Research Article

Mechanical Properties and Drying Shrinkage Investigation of Alkali-Activated Mortar Using Waste Glass Powder

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1. Introduction

Due to the worldwide increase in the use of glass products, the pursuit for waste glass recycling as a means of used glass disposal has similarly become an increasing trend [1–3]. The traditional landfilling of waste glass undesirably leads to environmental pollution and is unsustainable [4]. Different from the landfilling method, waste glass can be beneficially recycled to produce alkali-activated mortar (AAM) [5, 6] or alkali-activated concrete (AAC) [7, 8].

AAM and AAC often have better mechanical properties in the presence of waste glass powder (WGP) [9–11]. The literature indicates that the compressive strength of AAM [12] or AAC [13] could be improved significantly by blending with WGP. Due to the increased brittleness, however, the flexural strength growth of AAM or AAC has been reported to be insignificant when compared to the compressive strength growth rate. This increase in brittleness may exacerbate the risk of cracking, which ultimately poses a challenge and inhibits their (AAM and AAC) practical application and usage in the industry.

The dry shrinkage of AAM is usually greater than that of ordinary Portland concrete (OPC). Therefore, reducing shrinkage and cracking remains a key challenge [14]. Due to the potential reactivity of SiO₂ in WGP, it is effective in decreasing the early and long-term drying shrinkage of AAM [15]. When the alkali content was 8.31%, the addition of 14.57% WGP resulted in about 15.8% and 20.3% drying shrinkage reduction at 1 day and 120 days, respectively [16]. However, the drying shrinkage of AAM modified with WGP was still much higher than that of OPC [17].

In this study, the effects of Silica Fume (SF) and Nano-SiO₂ (NS) on the strength and dry shrinkage of AAM were comparatively evaluated. The correlations between compressive strength and curing age were analyzed. A prediction model for drying shrinkage analysis was established using the Backpropagation (BP) neural network [18].

2. Materials and Test Methods

The materials and test methods used in the study are discussed as follows. The test includes compressive, flexural, and shrinkage evaluation.

2.1. Materials. The cementitious material and alkali used in the study along with the mix-design proportions are presented and described in this section.
2.1.1. Cementitious Material. A composite cementitious material composed of slag powder (SP), SF, NS, and WGP (300 mesh) was used. Table 1 shows the chemical composition of each component in the composite cementitious material.

2.1.2. Sand. Quartz sand (40~70 mesh size) with a density of 3.65 g/cm³ was used as the fine aggregate for all the mix-designs.

2.1.3. Alkali Activator. The alkaline activators used in this study comprised of reagent sodium hydroxide (NaOH) flakes (96% purity) and sodium silicate (the SiO₂/Na₂O ratio modulus was 2.3). NaOH and sodium silicate were mixed to obtain an alkali activator with a modulus of 1.3 (ratio of SiO₂ to Na₂O).

2.2. Mix-Design Proportions. The activator solution was cementitious material ratio of 0.50, and the sand to cementitious material ratio of 1 was kept constant for all the mix-designs. The Na₂O concentration was kept at 6.0% (by mass of cementitious material in the alkaline activator solution). For AAM, SP was partially replaced by SF (5%, 10%, 15%, 20%, and 25%) and NS (0.5%, 1%, 1.5%, 2%, and 3%) by weight of the cementitious material. In the control group, the WGP and SP were kept at 30% and 70% by mass of the whole cementitious material, respectively. Table 2 presents the detailed AAM mix proportion.

2.3. Test Methods. The compressive and flexural strength tests were conducted in accordance with the Chinese Test Method for Strength of Cement Mortar (GB/T17671-1999, IOS) [19]. For each mix, 40 mm × 40 mm × 160 mm prismatic specimens were prepared and tested. The specimens were cured under standard curing conditions (20 ± 2°C, relative humidity ≥ 95%) for 3, 7, 28, and 56 days, respectively.

The dry shrinkage test of AAM was executed following the Chinese Hydraulic Concrete Test Standard SL352-2006 [20]. Prismatic specimens of 40 mm × 40 mm × 160 mm in dimensions were used. The specimens were demoulded after curing in the standard curing box for 48 hours. The specimens were thereafter placed into the dry shrinkage curing box (20 ± 2°C and 60 ± 5% relative humidity) after measuring the initial lengths. Measurements were conducted at ages of 3, 7, 28, and 56 days, respectively.

For all the tests, i.e., compressive strength, flexural strength, and shrinkage, three specimen replicates were used per test condition per mix-design proportion.

3. Test Results and Analysis

The test results are presented and analyzed in this section. The analysis includes the strength drying-shrinkage response behavior of SF and NS additives.

3.1. Effects of SF and NS on Compressive and Flexural Strength. Figure 1 shows the effects of SF dosage on the compressive and flexural strength of AAM. The results show that SF had an adverse effect on compressive strength. And the degree of this effect was more pronounced with an increase in the SF dosage.

As shown in Figure 1(a), when the SF content was 5% (S1) by weight of the cementitious material, the 28-day compressive strength increased by 2.6%. And when the SF content was 10%, 15%, 20%, and 25%, respectively, the 28-day compressive strength decreased by 10.2%, 19.8%, 23%, and 26.15%, respectively. It indicated that the compressive strength decreased more rapidly once the SF content was higher than 10%. After 56 days of curing, the compressive strength containing 5% SF decreased by about 2.34% compared to the control group. When SF was 10%, 15%, 20%, and 25%, respectively, the compressive strength decreased by 15.74%, 21.3%, 22.05%, and 24.62%, respectively.

As shown in Figure 1(b), the 28-day flexural strength increased by 1.5% when SF was 5% (S1) by weight of the cementitious material. When the dosage reached 10%, 15%, 20%, and 25%, respectively, reductions of 12.3%, 13.8%, 13.8%, and 24.6% in the 28-day flexural strength were observed, respectively. At the age of 56 days, the flexural strength with 5% SF was increased by 1.5%. When the SF content was 10%, 15%, 20%, and 25%, the flexural strength was decreased by 15.5%, 16.9%, 18.3%, and 23.9%, respectively. However, the reduction in flexural strength was much lower than that of the compressive strength, indicating an obvious enhancement of the AAM toughness. But when the SF content was higher than 10%, the flexural strength decreased rapidly.

Overall, Figure 1 suggests that 5% (S1) is the optimum SF dosage for simultaneously maximizing both the AAM compressive and flexural strengths.

Because the amorphous SiO₂ in SF promotes the formation of gel [21], when SF content was 5%, it influenced the mechanical properties of AAM positively. When SF content was greater than 10%, it would cause a decrease in the calcium-silicon ratio in AAM. An excessively high content of active amorphous SiO₂ not only slowed the hydrolysis of Si–O–Si [22], but also increased the degree of silicate ion polymerization. Silicates tend to form monomers rather than polymers, thus reducing the polymerization degree of AAM.

At the same time, SF participated in the reaction, which caused water consumption, resulting in slow dissolution of the calcium-rich phase in SP, which is not conducive for the formation of stable polymerization products [23]. Consequently, when the SF content was greater than 10%, it adversely affected the mechanical performance of AAM and, hence, caused a decay in the strength magnitudes.

Figure 2 shows the effect of NS content on the compressive and flexural strengths of AAM. The results show that NS could be contributing to both the compressive and flexural strength.

As shown in Figure 2(a), the compressive strength initially increased and then decreased as the NS dosage was increased. When 2% NS (NS4) by weight of cementitious material was added, the compressive strength at the age of 28 days and 56 days peaked at 82.07 MPa (with a 15.7% rise) and 89.05 MPa (with an 8.8% rise), respectively.
Similarly, the AAM flexural strength variation as a function of NS content was almost the same as that of the compressive strength trend. In the presence of 2% NS by weight of cementitious material, the 28-day and 56-day flexural strengths increased by 15.8% and 18.7%, respectively. (V_ceived results indicated that the flexural strength was more efficiently enhanced by blending with 2% NS by weight of cementitious material.

Overall, Figure 2 suggests that 2% (NS4) is the optimum NS dosage for simultaneously maximizing both the AAM compressive and flexural strengths.

Based on the graphical trends in Figure 2, it is apparent that the mechanical properties of AAM had a clear relationship with the degree of mix polycondensation [24]. Due to its surface and nucleation effects, NS will promote the reaction and dissolution of the calcium-rich phase in the slag to form a stable polymerization product. With an increase in the NS content, the mechanical strength of AAM would also increase. When the amount of NS is greater than 2% by weight of cementitious material, the NS size and surface effects are particularly stronger due to the electrostatic effects of NS and the highly active chemical bonds [25]. This leads to the phenomenon of agglomeration of NS, which cannot fully exert the surface of NS. The effect also makes part of the NS unreactive, resulting in a decrease in the mechanical strength of the AAM [26].
3.2. Effects of SF and NS on the Bending-Compressive Strength Ratio. The ratio of bending-compressive strength (Rt) is a vital index of the toughness of cementitious materials. The Rt values are illustrated in Figure 3 and indicate a gradual decline with age.

As shown in Figure 3(a), Rt with an increase in the SF dosage, indicating a decay in AAM toughness. When the SF content was 5% and 25% by weight of cementitious material, respectively, the Rt at 56 days was 8.7% and 6.3%, respectively.

As shown in Figure 3(b), for NS-reinforced AAM, the reduction rate of early Rt was faster than that of AAM in the absence of NS. With aging, the development of compressive and flexural strengths tended to be slow, but the flexural strength growth was higher than the compressive strength, thus increasing the overall toughness of AAM. When the NS dosage was increased from 0.5% to 3% by weight of cementitious material, respectively, the Rt at 56 days increased from 8.8% to 9.8%, respectively, indicating that NS could improve the AAM toughness.
3.3. Effects of SF and NS on Drying Shrinkage. The effects of SF content on drying shrinkage are graphically illustrated in Figure 4. When the SF content was 5%, 10%, 15%, 20%, and 25% by weight of cementitious material, respectively, the 3-day dry shrinkage increased by 13.9%, 9.8%, 17.5%, 55.1%, and 59.6%, respectively, whereas the 7-day drying shrinkage increased by 29.5%, 36%, 37.1%, 73.2%, and 84.1%, respectively. By contrast and in comparison to the control group, the drying shrinkage desirably decreased at 28 days and 56 days curing ages.

SF can improve the reaction rate [21], which increases the water consumption and, ultimately, leads to a relatively high early drying shrinkage as evident in Figure 4 for 3 and 7 days curing ages.

When the SF content was less than 10%, the drying shrinkage was gradually lower than that of the control group due to the improvement in the matrix pore structure.

When the SF content was 10%, more low-density C-S-H gels were formed [27], resulting in higher drying shrinkage; thus, a maximum drying shrinkage at 56 days was observed. However, when the SF content was more than 10%, some of the SF particles did not participate in the hydration reaction, thereby filling in the AAM pores and, ultimately, reducing the drying shrinkage.

The effects of NS on the drying shrinkage of AAM are shown in Figure 5. With the increase in the amount of NS, the 7-day drying shrinkage relative to the control group increased by −22.8%, −5%, 33.5%, 35.1%, and 69.2%, respectively. It can be seen from the 28-day and 56-day drying shrinkage values that the growth rate of the drying shrinkage values in the later period began to become placid. The results showed that the drying shrinkage of AAM increased with an increase in the NS content of about 0.5%–3%.

The surface and nucleation effects of NS help to promote the reaction rate of AAM [28]. As the amount of NS increases, the reaction makes the water consumption to increase, which leads to an increase in the early drying shrinkage. In this study, the amount of slag is the largest and the pore size in the matrix is mostly less than 10 nm or greater than 200 nm [29]. This is because the capillary pores are composed of mesopores and macropores, which is one of the reasons for the moisture migration pores between the matrix particles.

The shrinkage value mainly depends on the water loss of the mesopores and pore size of the macropores [30]. With an increase in the degree of matrix polymerization and loss of water dispersion, the reaction slows down and the pore structure of NS becomes refined. So when the amount of NS particles is less than 1.5%, the postdrying shrinkage value is lower than that of the control group. When the amount of NS particles is greater than 1.5%, due to the agglomeration phenomenon [31], the NS cannot fully react, which may cause the degree of polymerization within the matrix to be different—resulting in voids and a drying shrinkage value greater than the control group.

3.4. Compressive Strength Prediction Based on Linear Regression Analysis. It is a known fact that curing age plays a crucial role in the development of the compressive strength of AAM. However, the evolution of the compressive strength of the AAM is quite different from that of OPC. The relationships between age and compressive strength are illustrated in Figure 6.

As shown in Figure 6, $R^2$ (the coefficient of determination) is the fitting degree and defines the strength of the relationship between the variables, i.e., the higher the $R^2$ value, the stronger the relationship and the higher the prediction accuracy [32]. The fitting degree indexes in Figure 6 are all greater than 0.94 (i.e., $R^2 \geq 94\%$), which proves that the fitting degree is high and the correlation is...
Figure 6: Continued.
Figure 6: Prediction models and relative error of SF and NS on the compressive strengths. (a) A0 (0%). (b) S1 (5% SF). (c) S2 (10% SF). (d) S3 (15% SF). (e) S4 (20% SF). (f) S5 (25% SF). (g) NS1 (0.5% NS). (h) NS2 (1% NS). (i) NS3 (1.5% NS). (j) NS4 (2% NS). (k) NS5 (3% NS). (l) The relative error.
strong. Therefore, a prediction curve of compressive strength can be obtained for AAM containing SF or NS as follows:

\[ y(x) = a \ln(x) + b. \]  

The regression coefficients, \(a\) and \(b\), are listed in Table 3.

To verify the applicability of the prediction model, the calculated compressive strength was compared with the measured test data. As shown in Figure 6(i), the relative error of the compressive strength between the calculated value and the experimental data did not exceed 5%, which means that the model predictions were in agreement with the experimental data.

The compressive strength model of AAM was obtained with relatively high reliability, i.e., \(R^2 > 90\%\). However, because the compressive strength is also affected by other factors such as the water-to-cementitious material ratio, curing conditions, and specimen size, further analysis was necessary to validate the model predictions.

3.5. Drying Shrinkage Prediction Model Based on BP Neural Network. From the perspective of the drying shrinkage mechanism of alkali-activated materials, the pore structure theory [33, 34] assumes that drying shrinkage was mainly caused by changes in its pore distribution and capillary tension, while the C-S-H gel theory [35] considers that the drying shrinkage of AAM was predominantly due to the low-density (LD) C-S-H gel, which causes drying shrinkage. Therefore, it was considered that the factors affecting the drying shrinkage include the types of gelling materials, water-to-cementitious material ratio, curing conditions, and test block size [36]. At the same time, the factors influencing the drying shrinkage of AAM also had similar impacts on the compressive strength, suggesting the existence of some correlations. Therefore, it was deemed possible to establish a prediction model for age, compressive strength, and drying shrinkage, respectively.

In order to effectively predict the size change caused by shrinkage, a nonparametric method was proposed. That is, to use BP neural network [18] to train the measured data and effectively establish a model to predict shrinkage. The drying shrinkage prediction model uses a multilayer Backpropagation algorithm, which relies on learning from the measured data and appropriately adjusting the weights of the neural network. BP neural network can describe the changes in drying shrinkage with time and compressive strength [18].

To verify the applicability of AAM age and compressive strength to the drying shrinkage prediction curve, the calculated values of drying shrinkage were compared with the test data. As shown in Figure 7(l), the prediction error is no more than 15%, meaning that the model prediction was in agreement with experimental data, thus substantiating that the model can predict the drying shrinkage of AAM.

Figure 8 shows the effects of the compressive strength of AAM on drying shrinkage. It can be seen from Figure 8(a) that when the SF content is less than 10%, the slope of the curve will increase, indicating that SF reaction leads to water consumption, which causes the drying shrinkage value to rise. When the SF content is equal to 10%, the slope of the curve is the largest, indicating that SF not only causes water consumption at this time but also forms a low-density C-S-H gel that accelerates the rise of the drying shrinkage value.

When the SF content is greater than 10%, the SF may not fully react and the partially unreacted SF fills the voids, thereby reducing the increase in the shrinkage value. However, this affects the strength development, resulting in a decrease in the slope of the curve.

In Figure 8(b), the incorporation of NS helps to promote the reaction rate of the matrix, resulting in water consumption, but part of the stable gel produced makes the early strength development rate greater than the drying shrinkage evolution and the slope of the front part of the curve to be smaller. Above 1.5%, the slope decreases as the NS doping amount increases. When the doping amount of NS is 1.5%, the reaction leads to excessive water consumption, so that the drying shrinkage in the later period increases faster, and hence, the slope of the curve will increase. When the doping amount of NS is greater than 1.5%, its agglomeration will lead to a lower density of the matrix, resulting in a larger drying shrinkage value, which also affects the strength development, and hence, the slope of the curve increases.

From Figures 7 and 8, it can be deduced that the BP neural network can establish a prediction model based on age, compressive strength, and drying shrinkage value. And by adjusting the regression coefficients, the drying shrinkage prediction model can be formulated based on knowing the curing age and compressive strength. Thus, the drying shrinkage value of modified alkali-activated mortar prepared using SF and NS with waste glass can be predicted with the following model:

\[
\begin{align*}
  z &= w_1 \tan \left( m_1 x + m_2 y + b_1 \right) + w_2 \tan \left( m_3 x + m_4 y + b_2 \right) \\
  &+ w_3 \tan \left( m_5 x + m_6 y + b_3 \right) + b_4, \\
  \tan \left( x \right) &= \frac{2}{1 + e^{-x}} - 1, \\
\end{align*}
\]

where \(z\) is drying shrinkage value, \(x\) is age, and \(y\) is compressive strength. The respective model fitting parameters and coefficients are listed in Table 4.

In actual field construction projects, it is usually difficult to measure the drying shrinkage of a structure. Thus, the compressive strength is often used as one of the detection and shrinkage representative measures. By measuring the age and compressive strength, drying shrinkage can be predicted in an engineering structure. These predictions and assessments can be used to avoid large drying shrinkage related cracks in the structure and other hazardous failures.

In this paper, the prediction curves for age, compressive strength, and drying shrinkage established using BP neural network can predict the drying shrinkage of modified AAM made from SF and NS using waste glass powder-based additives. However, in actual engineering practice, its drying shrinkage is also affected by many interactive factors (such as water-to-cementitious material ratio, curing environment,
Table 3: The fitting-curve parameters.

| Param | A0  | S1  | S2  | S3  | S4  | S5  | NS1 | NS2 | NS3 | NS4 | NS5 |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| a     | 10.46 | 9.97 | 7.96 | 8.02 | 8.28 | 8.72 | 11.34 | 11.93 | 12.4 | 12.88 | 13.09 |
| b     | 38.22 | 39.71 | 37.16 | 31.15 | 29.17 | 24.72 | 38.33 | 38.43 | 38.27 | 38.65 | 35.45 |
| R²    | 0.96  | 0.98 | 0.97 | 0.98 | 0.95 | 0.97 | 0.98 | 0.98 | 0.98 | 0.97 | 0.98 |

Figure 7: Continued.
Figure 7: Effects of age on drying shrinkage and relative error. (a) A0 (0%). (b) S1 (5% SF). (c) S2 (10% SF). (d) S3 (15% SF). (e) S4 (20% SF). (f) S5 (25% SF). (g) NS1 (0.5% NS). (h) NS2 (1% NS). (i) NS3 (1.5% NS). (j) NS4 (2% NS). (k) NS5 (3% NS). (l) The relative error.
specimen size, and type of cementing material). Prior to shrinkage value verification, the proposed prediction model should not be considered to be universal—validation is still warranted. However, the establishment of this prediction model also provides reference datum for the practical application of AAM in engineering structures.

4. Conclusions and Recommendations

In this study, AAM prepared with different amounts of SF- and NS-modified waste glass was used to investigate the compressive strength, flexural strength, ratio of bending-compressive strength (Rt), and drying shrinkage properties along with a prediction model establishment. From the study results and findings, the following conclusions are drawn:

(1) With an increase of the curing age, the compressive and flexural strengths of AAM increased, with the early strength development being faster than the later. The early drying shrinkage growth was also rapid, but decayed with age.

(2) Low content of SF can improve the flexural strength and toughness of the AAM as well as help to improve the matrix pore structure and, consequently, suppress the increase in drying shrinkage. When the amount of SF is greater than 10%, the strength of the AAM rapidly decays and adversely affects the Rt, which ultimately results in increased brittleness. Therefore, the recommended optimum SF dosage is 5.0% for optimal performance.

(3) NS has a positive influence on the mechanical properties and toughness of AAM. When the NS dosage was 1.5%, it effectively suppressed the drying shrinkage. When the amount of NS was 2%, AAM had the highest compressive and flexural strengths, which inadvertently results in NS particle agglomeration, which not only increased the drying

![Figure 8: Effects of compressive strength on drying shrinkage. (a) SF group. (b) NS group.](image)

**Table 4:** The curve-fitting parameters of drying shrinkage.

| Param | A0 | S1  | S2  | S3  | S4  | S5  | NS1 | NS2 | NS3 | NS4 | NS5 |
|-------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \(b_1\) | 1.045 | 2.176 | 2.208 | 2.758 | 2.675 | 2.486 | 2.407 | 2.085 | 2.102 | 1.597 | 2.186 |
| \(b_2\) | 0.071 | 0.261 | 0.651 | 0.277 | 0.038 | 0.648 | 0.510 | 0.315 | 0.289 | 0.868 | 0.963 |
| \(b_3\) | 1.212 | 0.842 | 1.137 | 0.663 | 1.507 | 2.873 | 1.743 | 2.195 | 0.733 | 1.893 | 0.992 |
| \(m_1\) | 0.579 | 2.611 | 2.392 | 2.079 | 1.816 | 0.546 | 1.684 | 1.198 | 2.497 | 0.011 | 2.443 |
| \(m_2\) | 0.813 | 0.684 | 0.432 | 0.517 | 0.955 | 1.281 | 1.067 | 0.683 | 0.386 | 0.711 | 0.109 |
| \(m_3\) | 1.655 | 0.078 | 3.504 | 0.682 | 0.128 | 2.278 | 0.404 | 2.061 | 0.312 | 2.252 | 0.834 |
| \(m_4\) | 2.144 | 1.767 | 0.063 | 1.794 | 0.073 | 0.484 | 1.975 | 0.894 | 2.028 | 4.145 | 2.606 |
| \(w_1\) | 1.867 | 0.702 | 0.854 | 1.383 | 0.811 | 0.370 | 0.445 | 0.116 | 0.874 | 2.953 | 1.081 |
| \(w_2\) | 0.178 | 0.683 | 0.473 | 0.316 | 0.269 | 0.046 | 0.202 | 0.448 | 0.918 | 0.115 | 0.548 |
| \(w_3\) | 1.211 | 0.900 | 0.178 | 0.725 | 0.304 | 0.171 | 0.589 | 0.564 | 1.582 | 0.962 | 1.567 |
| \(w_4\) | 0.245 | 1.200 | 1.272 | 0.457 | 1.304 | 1.590 | 1.218 | 0.659 | 0.911 | 0.839 | 0.502 |
shrinkage, but also adversely affected its strength development. Therefore, the recommended optimum NS dosage is 1.5% for optimal performance.

(4) Through regression analysis, a compressive strength prediction model of the AAM was generated. The relative error of the predicted value of the compressive strength and the experimental data did not exceed 5%, i.e., 95% prediction accuracy. Therefore, the model was effectively reliable for SF and NS analysis as well as prediction of the AAM compressive strength.

(5) Based on the BP neural network, a prediction model based on age, compressive strength, and drying shrinkage were mathematically established. The model exhibited good prediction accuracy and could reasonably predict the drying shrinkage of AAM containing SF or NS.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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References

[1] Y. Qi, X. Xiao, Y. Lu, J. Shu, J. Wang, and M. Chen, “Cathode ray tubes glass recycling: a review,” Science of the Total Environment, vol. 650, pp. 2842–2849, 2019.

[2] A. Mohajerani, J. Vajna, T. H. H. Cheung, H. Kurmus, A. Arulrajah, and S. Horpibulsuk, “Practical recycling applications of crushed waste glass in construction materials: a review,” Construction and Building Materials, vol. 156, pp. 443–467, 2017.

[3] G. A. Blengini, M. Busto, M. Fantoni, and D. Fino, “Eco-efficient waste glass recycling: integrated waste management and green product development through LCA,” Waste Management, vol. 32, no. 5, pp. 1000–1008, 2012.

[4] S. C. Paul, B. Savija, A. J. Babafemi et al., “A comprehensive review on mechanical and durability properties of cement-based materials containing waste recycled glass,” Journal of Cleaner Production, vol. 198, pp. 891–906, 2018.

[5] G. F. Huseien, A. R. M. Sam, K. W. Shah, M. A. Asaad, M. M. Tahir, and J. Mirza, “Properties of ceramic tile waste based alkali-activated mortars incorporating GBFS and fly ash,” Construction and Building Materials, vol. 214, pp. 355–368, 2019.

[6] P. Shoaei, F. Améri, H. Reza Musaei, T. Ghasemi, and C. B. Cheah, “Glass powder as a partial precursor in Portland cement and alkali-activated slag mortar: a comprehensive comparative study,” Construction and Building Materials, vol. 251, Article ID 118991, 2020.

[7] H. A. Abdel-Gawwad, M. S. Mohammed, S. E. Zakery et al., “Preparation, performance, and stability of alkali-activated-concrete waste-lead bearing sludge composites,” Journal of Cleaner Production, vol. 259, Article ID 120924, 2020.

[8] M. Najimi and N. Ghafoori, “Engineering properties of natural pozzolan/slag based alkali-activated concrete,” Construction and Building Materials, vol. 208, pp. 46–62, 2019.

[9] C.-C. Wang, H.-Y. Wang, B.-T. Chen, and Y.-C. Peng, “Study on the engineering properties and prediction models of an alkali-activated mortar material containing recycled waste glass,” Construction and Building Materials, vol. 132, pp. 130–141, 2017.

[10] Z. D. Abdollahnejad, Effects of Waste Ground Glass and Lime on the Crystallinity and Strength of Geopolymers, pp. 1–38, Magazine of Concrete Research, 2018.

[11] R. M. D. Gutiérrez, M. A. V. Caicedo, and L. A. G. Apomete, “Alkali-activated metakaolin mortars using glass waste as fine aggregate: mechanical and photocatalytic properties,” Construction and Building Materials, vol. 235, Article ID 117510, 2020.

[12] L. Bostancı, “Effect of waste glass powder addition on properties of alkali-activated silica fume mortars,” Journal of Building Engineering, vol. 29, Article ID 101154, 2020.

[13] S. Zhang, A. Keulen, K. Arbi, and G. Ye, “Waste glass as partial mineral precursor in alkali-activated slag/fly ash system,” Cement and Concrete Research, vol. 102, pp. 29–40, 2017.

[14] H. Ye and A. Radlińska, “Shrinkage mechanisms of alkali-activated slag,” Cement and Concrete Research, vol. 88, pp. 126–135, 2016.

[15] M. Cyr, R. Idir, and T. Poinot, “Properties of inorganic polymer (geopolymer) mortars made of glass cullet,” Journal of Materials Science, vol. 47, no. 6, pp. 2782–2797, 2012.

[16] L. Zhang and Y. Yue, “Influence of waste glass powder usage on the properties of alkali-activated slag mortars based on response surface methodology,” Construction and Building Materials, vol. 181, pp. 527–534, 2018.

[17] Y. Liu, C. Shi, Z. Zhang, and N. Li, “An overview on the reuse of waste glasses in alkali-activated materials,” Resources, Conservation and Recycling, vol. 144, pp. 297–309, 2019.

[18] L. Bal and F. Bule-Bodin, “Artificial neural network for predicting drying shrinkage of concrete,” Construction and Building Materials, vol. 38, pp. 248–254, 2013.

[19] GB/T17671-1999, Test Method for Strength of Cement Mortar (IOS), Standards Press of China, Beijing, China, 1999.

[20] SL352-2006, Hydraulic Concrete Test Regulations, China Water & Power Press, Beijing, China, 2006.

[21] A. Autef, E. Joussein, G. Gasgnier, and S. Rossignol, “Role of the silica source on the geopolymerization rate,” Journal of Non-crystalline Solids, vol. 358, no. 21, pp. 2886–2893, 2012.

[22] L. Loyd, Ph.d. Thesis, University of Melbourne, Australia, 2008.

[23] J. S. J. V. D. Shindunata and G. C. Lukey, “Effect of curing temperature and silicate concentration on fly ash based geopolymerisation,” Industrial and Engineering Chemistry Research, vol. 45, no. 10, pp. 59–68, 2006.

[24] D. Papias, I. P. Giannopoulou, and T. Perraki, “Effect of synthesis parameters on the mechanical properties of fly ash based geopolymers,” Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol. 301, no. 1-3, pp. 246–254, 2007.

[25] J. Liu, A. X. Sheng, and F. Liu, “Nano minerals and their environmental effects,” Earth Science, vol. 43, pp. 1450–1463, 2018.
[26] W. J. Wang, X. R. Zhu, and P. F. Fang, “Research on solidification mechanism of cemented soil with nano-silica powder,” *Journal of Zhejiang University (Engineering)*, vol. 39, pp. 148–153, 2005.

[27] R. Liu, F. Han, and P. Yan, “Characteristics of two types of C-S-H gel in hardened complex binder pastes blended with slag,” *Science China Technological Sciences*, vol. 56, no. 6, pp. 1395–1402, 2013.

[28] K. Gao, K.-L. Lin, D. Wang et al., “Effect of nano-SiO2 on the alkali-activated characteristics of metakaolin-based geopolymers,” *Construction and Building Materials*, vol. 48, pp. 441–447, 2013.

[29] C. Shi, “Strength, pore structure and permeability of alkali-activated slag mortars,” *Cement and Concrete Research*, vol. 26, no. 12, pp. 1789–1799, 1996.

[30] F. Collins and J. G. Sanjayan, “Effect of pore size distribution on drying shrinking of alkali-activated slag concrete,” *Cement and Concrete Research*, vol. 30, no. 9, pp. 1401–1406, 2000.

[31] Z. Dan, R. W. Sun, and H. J. Xiao, “Effects of nano-SiO2 particles on the mechanical and microstructural properties of ultra-high performance cementitious composites,” *Cement and Concrete Composites*, vol. 56, pp. 25–31, 2015.

[32] L. F. Walubita, T. Scullion, S. I. Lee, A. N. M. Faruk, S. Nazarian, and I. Abdallah, “Texas flexible pavements and overlays: year 5 report - complete data documentation,” Technical Report, Texas A&M Transportation Institute (TTI), College Station, TX, USA, 2017.

[33] F. H. Wittmann, “Creep and shrinkage mechanisms,” in *Creep and Shrinkage in Concrete Structures*, Z. P. Bazant and F. H. Wittmann, Eds., pp. 129–161, Wiley, Chichester, UK, 1982.

[34] J. F. Young, “Physical mechanisms and their mathematical descriptions,” in *Mathematical Modelling of Creep and Shrinkage of Concrete*, Z. P. Bazant, Ed., pp. 63–98, Wiley, Chichester, UK, 1988.

[35] P. D. Tennis and H. M. Jennings, “A model for two types of calcium silicate hydrate in the microstructure of Portland cement pastes,” *Cement and Concrete Research*, vol. 30, no. 6, pp. 855–863, 2000.

[36] M. Mastali, P. Kinnunen, A. Dalvand, R. Mohammadi Firouz, and M. Illikainen, “Drying shrinkage in alkali-activated binder—a critical review,” *Construction and Building Materials*, vol. 190, pp. 533–550, 2018.