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Study on the mechanical properties of expandable foam grout (EFG) based on mixing ingredients

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ABSTRACT: Expandable foam grout (EFG) is a cement mixture containing aluminum powder, bentonite, and an accelerator to fill underground cavities based on volume expansion and high flowability. The key properties of EFG, such as expansion, flowability, and compressive strength, need to be determined based on the specific objectives of the EFG application. This study aimed to observe the changes in the properties of EFG with varying contents of mixing ingredients. The expansion ratio, flow consistency, and compressive strength of EFG mixtures with different mixing ratios were measured. Based on test results, the contents of mixing ingredients are closely related to the mechanical properties. Aluminum powder plays a significant role in the volume expansion of EFG, which induces strength reduction. The gas bubbles generated by aluminum powder also reduce flowability. Additionally, bentonite and accelerator contents can control flowability, and the accelerator content affects volume expansion performance. Therefore, the EFG performance can be controlled by ingredient contents considering the purpose of EFG application.

KEYWORDS: Cavity-filling, compressive strength, expandable foam grout (EFG), flowability, volume expansion

1 INTRODUCTION

In urban areas, ground subsidence is primarily caused by soil loss from the damage or collapse of temporary retaining structures during underground construction, as well as pipeline failures. In recent years, rapid changes in groundwater levels due to heavy rainfall have also been identified as potential triggers for underground cavities or ground subsidence. To minimize these accidents, appropriate methods and materials are required to restore underground cavities or loose layers. Typical examples include cavities behind slurry walls and tunnel linings as well as those beneath roadways. These voids and cavities have various sizes and shapes. The restoration methods include excavating the surrounding ground, backfilling the excavated area, or directly injecting flowable materials into the cavities. In urban areas, it is generally more appropriate to inject flowable materials directly into cavities because it minimizes repair time and traffic restrictions.

In such cases, the injected material should have minimal impact on the surrounding ground. Therefore, materials that flow naturally by gravity are preferred to those injected under pressure. However, highly flowable materials exhibit self-leveling properties under gravity, making it difficult to completely fill cavities with diverse shapes. Therefore, in this study, expandable foam grout (EFG) was employed as a cavity-filling material owing to its high flowability and volume expansion. EFG is a grouting material that undergoes volume expansion owing to the gas bubbles generated during the early curing stage. This expansion enables the EFG to fill the entire cavity after injection. Designed specifically for cavities beneath roadways, EFG exhibits higher flowability than conventional controlled low-strength materials (CLSM) and a compressive strength that allows for re-excavation. Considering the target ground conditions, the strength can be set to ensure sufficient stability through an appropriate mix design even if re-excavation becomes difficult. Determining the suitable properties of EFG requires a thorough understanding of the target ground conditions, followed by an appropriate mix design.

To identify the suitable EFG properties for the target ground conditions and determine the corresponding mixing design, it is essential to evaluate the EFG characteristics with respect to its mixture ingredients. In this study, the effects of different ingredients on the flowability, volume expansion, and compressive strength of EFG are investigated. First, the key ingredients required for preparing EFG are introduced, and the experimental methods used to evaluate the flowability, volume expansion, and compressive strength are described. In the following section, the results obtained from the experiments are analyzed and discussed. This study provides a fundamental understanding of the influence of individual ingredients on the properties of EFG.

2 EXPANDABLE FOAM GROUT EFG

Expandable foam grout (EFG) is a cementitious material developed to fill cavities of various shapes. Its key characteristics include high flowability, high volumetric expansion, and low long-term strength. In this study, EFG was prepared by mixing water, cement, aluminum powder, bentonite, and an accelerator, as described in detail below.

Among these ingredients, the effect of water content is the most significant because it directly affects the flowability of the material and influences the resulting strength, depending on the water-to-cement ratio (w/c). The temperature of the mixing water is also a key factor in determining the initial reaction rate within EFG mixtures (Han et al., 2024a). To minimize the variation in the properties of EFG mixtures due to water temperature, tap water at a constant temperature of 20 °C was used for all mixtures. Cement imparts strength to EFG from the hydration of CaO in cement particles. Ordinary Portland cement (Grade 53), the most widely used cement, was selected for the experiments. The chemical composition of the cement is shown in Figure 1, with the major constituents being CaO (61.6%), SiO_2 (18.8%), Al_2O_3, Fe_2O_3, and MgO. Most cement particles were smaller than 75 μm, with a median diameter of 14 μm.

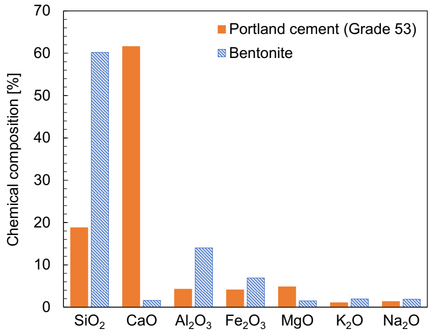

Figure 1. Chemical composition of Portland cement and bentonite.

Bentonite, which expands in volume upon absorbing free water, helps to reduce the leakage of injected EFG mixtures into cracks or voids during cavity filling. The bentonite used in this study consisted primarily of SiO_2 (60.2%), Al_2O_3 (14%), and Fe_2O_3 (6.9%), with a particle size smaller than 150 µm.

In this study, aluminum powder was used to induce volume expansion of the EFG. Aluminum powder reacts with hydroxide ions under alkaline conditions such as in cement paste to produce hydrogen gas. When this reaction occurs within cement paste, some of the generated gas bubbles remain trapped, increasing the number or size of voids, and consequently expanding the overall volume of the mixture. Note that this volume expansion process occurs before cement setting. The aluminum powder used in this study had a purity greater than 99.5%. It was of lamellar type with a large specific surface area and a unit weight in the range of 0.09 to 0.13 g/cm^3.

Accelerators are generally used to shorten the setting time of cement-based materials, and the same effect has been observed for EFG. In the early curing stage of EFG, both cement setting and volume expansion occur, and the duration of volume expansion is closely related to the setting time of the cement. Therefore, shortening the cement setting time reduces the period available for volume expansion, which affects the expansion ratio of the EFG. In this study, a white liquid alkali-free accelerator was used. The alumina ions ($Al(OH)_4^-$) and sulfate ions (SO_4^{2-}) contained in the alkali-free accelerator react with tricalcium aluminate (C_3A) and calcium ions (Ca^{2+}) in the cement paste to form ettringite, which accelerates the cement setting of EFG (Li et al. 2020; Maltese et al. 2007; Salvador et al. 2016).

When individual ingredients are combined, they interact through chemical reactions and other mechanisms, affecting the flowability, strength, and volume expansion properties of EFG. Consequently, the properties of EFG vary depending on the mixing ratios of the ingredients. This study focuses on the change in EFG properties according to the ingredient proportions. To determine the mixing ratios, the target performance levels were established for the three most critical properties: flowability, volume expansion, and compressive strength. First, high flowability is essential to enable easy placement into cavities and allow the material to disperse uniformly within the cavity space. According to ACI 229R (2013), CLSMs with a flow consistency of 200 mm or greater are classified as highly flowable. However, when the flow consistency exceeds 300 mm, additional tests are recommended to ensure resistance to segregation. In this study, the EFG mixtures were designed to achieve a flow consistency of at least 200 mm.

When highly flowable materials are injected into a cavity, their self-leveling behavior can prevent them from fully filling the roof of the cavity. The EFG was designed with a volume expansion that allowed it to fill the entire cavity. Greater volume expansion can also reduce material usage and costs. However, considering the potential non-uniformity and segregation of the materials, the target expansion ratio in this study was set at 50–100%. After complete cavity filling, a certain strength is required to ensure stable ground behavior, whereas an upper bound on the strength is necessary for easy re-excavation. Therefore, the target compressive strength at 28 d was set below 2.1 MPa in this study, in accordance with the recommendations of ACI 229R (2013). Note that the target compressive strength over the curing time should be determined according to the specific construction requirements.

Based on these target performance criteria, the mixing ratios of the EFG were determined to analyze the influence of each ingredient on its properties. Considering the target strength (under 2.1 MPa at 28 d), the water-to-cement ratios (w/c) were set to 77%, 80%, 83%, 87%, and 91%. For the target expansion ratio (50–100%), the aluminum content by water weight was set to 0.05%, 0.06%, 0.08%, 0.10%, 0.12%, and 0.14%. In addition, the bentonite content by water weight ranged from 0% to 0.6%, and the accelerator content ranged from 2% to 3%. For sample preparation, dry solid-type ingredients were first mixed, followed by the addition of water and mixing for 60 s. The accelerator was then added and mixed for an additional 30 s. The resulting mixtures were used as EFG samples for testing.

3 EXPERIMENTAL STUDY

3.1 *Flow test*

Various methods have been reported to evaluate the flowability of cementitious materials. In this study, the flowability of EFG was measured using the CLSM flow test method specified in ASTM D6103 (2017). The procedure was as follows. An open-ended cylindrical mold with an inner diameter of 100 mm and a height of 200 mm was placed on a flat plate. The mold was filled with the sample and lifted vertically, allowing the sample to spread over the plate. The largest diameter of the spread sample was measured, followed by that perpendicular to it. The average of these two measurements was recorded as the flow consistency of the sample. For each mixing ratio, the test was conducted at least thrice, and the average value was used as the flow consistency.

3.2 *Expansion test*

As there is no standard method for measuring the volume expansion of EFG, a custom test was conducted using 50 mL conical tubes. The initial volume and final volume after expansion were measured to calculate the expansion ratio. The specific test method was as follows. For each test, 15 mL or 20 mL of EFG was placed in a conical tube and the sample was cured for 24 h in a sealed container at a constant temperature. Note that the tubes were left uncapped to avoid excessive internal pressure. After curing, the expanded top surface was often uneven, which made it difficult to conduct precise volume measurements. Therefore, the final volume was calculated as the average of the highest and lowest scale readings of the tube. The expansion ratio was then determined from the initial and final volumes. The test was repeated at least three times for each EFG mixture and the average expansion ratio was reported.

3.3 *Unconfined compressive strength test*

Cylindrical specimens with a diameter of 50 mm and height of 100 mm were prepared for unconfined compressive strength (UCS) testing. Freshly mixed EFG was cast into molds and cured at 20 °C for 1 d before demolding. If the specimens lacked sufficient strength for demolding, they were cured for an additional 2 d. After demolding, the specimens were sealed with a plastic wrap and cured at a constant temperature until testing. UCS tests were performed at curing ages of 1, 3, 7, 14, and 28

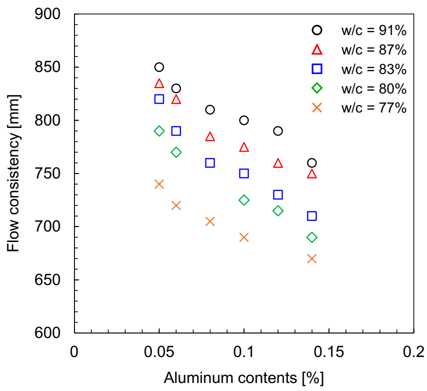

Figure 2. Flow consistency of EFG mixtures containing different water–cement and aluminum contents.

d at a loading rate of 1 mm/min. The test was terminated when a visible failure occurred in the test specimen. Stress–displacement curves were recorded, and the peak stress was reported as the unconfined compressive strength. Each test was repeated at least thrice for the same mixing ratio and curing age, and the average value was reported as the compressive strength.

4 EXPERIMENTAL RESULTS AND ANALYSES

4.1 *Flow consistency*

According to ACI 229R (2013), CLSMs with a flow consistency of 200 mm or greater, as measured using the flow testing method in ASTM D6103 (2017), are classified as highly flowable. However, when the flow consistency exceeds 300 mm, segregation of the material may occur; and therefore, the stability against segregation must be evaluated (Han et al. 2024b). In this study, all EFG specimens exhibited flow consistency values greater than 300 mm. Consequently, it was essential to evaluate the potential for segregation in the EFG mixtures. Various methods are available to assess segregation in CLSMs, grouting materials, and mortar. However, these methods are not directly applicable owing to the volume-expansion characteristics of EFG. Therefore, the segregation potential was assessed by monitoring the expansion test and conducting visual inspections during curing. No segregation was observed in the EFG samples during expansion and curing.

The influence of the mixture ingredients on the flowability of the EFG is summarized as follows. Figure 2 shows the variation in flow consistency with changes in the water-to-cement ratio (w/c) and aluminum content, while maintaining constant bentonite and accelerator contents. For all w/c values, the flow consistency decreases as the aluminum content increases, and similar slopes are observed. This decrease is likely due to the reaction of aluminum during the early curing

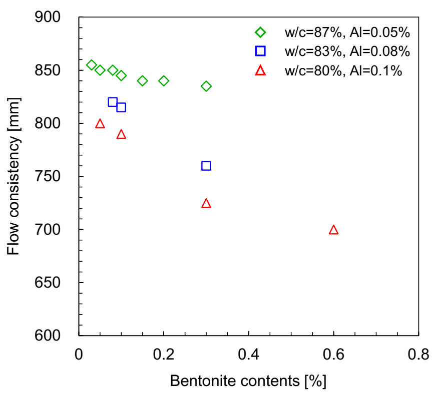

Figure 3. Flow consistency of EFG mixtures containing different bentonite contents.

stage of the EFG, which generates numerous hydrogen gas bubbles and consumes water in the process. A higher aluminum content allows for more extensive aluminum reactions, leading to lower flow consistency. At a constant aluminum content, the flow consistency ranges from 750 to 850 mm for w/c = 91% and from 650 to 750 mm for w/c = 77%. A decrease in the w/c ratio reduces the flow consistency. EFG mixtures with a higher w/c contain greater water content. As water has the most significant influence on the flowability of cementitious materials, a higher flow consistency is observed at higher w/c values. Figure 3 presents the variation in flow consistency for variation in the bentonite content only at a constant w/c and aluminum content. The flow consistency decreases as the bentonite content increases because dried bentonite absorbs water from the mixture.

4.2 *Expansion ratio*

As EFG contains multiple mixing ingredients, it is necessary to evaluate the influence of each ingredient on its expansion performance. Figure 4 presents the measured expansion ratios with varying w/c and aluminum contents, while keeping the bentonite and accelerator contents constant. The expansion ratio increases linearly with aluminum content, which is a key component responsible for volume expansion. At a constant aluminum content, a variation in w/c results in changes within a range of approximately 10%, with no significant trend. At Al = 0.05%, 0.08%, and 0.14%, the expansion ratio is approximately 25%, 45%, and 80%, respectively. Figure 5 shows the effect of bentonite content on the expansion ratio. At a constant w/c and aluminum content, the bentonite content has little effect on the expansion ratio. The decreased expansion ratios were measured with an increase in accelerator contents (ER = 60% to 47% at 2% to 3% accelerator). As EFG expansion occurs during the setting stage, the use of accelerators shortens the setting time, thereby limiting the expansion potential of the material (Han et al. 2024b).

4.3 *Unconfined compressive strength*

The target unconfined compressive strength (UCS) of the EFG must be selected according to the performance requirements of the ground conditions. In this study, considering both the ground stability after cavity filling and the ease of re-excavation, the target compressive strength at 28 d was set to approximately 2,000 kPa, and the mixing ratios were determined accordingly.

The measured compressive strength ranged from 75 to 430 kPa at 1 d, 580 to 2,050 kPa at 3 d, 1,000 to 3,500 kPa at 7 d, 1,150 to 3,500 kPa at 14 d, and 1,250 to 4,100 kPa at 28 d. In general, the compressive strength decreased with increasing w/c because of the higher water content.

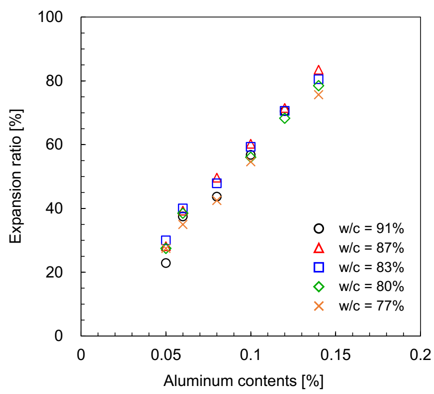

Figure 4. Expansion ratio of EFG mixtures containing different water–cement ratios and aluminum contents.

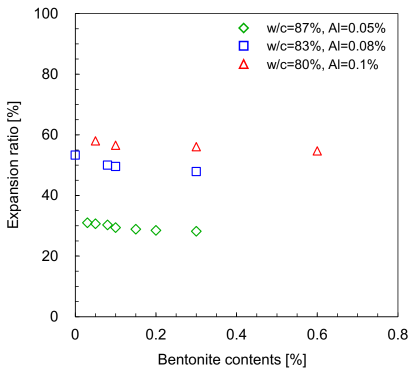

Figure 5. Expansion ratio of EFG mixtures containing different bentonite contents.

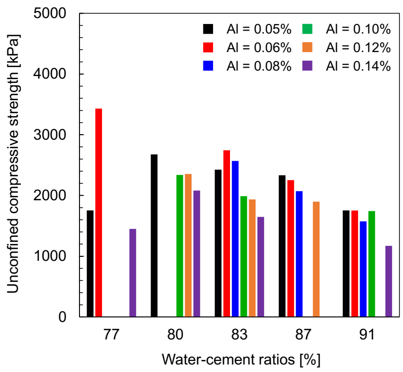

Figure 6. Unconfined compressive strength of EFG containing different water–cement ratios and aluminum contents at 14 d.

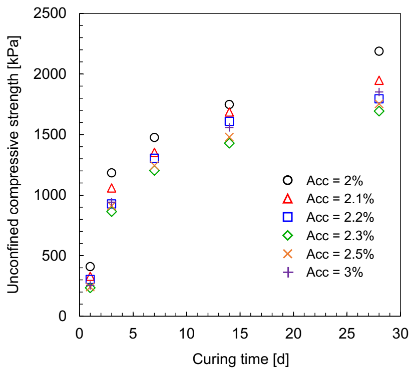

Figure 7. Unconfined compressive strength of EFG containing different accelerator contents.

The strength also tended to decrease with increasing aluminum content. Figure 6 illustrates the compressive strength at 14 d as a function of the aluminum content and w/c. At 14 d, the compressive strength generally decreases as the aluminum content increases. At 1 d, the relationship between the aluminum content and compressive strength is less clear, but the trend becomes more distinct with longer curing periods. This is likely due to the increased porosity associated with higher aluminum content, which in turn reduces the long-term strength. In contrast, at 1 d, the products formed during the expansion process may have provided additional structural rigidity (Han et al. 2024a).

Figure 7 shows the compressive strength as a function of the accelerator content. At the same curing age, the compressive strength generally decreases as the accelerator content increases. Typically, a higher accelerator content reduces the expansion period and expansion ratio, which in turn decreases the porosity of the EFG. In most cementitious materials, a higher porosity corresponds to a lower strength. However, the EFG specimens with lower porosity (higher accelerator content) exhibit a lower compressive strength. Simultaneous aluminum and accelerator reactions during early curing consume water and produce reaction products that may create a robust structure.

5 CONCLUSIONS

In this study, the flowability, expansion, and compressive strength of EFG samples with various mixing ratios were evaluated, and the variations in each property according to the mixing ingredients were presented.

The flowability was most affected by the water content. The gas bubbles generated by the aluminum reaction contributed to reduced flowability, and the flowability was further reduced with increasing bentonite and accelerator contents.

The expansion ratio was primarily influenced by the aluminum content, whereas the water-to-cement ratio (w/c) had little effect. Accelerators shortened the expansion period of the EFG, thereby reducing the expansion ratio.

Higher w/c values generally resulted in lower compressive strengths. An increase in the aluminum content tended to decrease the compressive strength, and this effect became more pronounced with longer curing times. It was anticipated that increasing the accelerator content would result in higher compressive strength, since cementitious materials generally exhibit higher compressive strength at lower porosity. However, the compressive strength reduced with higher accelerator content, possibly because the combined structure formed by the early aluminum and accelerator reactions was more rigid.

This study indicates that the properties of EFG may differ from those of conventional cementitious materials when multiple ingredients are combined. This study also provides a basis for predicting EFG properties a priori based on the mixing ratios at the mixing design stage.

6 ACKNOWLEDGEMENTS

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