QUANTA-FEG 250, USA) was used to characterise the morphology of the grouting materials for 7 days. The pore structure analysis was performed on a Macro MR12-150V-I triaxial core holder low-field Nuclear Magnetic Resonance (NMR) apparatus. An 8-channel TAM hydration calorimeter (Thermometric, USA) was chosen to record the hydration heat release rate of the different material ratios. Thermogravimetric-Differential Scanning Calorimetry (TG-DSC) curves were obtained from 30 to 1000 °C by means of a Mettler Toledo 1600 HT thermogravimetric analyser at a constant rate of 10 $°C·min^{-1}$.

RESULTS AND DISCUSSION

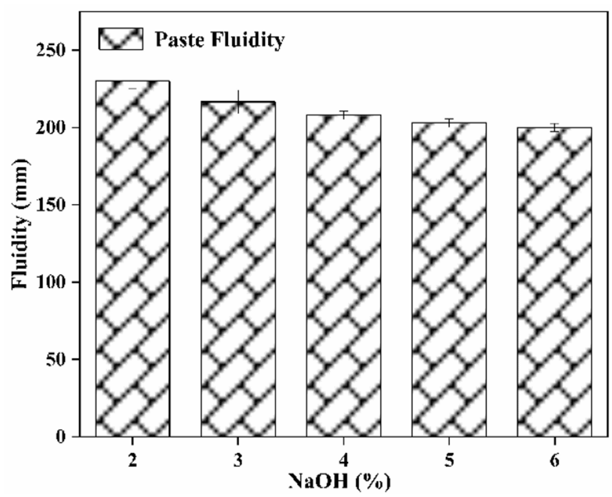
Performance of MSWI BA

A water-cement ratio of 0.5 was used to explore the performance of the bottom ash from waste incineration, and the results are shown in Figure 3. It can be seen in Figure 3a that the setting time for the bottom ash from the waste incineration is longer than that of the other solid waste. Indeed, the waste materials have been collected from several sources and are, therefore, of a complex composition and low activity.

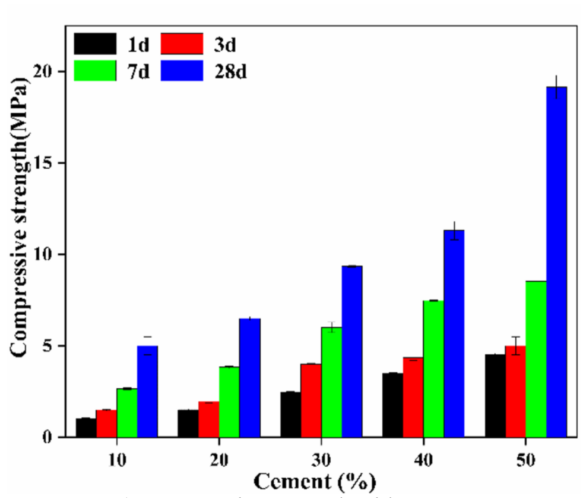
Under alkali activation reactions, the initial setting time takes about 5 – 8 h and the final setting takes about 9 – 14 h. It can be seen from Figure 3b that the flow of the waste incineration bottom ash at a 0.5 water-cement ratio meets the construction requirements (over 200 nm), which can meet the general requirements of grouting repair materials, and shows a trend of decreasing fluidity with an increase in the alkali content.



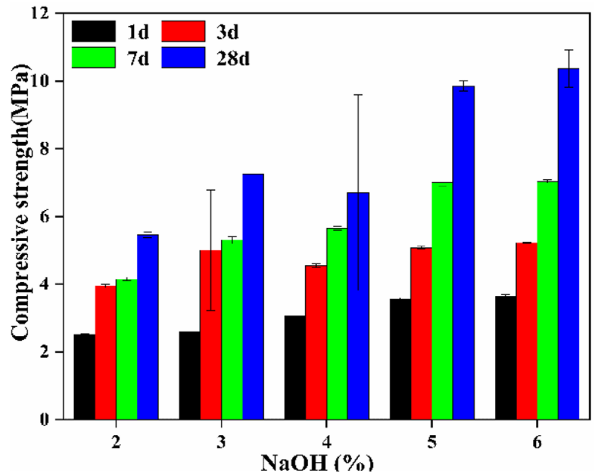
a) Setting time



b) Flowability



c) Compressive strength with cement



d) Compressive strength with sodium hydroxide

Figure 3. Research on the performance of MSWI BA.

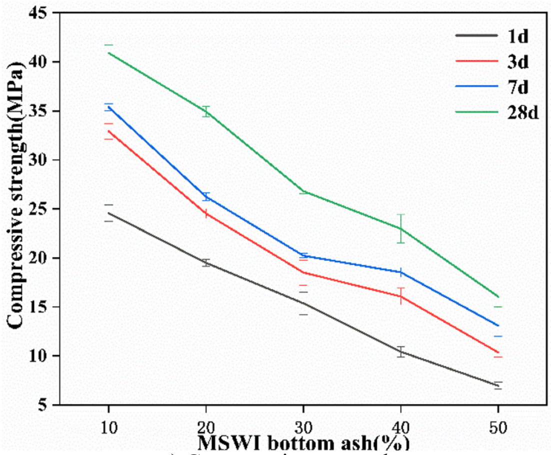
Therefore, the fluidity and setting time should be comprehensively considered in any application. Figures 3c and d compared the strength development of adding the cement and alkali to the refuse bottom ash at different ages, and it can be found that the alkali activation can obtain higher strength in the early stage (2 MPa for 1 day). Also, the alkali activation reactions have particular advantages in the later stage when the amount of cement is lower, but the cement sample has more advantages in the later stage when the cement content exceeds 40 %. It should be noted that with a 50 % cement content, the compressive strength is close to 20 MPa.

Therefore, MSWI BA has a certain cementitious ability, but it has drawbacks, such as a long setting time, low early and late strength, and cannot meet the performance requirements of grouting repair roadbed materials when used alone. However, it can be used as an auxiliary material for other materials and has unique advantages in generating economic and environmental value.

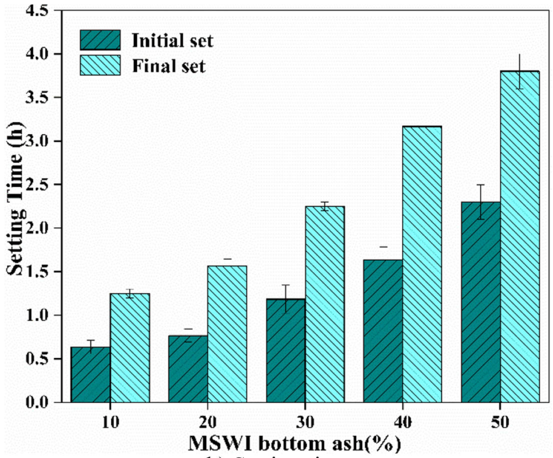
Optimisation of the MSWI BA performance

In view of the fact that the sole use of MSWI BA cannot meet the requirements of engineering applications, a new type of grouting material is considered to be developed by combining with other kinds of solid waste alkali activation technologies. Because the working properties of materials is mainly related to the water-cement ratio, and can be adjusted through admixtures in the later period, only the strength and setting time of different kinds of solid waste and MSWI BA are studied here.

Figure 4 shows the effect of adding MSWI BA to GBFS on the material properties. It can be seen that the compressive strength is generally very high under the addition of the mineral powder, which can reach more than 40 MPa. However, the setting time is only 0.5 – 3.5 h, which cannot provide sufficient construction time. The compressive strength of the hardened slurry decreases with an increase in the MSWI BA content. The initial setting and final setting times showed

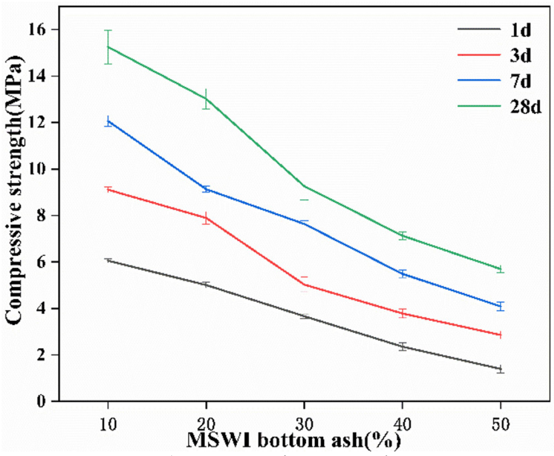


a) Compressive strength

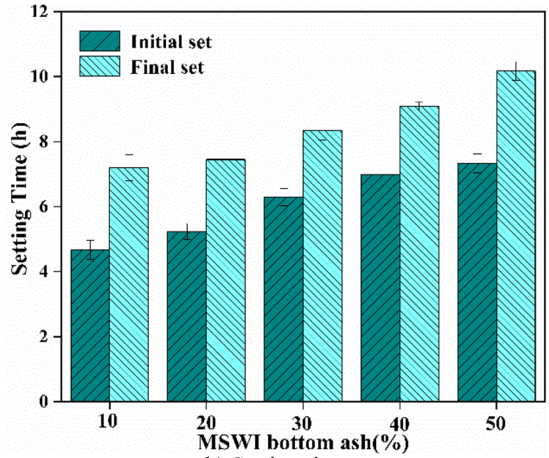


b) Setting time

Figure 4. The effect of adding MSWI BA to GBFS.

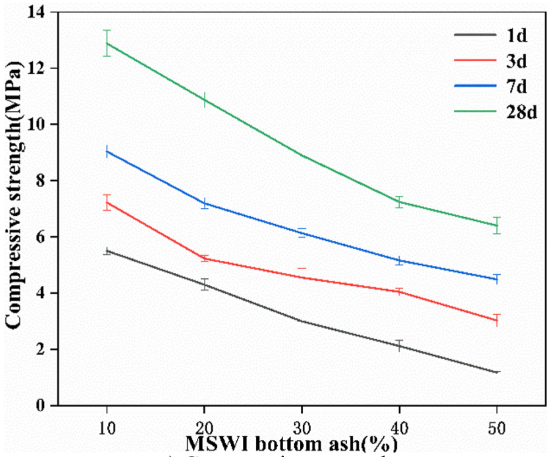


a) Compressive strength

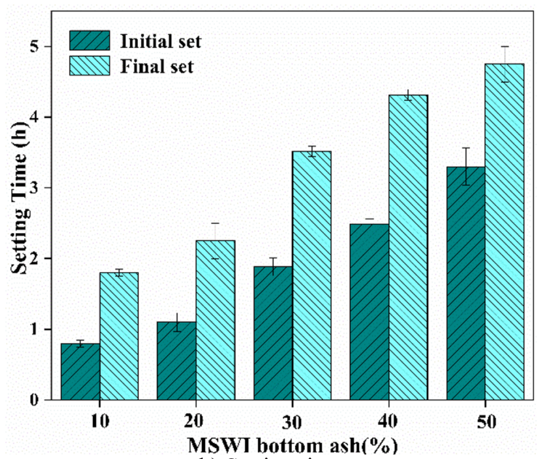


b) Setting time

Figure 5. The effect of adding MSWI BA to fly ash.



a) Compressive strength

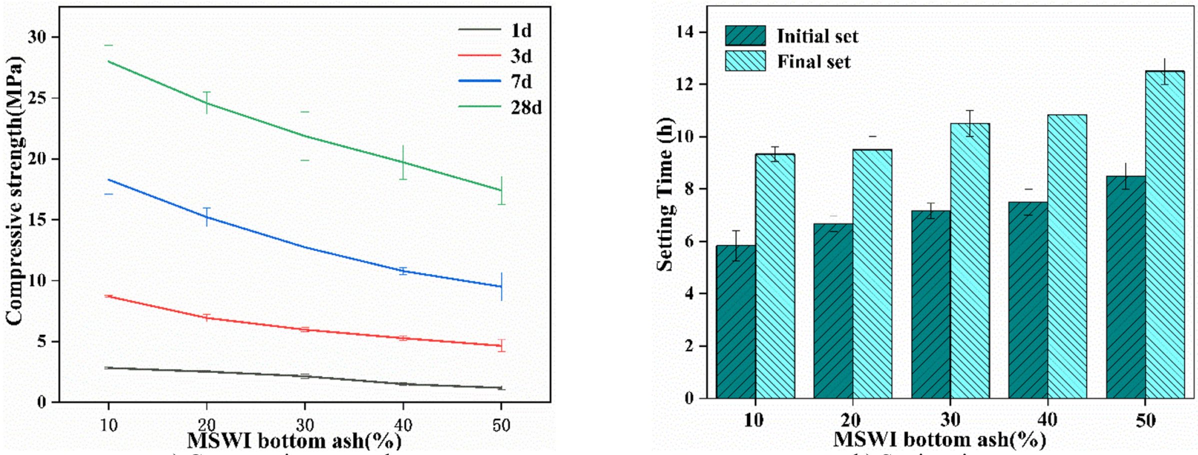


b) Setting time

Figure 6. The effect of adding MSWI BA to steel slag.

the same phenomenon, and both significantly increased with the increase in the MSWI BA content. This demonstrates that the activity of GBFS in MSWI BA-based cementitious materials is dominant.

As can be seen from Figure 5 and 6, although the combination of MSWI BA and fly ash or steel slag can also show good performance, for example, the 28-d strength is close to 16 and 14 MPa, respectively, it still cannot meet the strength requirement of 20 MPa. In addition, the setting time increases with the increase in the MSWI BA incorporation, which indicates that the reactivity of the fly ash and steel slag is better than that of MSWI FA.



a) Compressive strength

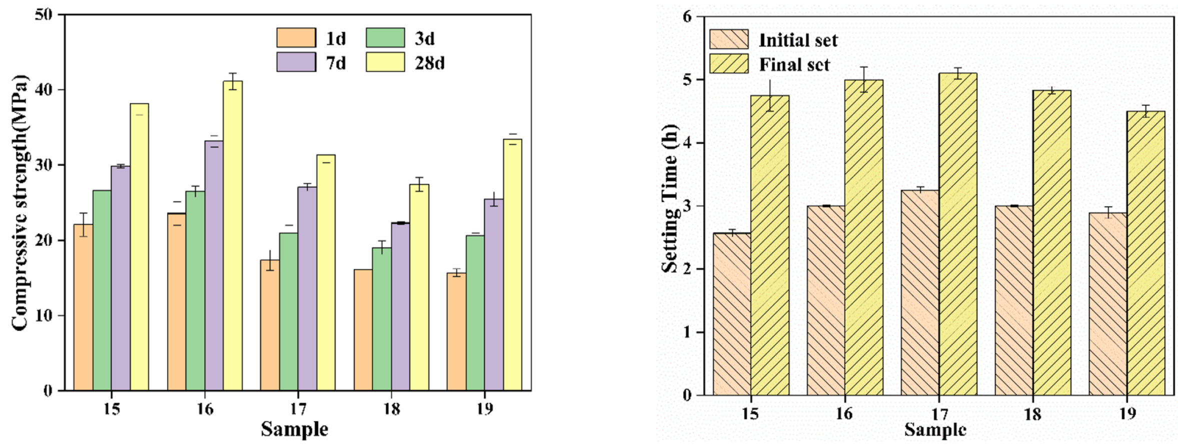
b) Setting time

Figure 7. The effect of adding MSWI BA to cement.

It can be clearly seen from Figure 7 that when the MSWI BA content is 50 %, the 28-d strength can reach 20 MPa; when the content is greater than 50 %, the strength condition can meet the demand for grouting materials. However, the cement-MSWI BA mix takes about 6 – 12 hours to set, which is one of the disadvantages of restricting the timely opening of roads.

Table 2. Material ratios (g).

Sample	Cement	Na_2SiO_3	MSWI BA	GBFS	Superplasticiser	Water
15	15	15	135	30	0.22	110
16	20	15	135	25	0.22	110
17	25	15	135	20	0.22	110
18	30	15	135	15	0.22	110
19	20	15	140	20	0.22	110



a) Compressive strength

b) Setting time

Figure 8. Research on the performance of the cement and mineral powder mixed in the MSWI BA.

Considering the requirements of the construction time and strength, research on mixing cement and GBFS in the MSWI BA was carried out again, in order to obtain the material proportions with a higher early strength with the appropriate setting time. Further verification was carried out according to the material ratios in Table 2, and the most ideal five groups were selected for detailed exploration. It can be found from Figure 8 that with the improvement in the cement and mineral powder, the 1-d strength can be close to 20 MPa, and the 28-d strength can reach 30 – 40 MPa. The setting time can be controlled in 2 – 5 h, both the early strength and setting time nearly meet the requirements.

Moreover, it can be found that under the conditions of the same water consumption and Na_2SiO_3, the higher the amount of mineral powder, the faster the condensation and the higher the early strength. The more cement, the higher the later strength.

SEM analysis

The SEM pictures of samples 15 to 19 for 7 days are shown in Figure 9. It can be seen that all five pictures show flocculent products and granular products. Overall, the microstructure is relatively complete, and there are no large defects and holes. The larger the amount of MSWI BA, the less complete the microstructure, which is caused by the low activity of MSWI BA. Among them, the clear outline of the granular product is the probability of the incomplete hydration of the MSWI BA and cement particles. Combined with the previous compressive strength and setting time, GBFS reacts quickly with sodium silicate, and it can be inferred that the construction of its structure is fast and rough. Cement, on the other hand, reacts relatively slowly, and its product formation is gradual and dense.

Pore structure analysis

Figure 10 shows the pore size distribution of each sample, and it can be clearly seen that each sample in the figure shows two peaks. One is between 1 and 100 nm, and the other is larger than 100 nm. The structure of No. 16 proportioning holes is optimal. That is, when the dosage of cement, MSWIBA and GBFS are 30, 135 and 15 g respectively, the number of small and large holes in the microstructure is the lowest. This is consistent with the results of the previous SEM analysis. The addition of cement and GBFS is beneficial to the benign development of the MSWI BA pore structure, and the effect of the cement is more significant. More GBFS can quickly generate a large amount of hydration products and improve strength, but its microstructure is not dense compared to the cement.

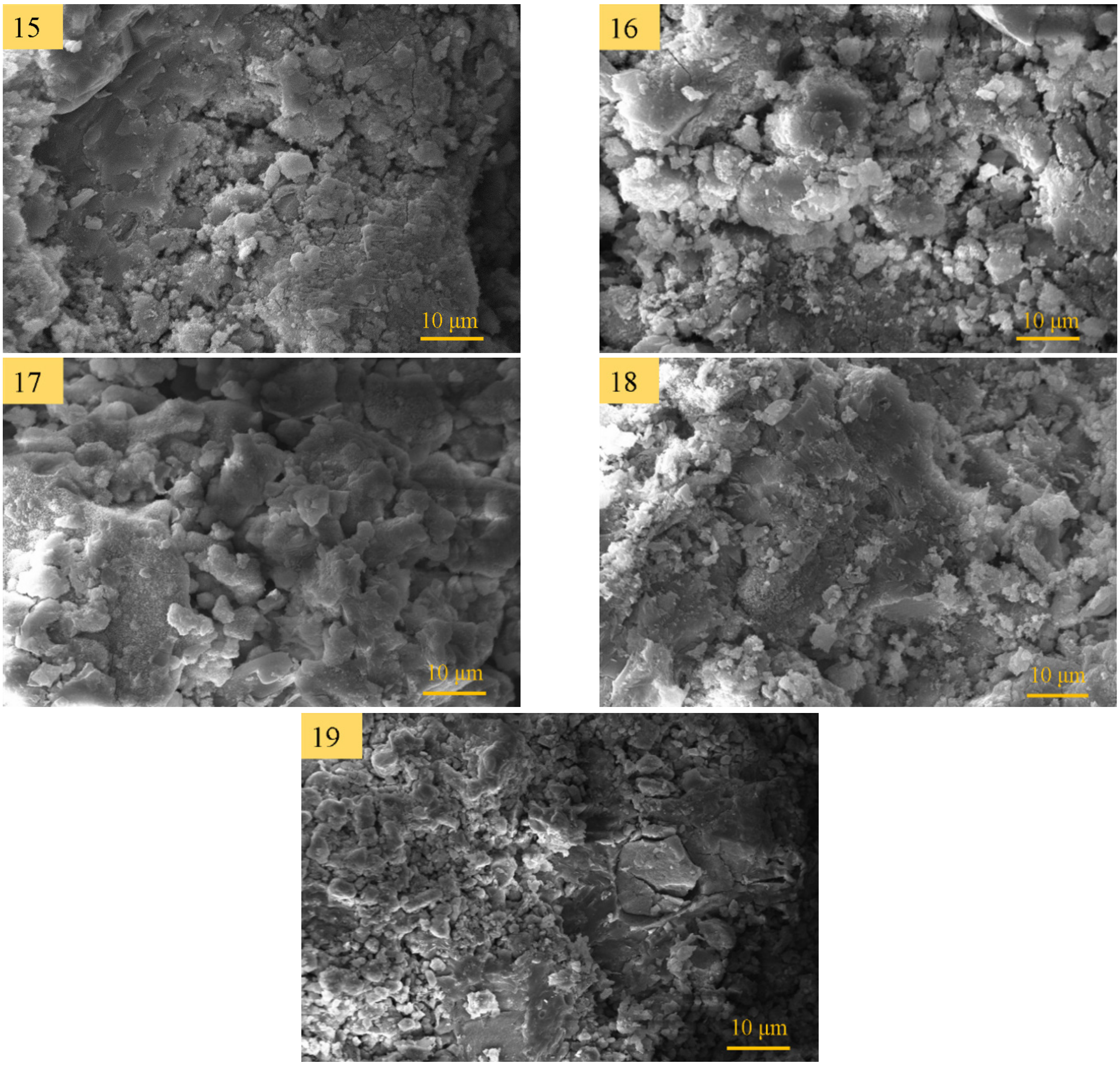


Figure 9. SEM pictures of the samples at 7 d.

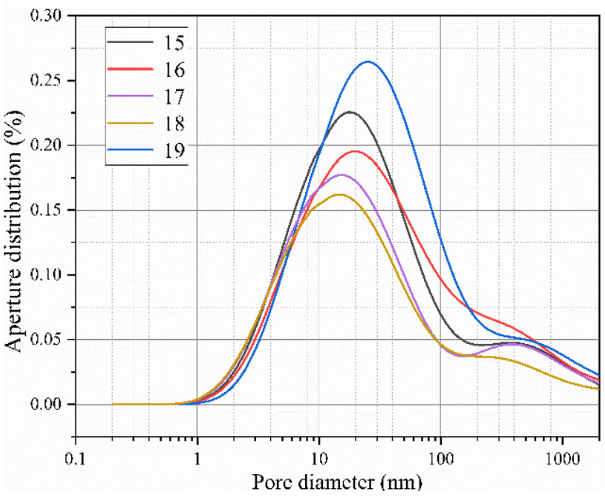


Figure 10. Pore structure of samples at 7 d.

Hydration calorimetric analysis

Figure 11 shows the effect of different raw material dosage on the intensity of chemical reaction. From the perspective of hydration reaction, the effect of the ratio of materials in each group on hydration is further expounded. It can be clearly seen that the main exothermic peak occurs about 10 hours after the material is in contact with water. Among them, group 16 shows the highest exothermic reaction peak, which explains the intrinsic reason for its high early intensity. In combination with Table 2, it can be found that the higher reaction exothermic peak is related to the content of mineral powder to a certain extent, which indicates that in the presence of Na_2SiO_3, the activity of mineral powder is higher than that of other components.

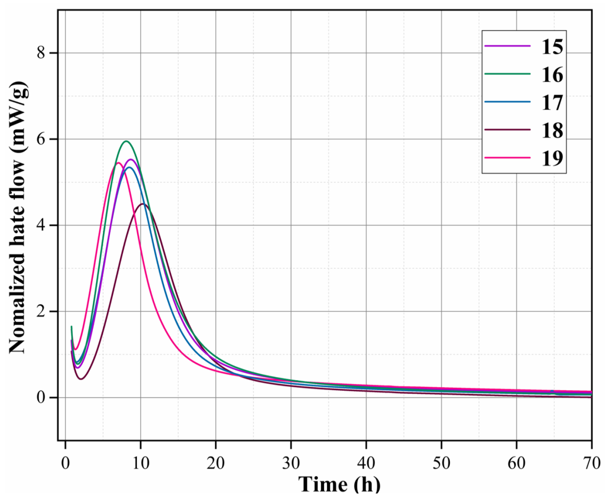


Figure 11. Hydration rate curve.

Figure 12 shows the total heat release of the five groups of materials over a 70-hour period, which can explain the reaction degree of the materials to a certain extent. It can be seen that the total heat release shows the following rule: 16 > 15 > 19 > 17 > 18. The total heat release was consistent with the 1 d and 3 d strength of the 5 groups of materials. It can be understood that the strength is mainly controlled by the degree of hydration reaction in the early stage.

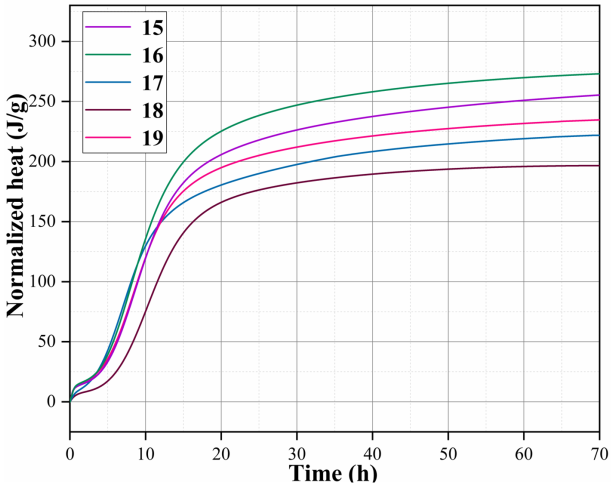


Figure 12. Hydration heat release curve.

Thermal gravimetric analysis

Figure 13 shows the mass loss of five groups of materials from 30 to 1000 °C. It can explain the degree of reaction of each group of materials after 7 days from the point of view of the reaction products. It can be found that the 7-d mass loss is significantly correlated with the 7-d strength. The mass loss is mainly related to the calcium silicate hydrate and calcium hydroxide. The development of the early strength is further explained from the point of view of the product generation.

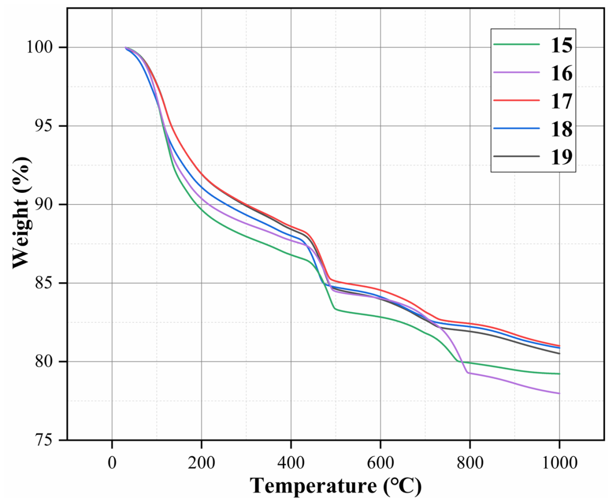


Figure 13. Mass loss curve.

CONCLUSIONS

MSWI BA has a certain amount of reactivity, but it cannot be applied in engineering alone because of its low activity. Fly ash and steel slag can improve the compressive strength and setting time of MSWI BA, but the improvement effect is not significant.

The combination of MSWI BA and GBFS can provide a compressive strength of nearly 40 MPa, but the setting time is too short (0.5 – 3 h) to provide sufficient enough time for the construction process. Simultaneously, the use of large quantities of cement can also meet the strength requirements, but its slow setting becomes a limiting factor.

Adding cement and GBFS together in MSWI BA can meet the requirements of grouting repaired roadbeds. It is worth noting that when the dosage of cement, MSWIBA and GBFS are 30 g 135 g and 15 g, respectively, the microstructure is the densest.

REFERENCES

1. Zhang Y., Wang L., Chen L., Ma B., Zhang Y., Ni W., Tsang D.C.W. (2021): Treatment of municipal solid waste incineration fly ash: State-of-the-art technologies and future perspectives. *Journal of Hazardous Materials, 411*, 125132. Doi: 10.1016/j.jhazmat.2021.125132
2. Cho B.H., Nam B.H., An J., Youn H. (2020): Municipal Solid Waste Incineration (MSWI) Ashes as Construction Materials-A Review. *Materials, 13*(14), 3143. Doi: 10.3390/ma13143143
3. Clavier K.A., Paris J.M., Ferraro C.C., Townsend T.G. (2020): Opportunities and challenges associated with using municipal waste incineration ash as a raw ingredient in cement production – a review. *Resources, Conservation and Recycling, 160*, 104888. Doi: 10.1016/j.resconrec.2020.104888
4. Assi A., Bilo F., Zanoletti A., Ponti J., Valsesia A., La Spina R., Zacco A., Bontempi E. (2020): The zero-waste approach in municipal solid waste incineration: reuse of bottom ash to stabilize fly ash. *Journal of Cleaner Production, 245*, 118779. Doi: 10.1016/j.jclepro.2019.118779
5. Yan K., Gao F., Sun H., Ge D., Yang S. (2019): Effects of municipal solid waste incineration fly ash on the characterization of cement-stabilized macadam. *Construction and Building Materials, 207*, 181-189. Doi: 10.1016/j.conbuildmat.2019.02.048
6. Maldonado-Alameda A., Giro-Paloma J., Rodríguez-Romero A., Serret J., Menargues A., Andrés A., Chimenos J.M. (2021): Environmental potential assessment of MSWI bottom ash-based alkali-activated binders. *Journal of Hazardous Materials, 416*, 125828. Doi: 10.1016/j.jhazmat.2021.125828
7. Zhang S.P., Ghouleh Z., Shao Y.X., Zhang S.P., Ghouleh Z., Shao Y.X. (2021): Green concrete made from MSWI residues derived eco-cement and bottom ash aggregates. *Construction and Building Materials, 297*(23), 123818. Doi: 10.1016/j.conbuildmat.2021.123818
8. Maldonado-Alameda A., Giro-Paloma J., Rodríguez-Romero A., Serret J., Menargues A., Andrés A., Chimenos J.M. (2021): Environmental potential assessment of MSWI bottom ash-based alkali-activated binders. *Journal of Hazardous Materials, 416*(15), 125828. Doi: 10.1016/j.jhazmat.2021.125828
9. Zhang S.P., Ghouleh Z., He Z., Hu L.L, Shao Y.X. (2021): Use of municipal solid waste incineration bottom ash as a supplementary cementitious material in dry-cast concrete. *Construction and Building Materials, 266*, 120890. Doi: 10.1016/j.conbuildmat.2020.120890
10. Flesoura G., Dilissen N., Dimitrakis G., Vleugels J., Pontikes Y. (2021): A new approach for the vitrification of municipal solid waste incinerator bottom ash by microwave irradiation. *Journal of Cleaner Production, 284*, 124787. Doi: 10.1016/j.jclepro.2020.124787
11. Van De Wouw P.M.F., Loginova E., Florea M.V.A., Brouwers H.J.H. (2020): Compositional modelling and crushing behaviour of MSWI bottom ash material classes. *Waste Management, 101*,168-282. Doi: 10.1016/j.wasman.2019.10.013
12. Huang G.D., Yang K., Sun Y.H., Lu Z.Y., Zhang X.Y., Zuo L., Feng Y.Q., Qian R.C., Qi Y., Ji Y.S., Xu Z.S. (2020): Influence of NaOH content on the alkali conversion mechanism in MSWI bottom ash alkali-activated mortars. *Construction and Building Materials, 248*, 118582. Doi: 10.1016/j.conbuildmat.2020.118582
13. Chen Z., Yang E.H. (2017): Early age hydration of blended cement with different size fractions of municipal solid waste incineration bottom ash. *Construction and Building Materials, 156*, 880-890. Doi: 10.1016/j.conbuildmat.2017.09.063
14. An J., Kim J., Nam B.H. (2017): Investigation on impacts of municipal solid waste incineration bottom ash on cement hydration. *Aci Materials Journal, 114*, 1-12. Doi: 10.14359/51689712
15. Chen D.H., Zhou W.J. Yi W., Won M. (2014): Full-depth concrete pavement repair with steel reinforcements. *Construction and Building Materials, 51*, 344-351. Doi: 10.1016/j.conbuildmat.2013.10.086
16. Temuujin J., Williams R.P., Van Riessen A. (2009): Effect of mechanical activation of fly ash on the properties of geopolymer cured at ambient temperature. *Journal of Materials Processing Technology, 209*, 5276-5280. Doi: 10.1016/j.jmatprotec.2009.03.016
17. Saludung A., Azeyanagi T., Ogawa Y., Kawai K. (2023): Mechanical and microstructural evolutions of fly ash/slag-based geopolymer at high temperatures: Effect of curing conditions. *Ceramics International, 49*(2), 2091-2101. Doi: 10.1016/j.ceramint.2022.09.175
18. Saha, S., Rajasekaran C. (2017): Enhancement of the properties of fly ash based geopolymer paste by incorporating ground granulated blast furnace slag. *Construction and Building Materials, 146*, 615-620. Doi: 10.1016/j.conbuildmat.2017.04.139.