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EFFECT OF SUPERPLASTICIZER DOSAGE ON WORKABILITY AND 28-DAY STRENGTH OF GGBFS-FA GEOPOLYMER MORTAR IN VIETNAM

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ABSTRACT: Using by-products such as ground granulated blast furnace slag (GGBFS) in binder can be a sustainable alternative to ordinary Portland cement, exhibiting rapid setting and workability loss, which can affect practical applications for this material in mortar and concrete. This research evaluates the effects of chemical admixture, which is a water-reducing and superplasticizer agent made from naphthalene formaldehyde sulfonate, at different dosages on the fresh and hardened properties of geopolymer mortar using GGBFS as a mineral admixture and fly ash (FA) as a filler. The results indicate that workability loss becomes evident when chemical admixture is used at 1.0% and 1.5% of binder weight. Despite the initial decrease in workability over time, the mix proportion using 1.0% and 1.5% chemical admixture demonstrates improved compressive strength at 28 days compared with the mix proportion using 0.5% chemical admixture, which can be up to 26.5% with a p-value is 1.8%. The optimal performance was observed at the mix proportion using 1.5% water reducing and superplasticizer, which balanced workability retention and mechanical strength development. The research promotes the use of eco-friendly GGBFS-FA-based geopolymers with assured performance toward the sustainable development of the construction sector in Vietnam.

Keywords: Geopolymer mortar, Industrial by-products, Workability, Sustainable development, Vietnam

1. INTRODUCTION

Vietnam has emerged as a major player in cement production, ranking third in the world with an estimated output of 120 million metric tons in 2024, according to the U.S. Geological Survey [1]. This rapid growth is driven by the country's booming construction sector. However, this expansion comes at an environmental cost, as cement production accounts for approximately 8% of global carbon dioxide (CO_2) emissions [2] [3]. Given these challenges, there is an urgent need to explore sustainable alternatives, such as geopolymer binders, which utilize industrial by-products such as ground granulated blast furnace slag (GGBFS) incorporated with alkali-activated materials to avoid using Portland cement in the mix proportion of concrete or mortar.

Based on this solution, researchers have turned to geopolymer technology, which offers comparable strength and durability while reducing greenhouse gas emissions by up to 80% compared to ordinary Portland cement [4]. Despite these advantages, geopolymer mortar faces practical challenges, particularly rapid workability loss, which can hinder its application in construction.

The Vietnamese government has recognized this potential through policies such as the National Green Growth Strategy (2021-2030), which promotes the use of industrial by-products in construction in Decision No. 1658/QD-TTg, 2021 [5]. However, when using GGBFS and fly ash (FA), workability and setting characteristics of concrete and mortar need to be tested, which vary depending on the properties of materials and processing methods. This study investigates the workability loss of geopolymer mortar incorporating GGBFS and an alkali-activated material.

Further, in the mix proportion, FA from a thermal power plant was used as a filler. Previous research has shown that chemical admixtures, such as water-reducing and superplasticizers, can improve workability but may also influence setting behavior and mechanical properties [6]. Composition of FA, such as silica, lime, and carbon contents, has a major impact on the pozzolanic reactivity that affects the performance of mortar [7] [8]. However, few studies have assessed reactivity and admixture compatibility of high-GGBFS mixes with FA in Vietnam's ambient conditions. In this research, experimental results demonstrate that chemical admixture dosages of 0.5% were not effective for geopolymer mortar. While the dosages of 1.0% and 1.5% by binder weight led to noticeable workability loss over time, they also enhanced 28-day compressive strength due to improved initial workability for geopolymer mortar using 70% GGBFS replaced for cement weight and an amount of FA as a filler. These findings suggest that optimizing admixture use can balance fresh condition performance and long-term strength development.

2. RESEARCH SIGNIFICANCE

This study implemented experiments for fresh conditions of geopolymer mortar incorporating GGBFS and FA. The research addresses the critical challenge of rapid workability loss in GGBFS-based binders by evaluating the impact of different dosages of naphthalene formaldehyde sulfonate-based superplasticizer on fresh and hardened properties. Findings reveal that higher admixture dosages (1.0–1.5%) enhance 28-day compressive strength by up to 26.5%, despite initial workability reduction. The study identifies an optimal dosage (1.5%) that balances strength development and workability, promoting broader adoption of sustainable construction materials in line with Vietnam's green growth strategies, which aim to reduce the amount of CO_2 emissions.

3. BACKGROUND OF INDUSTRIAL BY-PRODUCTS IN VIETNAM

3.1 Ground Granulated Blast Furnace Slag

3.1.1 Production of GGBFS in Vietnam

Vietnam's steel industry has undergone remarkable expansion in recent years, positioning the country among the top 20 steel-producing nations globally, with a crude steel output exceeding 20 million metric tons in 2023 [9]. Current estimates indicate an annual GGBFS production of approximately 2.5-3 million tons nationwide. GGBFS from Hoa Phat Group's factory is shown in Figure 1. This industrial by-product presents both opportunities for sustainable construction material development and challenges related to optimal utilization in Vietnam's rapidly growing construction sector.


(a) (b)

Fig. 1 (a) Hoa Phat Group's factory and (b) Ground granulated blast furnace slag (S95)

3.1.2 Current applications of GGBFS in Vietnam

The primary application of GGBFS in Vietnam is in blended cement production, particularly Portland slag cement (PSC). According to Vietnam Standards TCVN 4315:2020, GGBFS replacement ratios typically range from 30% to 70% in cement formulations. Leading cement manufacturers have adopted GGBFS as a key component in their low-carbon cement products. This substitution significantly reduces the clinker factor in cement production, resulting in up to 40% lower CO_2 emissions compared to conventional Portland cement [10].

Beyond blended cements, GGBFS plays an important role in enhancing the durability of high-performance concrete (HPC) applications, particularly in special conditions [11]. The material's low permeability effectively reduces chloride penetration, making it ideal for marine structures, while its ability to mitigate alkali-silica reaction (ASR) improves the long-term performance of concrete [12].

According to TCVN 11586:2014, GGBFS used for mortar and concrete is classified into four types based on specific surface area. Properties of each type are shown in Table 1.

Table 1. Specifications for GGBFS in Vietnam according to TCVN 11586:2014

Items	Type			
	S60	S75	S95	S105
Density (g/cm^3), ≥	2.8			
Specific surface area (cm^2/g), ≥	2750	3500	5000	7000
Activity index (%), ≤				
7 days	-	55	75	95
28 days	60	75	95	105
91 days	80	95	-	-
Workability (%), ≥	95	95	90	85
Moisture (%), ≤	1.0			
MgO (%), ≤	10.0			
SO_3 (%), ≤	4.0			
Cl^- (%), ≤	0.02			
Loss on ignition (%), ≤	3.0			

Some researchers in Vietnam have investigated alkali-activated GGBFS binders, which offer potential environmental benefits beyond traditional blended cements [13] [14] [15]. These geopolymer formulations utilize the latent hydraulic properties of GGBFS when activated by alkaline solutions, creating binders comparable to Portland cement. While still in the research and development phase, these innovations represent a promising direction for Vietnam's construction materials sector.

3.1.3 Future prospects and recommendations

Vietnamese Government initiatives are promoting the solutions for increased adoption, particularly through the National Green Growth Strategy (2021-2030), which explicitly promotes industrial by-product utilization [16]. Concurrently, research institutions are advancing technical solutions, focusing on optimizing alkali-activated GGBFS formulations for precast concrete applications and developing carbonation curing techniques to improve the performance of concrete or mortar using GGBFS [17] [18] [19]. These solutions can promote the environmental benefits of GGBFS in Vietnam's construction sector while addressing current utilization challenges.

3.2 Fly Ash

3.2.1 Coal-fired thermal power plants in Vietnam and their by-products

As of 2024, Vietnam operates 32 coal-fired thermal power plants with a total installed capacity exceeding 25 gigawatts (GW), accounting for approximately 36% of the nation's electricity generation. Pha Lai thermal power plant and its by-products are shown in Figure 2.

(a) (b)

Fig. 2 (a) Pha Lai thermal power plant and (b) fly ash (type F)

Vietnam's thermal power plants are generating a huge amount of fly ash, a fine particle by-product of coal combustion that has both environmental challenges and potential economic opportunities [20].

Most of Vietnam's coal-fired power plants produce an estimated 15-20 million tons of fly ash annually. In which a large portion of this by-product was disposed of in landfills or ash ponds, leading to soil and water contamination risks due to the leaching of heavy metals such as arsenic, lead, and mercury [21]. However, recent regulatory changes and technological advancements have encouraged the recycling of fly ash in construction materials, including cement, concrete, and bricks. The Vietnamese government has set a target to reuse at least 80% of fly ash by 2025, aligning with global trends toward circular economy practices in the power sector.

3.2.2 Current applications of fly ash in Vietnam

In Vietnam, approximately 60-70% of the country's annual production of 15-20 million tons of fly ash is now utilized, marking significant progress from previous years when most was disposed of in landfills. The cement industry remains the largest consumer, where fly ash is used as a supplementary cementitious material to replace 20-30% of ordinary Portland cement clinker. This application not only reduces production costs but also lowers the carbon footprint of cement manufacturing, aligning with Vietnam's sustainability goals. Further, fly ash is also used in mortar and concrete mixtures to enhance durability and workability. The applications for fly ash in the construction sector include the production of non-fired bricks and lightweight aggregates. In Vietnam, TCVN 10302:2014 regulates the properties of fly ash used in mortar and concrete, which is shown in Table 2.

Table 2. Specifications for fly ash in Vietnam according to TCVN 10302:2014

Items		For normal concrete and lightweight concrete	
		Type F	Type C
SiO_2, Al_2O_3, Fe_2O_3 (%), ≥		70	45
Moisture (%), ≤		3	
Loss on ignition (%), ≤		12	5
Content not finer than 45µm sieve (%), ≤		25	
Water unit weight to control sample (%), ≤		105	
Harmful alkali content (%), ≤		1.5	
Cl^- (%), ≤		0.1	
SO_3 (%), ≤		3	5
CaO (%)		≤ 10	> 10
Natural radioactivity concentration Aeff (Bq/kg)	Residential and public works	370	
	Industrial and urban road construction	740	

3.2.3 Future applications and recommendations

Vietnam's construction sector is expanding rapidly, and demand for sustainable building materials is expected to grow. Fly ash, when properly processed, can enhance the performance of cementitious composites while reducing CO_2 emissions by up to 30% compared to conventional mixes [22]. Future prospects include scaling up high-volume fly ash concrete applications in infrastructure projects and promoting geopolymer cement as a low-carbon alternative [23]. However, achieving these goals requires addressing key barriers, including inconsistent fly ash quality and limited technical expertise.

4. MATERIALS USED IN THIS STUDY

4.1 Binder And Filler

Table 3 presents the characteristics of the binders and filler utilized in this study. The control specimens employed ordinary Portland cement (OPC) of type PC40, with a measured density of

3.16 g/cm^3. The geopolymer mortar used GGBFS, sourced from the Hoa Phat steel manufacturing plant, along with an alkali-activated material (AAM) for binder. GGBFS has a specific area of 5292 cm^2/g. According to a study of Ngo S. H., the SEM of GGBFS shown that it has similar particle size to OPC which is about 30 μm. However, in GGBFS, many very small sized particles were observed [24].

Table 3. Binder and filler in mortar

Item	OPC[1]	GGBFS[2]	FA[3]	AAM[4]
Density (g/cm^3)	3.16	2.89	2.22	1.71
Loss on ignition (%)	3.87	0.05	6.72	-
SiO_2 (%)	-	36.74	59.86	-
Al_2O_3 (%)	-	15.27	12.24	-
CaO (%)	-	42.57	4.62	-
MgO (%)	-	5.52	-	-
SO_3 (%)	2.81	0.21	0.02	-
Cl^- (%)	-	0.001	0.001	-
pH	-	-	-	≥ 12
$Ca(OH)_2$ (%)	-	-	-	≥ 90

1 PC: Portland cement, 2 GGBFS: Ground granulated blast furnace slag (Type S95), 3 FA: Fly ash (Type F). 4 AAM: alkali-activated material


(a)


(b)

Fig. 3 (a) Ground granulated blast furnace slag (S95) and fly ash (type F) used in this study

Additionally, FA obtained from the Pha Lai coal-fired thermal power plant in northern Vietnam was used as a filler in the geopolymer mortar. The GGBFS, classified as type S95, exhibited a density of 2.89 g/cm^3. The FA, categorized as type F with particle size ranging from 1 to 10 μm, had a density of 2.22 g/cm^3 and a combined SiO_2, Al_2O_3, and Fe_2O_3 content of 76.72%, and a total unburnt carbon of 5.66%. The appearance of GGBFS and FA are shown in Figure 3. An alkali activator was used which has a main composition of ≥ 90% $Ca(OH)_2$.

Table 4. Quality of fine aggregate (river sand)

Item	NS*
Density in oven-dry condition (g/cm^3)	2.45
Density in saturated surface dry condition (g/cm^3)	2.49
Water absorption (%)	1.44
Fineness modulus (F.M.)	2.71

4.2 Aggregate

Natural fine aggregate used in mortar is shown in Table 4. The natural fine aggregate is river sand (NS). NS has a water absorption of 1.44%, a density in oven-dry condition of 2.45 g/cm^3, and a fineness modulus of 2.71.

5. MIX PROPORTIONS

Table 5 shows the mix proportions of geopolymer mortar in this study for the experiment. All mix proportions have a water-to-binder ratio (W/B) of 45%, with a water-reducing and superplasticizer agent as chemical admixture at a ratio of 0.5%, 1.0%, and 1.5% of the binder mass. The control specimen used a chemical admixture with a standard volume of 1.0%. After the mix proportion testing procedure, the unit weight of water was set at 270 kg/m^3 to ensure a workability for geopolymer mortar of 190 ± 20 mm. For the binder, the control specimen used OPC with PC40 type, while the other specimens replaced 70% of the OPC with GGBFS. The remaining portion of the binder is alkali-activated material, with a ratio of 30% of the OPC weight. FA was used as a filler in the mix proportion at a ratio of 20% of the binder to reduce the same amount of NS by weight.

For chemical admixture, water reducing and superplasticizer agent made from naphthalene formaldehyde sulfonate, which is recommended to be used as 1% of binder weight with a specific gravity of 1190 kg/m^3.

A total of 4 specimens were made following the mixing procedure in Figure 4. Since in the Vietnam Standards, the procedure for mortar mixing is not regulated, the procedure following the recommendation from JIS was applied. River sand was used in a saturated surface dry condition when mixing.

Test methods for mortar were conducted in fresh condition and hardened condition in accordance with the Vietnam standards. Workability was tested in accordance with TCVN 3121-3:2003. For hardened mortar, 40 mm × 40 mm × 160 mm specimens were prepared and had standard curing until compressive strength was achieved at 28 days.

6. RESULT AND DISCUSSION

6.1 Fresh Mortar

The flow spread of the control specimen and the geopolymer specimen was tested in accordance with TCVN 3121-3:2003 12 times over a period of 10 minutes. A total of 120 minutes of retention time was implemented. Images of the workability loss experiment are shown in Figure 5.

Table 5. Mix proportion of mortar.

Specimens[1]	Replacement ratio (%)		W/B (%)	Unit weight[2] (kg/m^3)						Chemical admixture[3] (%)
	GGBFS	FA		W	PC	NS	GGBFS	FA	AAM	
PC-NS	0	0	45	270	600	1342	0	0	0	1.0
GGBFS-NS-1	70	20	45	270	0	1059	420	120	105	0.5
GGBFS-NS-2	70	20	45	270	0	1059	420	120	105	1.0
GGBFS-NS-3	70	20	45	270	0	1059	420	120	105	1.5

Note: 1 Specimen names have format as binder-filler and fine aggregate; 2 W: water, PC: Portland cement, NS: river sand, RS: recycled fine aggregate, GGBFS: ground granulated blast furnance slag, FA: fly ash; 3 Water reducing and superplasticizer agent made from naphthalene formaldehyde sunfonate, % of binder weight.

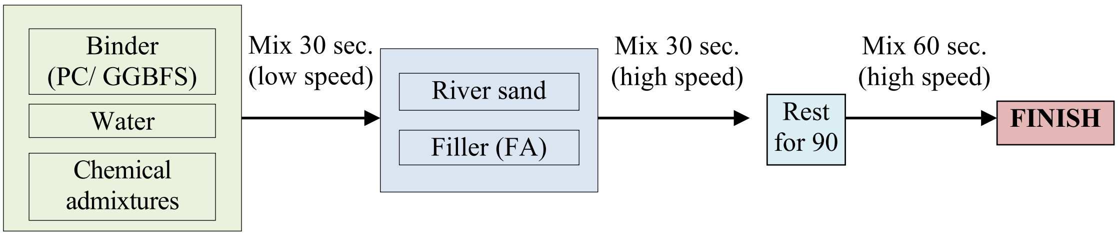

Fig. 4 Mortar specimen mixing steps

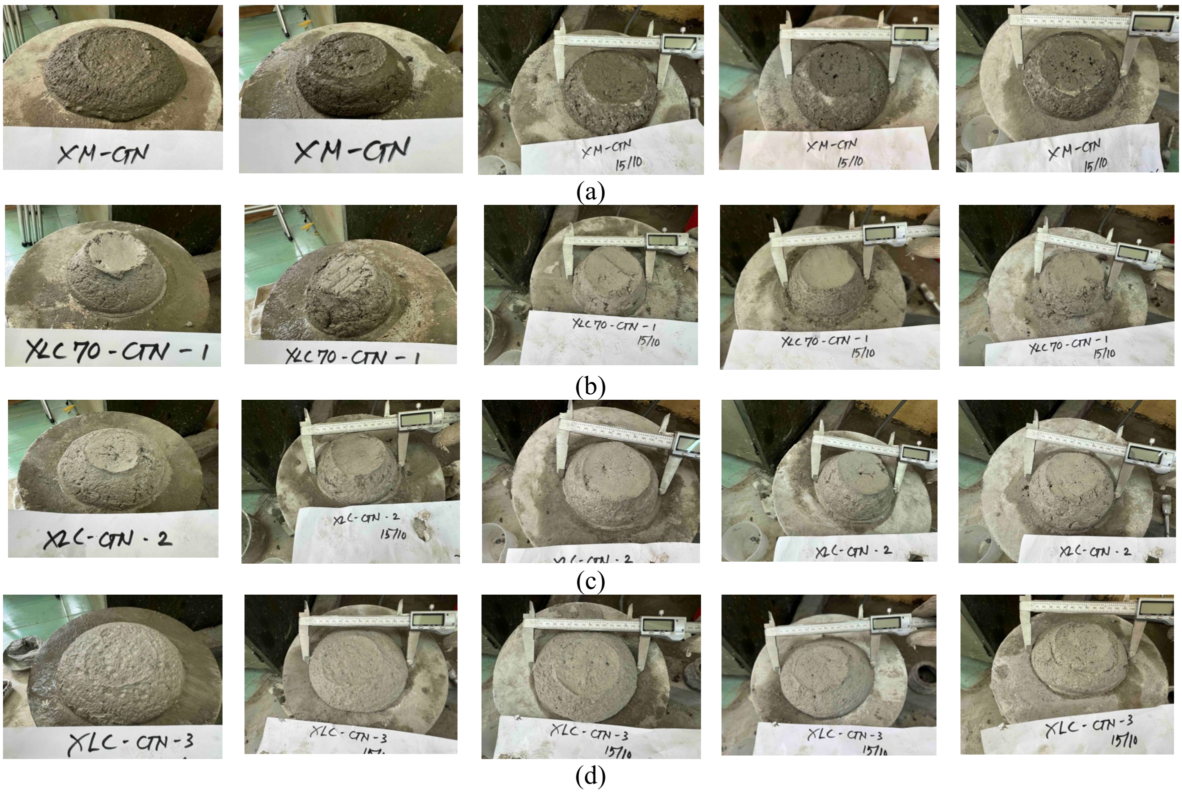

Fig. 5 Experiment for workability loss of mortar specimens (a) PC-NS; (b) GGBFS-NS-1; (c) GGBFS-NS-2; (d) GGBFS-NS-3

According to TCVN 3121-3:2003, jolting table with diameter of 300mm. The mass of the moving part of the jolting table is able to lift and lower vertically by 10mm ± 5mm. To measure the workability of mortar, place the cone-shaped mold in the middle of the jolting table. Take about 1 liter of fresh mortar sample and put it into the mold in two layers, each layer is tamped about 10 times. Use a knife to level off mortar on the mold surface, wipe off water and mortar on the surface around the mold. Slowly lift it vertically and let the machine jolt 15 times within 15 seconds. Use a caliper to measure the bottom diameter of the mortar block in two perpendicular directions, accurate to 1mm. The test result is the average of the two measurement results.

Each mix proportion has one sample. The samples were tested at 25±2 ºC. Experiment results are shown in Figure 6. Compared to the control specimen (PC-NS), both GGBFS-NS-2 and GGBFS-NS-3 exhibited significant workability loss within retention time at the first 20 minutes. GGBFS-NS-2 demonstrated a rapid decline in workability by 50 minutes of retention time, whereas GGBFS-NS-3 experienced a similar loss only after 110 minutes of retention time. Ultimately, the workability loss of GGBFS-NS-3 closely resembled that of the control specimen, while GGBFS-NS-2 displayed a substantially higher reduction in flow spread. This behavior can be attributed to the varying dosages of water-reducing and superplasticizer agents used in each mix proportion. This trend is also observed in study of Nath P. and P.K. Sarker [25]. For GGBFS-NS-1, since unit weight water is 270 kg/m^3 which is the same for all specimens and superplasticizer dosage is only 0.5% of binder weight, the initial flow spread was very small. For this reason, workability loss for GGBFS-NS-1 was very low compared to other specimens. Since GGBFS has high reactivity due to its amorphous calcium aluminosilicate structure, leading to rapid formation of C-A-S-H gels when activated. This accelerates early stiffening, reducing workability over time [26]. The experimental results indicated that when incorporating a high proportion of fine-particle materials such as GGBFS, AAM, and FA in geopolymer mortar, the optimal dosage of chemical admixture was 1.5% of the binder weight for maintaining adequate flow spread, which is similar to observation in a study of Siddique R. [27].

6.2 Hardened Mortar

All specimens were mixed and demolded after 24 hours then had a standard curing until experiment at 28 days. Each mix proportion has 6 specimens. According to TCVN 3121-11:2003, loading rate must be in the range of 100-400 N/s depending on mortar classification, for geopolymer mortar in this study, the loading rate of 400 N/s was used.

The specimens were demolded 24 hours after casting and subsequently cured at a controlled temperature of 25 ± 2 °C with a relative humidity of ≥95%. The mortar density was determined in a dry state using three samples for each mix proportion. A caliper with an accuracy of 0.1 mm was employed to measure the dimensions, and the average of three values for length, width, and height was recorded. The mass was measured using a scale with a precision of 0.1 g.

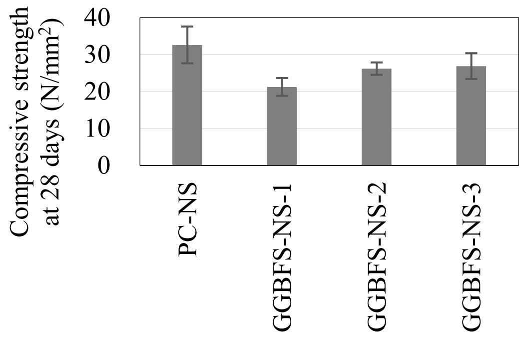

Fig. 7 Compressive strength of motar specimens at 28 days

Fig. 8 Compressive strength experiment for mortar specimens

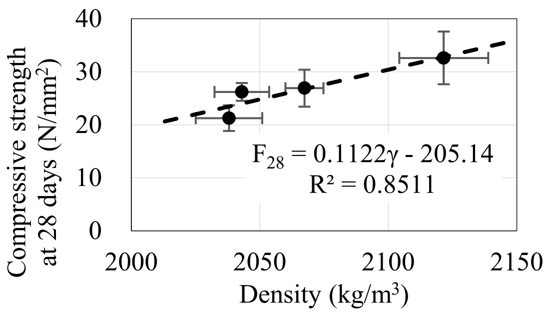

Fig. 9 Relationship between density and compressive strength at 28 days of mortar

Experiment results are shown in Figure 7. Some images of compressive strength experiments are shown in Figure 8. Regarding SEM figures in a study of Nguyen V. D., when using GGBFS, C-S-H gel can be formed with small and fine size of about 2-3 μm which can contribute to the development of compressive strength at 28-day [28]. Compare with control specimen, with 70% OPC replaced by GGBFS and 30% replaced by AAM, compessive strength of geopolymer mortar specimens had lower value, especially for the specimen GGBFS-NS-1 used 0.5% of chemical admixture which had lowest value of compessive strength. This trend is due to the low amount of water-reducing and superplasticizer agent and poor workability [29]. The fine particles in the geopolymer mortar could not fully promote their bearing effect, leading to uneven flow and incomplete filling of voids in the mortar. As a result, density of this specimen and the compressive strength were lower compared to the other specimens.

The relationship between density and compressive strength of geopolymer mortar is shown in Figure 9. For the specimens that used 1.0% and 1.5% water-reducing and superplasticizer agents, both density and compressive strength are higher than that of not using this chemical admixture. This trend shows that water-reducing and superplasticizer agent can help fine particles flowing and filling the voids in the geopolymer mortar [30].

7. CONCLUSION

Vietnam's industrial by-products (GGBFS and FA) demonstrate strong potential as sustainable cement alternatives. While GGBFS can be used as mineral admixture, FA can be used as filler. The quality of GGBFS and FA satisfied Vietnamese standards for use in mortar and concrete.

Fresh mortar revealed significant workability loss, particularly with 1.0-1.5% water reduction and superplasticizer agent, due to the material's rapid setting characteristics. In specimens used 0.5% water reduction and superplasticizer agent, workability was too low to observe any loss.

Hardened mortar analysis demonstrated that specimens with higher chemical admixture content (1.0-1.5%) achieved 20-29% greater 28-day compressive strength compared to the mix proportion using 0.5% water-reducing and superplasticizer agent.

In conclusion, this research promotes the potential use of GGBFS and FA in geopolymer mortar for Vietnam’s construction sector. As a result, workability issues can be managed through optimizing the amount of water-reducing and superplasticizer agent.

8. ACKNOWLEDGMENTS

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