INFLUENCE OF CEMENT SUBSTITUTION BY INDUSTRIAL BY-PRODUCTS ON THE PROPERTIES OF HIGH-PERFORMANCE MORTAR

ẢNH HƯỞNG CỦA VIỆC THAY THẾ XI MĂNG BẰNG PHỤ PHẨM CÔNG NGHIỆP ĐẾN CÁC TÍNH CHẤT KỸ THUẬT CỦA VỮA TÍNH NĂNG CAO

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Abstract - In this study, fly ash and ground granulated blast-furnace slag (GGBFS), by-products from the industry, are used as binder materials to manufacture high-performance mortars that will be used to repair marine concrete structures. Four mortar mixtures were designed with a constant water/binder ratio of 0.49 and the GGBFS was used to substitute for 0, 10, 20, and 30 wt.% of cement. Changes in the engineering properties of the mortars corresponding to the GGBFS replacement levels were evaluated. The findings proved that the presence of GGBFS significantly increased the mortar's strength rate at later ages and increased the early-stage water absorption level. At 56 days, the mortar specimens containing 30% GGBFS had the highest water absorption capacity of 8.2% and respective values of compressive and flexural strength of roughly 49 and 11 MPa. Additionally, it was discovered that adding more GGBFS to the mixtures reduced the drying shrinkage and delayed the setting time of the mortars.

Key words - High-performance mortar; fly ash; GGBFS; drying shrinkage; mechanical strength; water absorption.

Tóm tắt - Trong nghiên cứu này, tro bay và xỉ lò cao nghiền mịn (XLC), là các sản phẩm phụ trong quá trình sản xuất công nghiệp, được sử dụng làm chất kết dính trong sản xuất vữa tính năng cao dùng làm vật liệu gia cố hay sửa chữa cho các kết cấu công trình thủy. Bốn mẫu vữa được thiết kế với tỷ lệ nước/chất kết dính bằng 0,49 và XLC được dùng để thay thế cho 0, 10, 20 và 30% xi măng theo khối lượng. Những thay đổi về đặc tính kỹ thuật của vữa tương ứng với các hàm lượng XLC khác nhau được đánh giá. Kết quả nghiên cứu chỉ ra rằng, XLC góp phần tăng đáng kể sự phát triển cường độ cơ học của vữa ở các ngày tuổi muộn và tăng độ hút nước của vữa ở các ngày tuổi ban đầu. Các mẫu vữa chứa 30% XLC có cường độ chịu nén và chịu uốn lần lượt là 49 MPa và 11 MPa tại 56 ngày tuổi, độ hút nước là 8,2%. Kết quả nghiên cứu cũng nhận thấy rằng, XLC cũng góp phần làm giảm độ co khô và tăng thời thời gian ninh kết ban đầu của các mẫu vữa.

Từ khóa - Vữa tính năng cao; tro bay; xỉ lò cao nghiền mịn; độ co khô; cường độ cơ học; độ hút nước.

1. Introduction

Concrete is considered a durable material and its utilization is popular over all the world. In particular, concrete is essential for construction in corrosive environments like water. But since concrete's performance has improved, less concrete is now being used in marine structures to withstand corrosive chemicals. As a result, prolonged exposure to adverse weather, such as that found in saltwater or the ocean, reduced the strength of the concrete, which led to the collapse of concrete structures. Pollutants from marine environments cause the reinforcement cover to deteriorate over time, which in turn causes the reinforcement bars to be damaged. Marine constructions must be equipped with safety elements as well as defenses against ocean invasion due to the seawater's detrimental effects on their performance being particularly concerning. Because of this, researchers' interest in using concrete in harsh environments, such as the marine environment, has increased [1]. In light of the circumstances, to stop the deterioration of buildings while serving in a delicate environment, utilizing mortar is always seen as a practical countermeasure. In addition, employing mortars is recognized as a superior technique and material for restoration and repair to enhance the resilience and safety of concrete structures.

There are several different types of mortars available today, but these fixed materials are utilized before any tests in the lab [2]. Therefore, this investigation examines the creation of high-performance mortars by conducting several scientific tests, which can be used as repair mortars for marine structures. Due to its properties like high workability, high strength, and low drying shrinkage (DS), this mortar is primarily used as fillers and grouting chemicals. In addition, this research concentrates on the use of readily available industrial wastes such as GGBFS and fly ash. Up to now, the global amount of GGBFS is around 394 million tons [3], while the amount of fly ash is approximately 1,0 billion tons [4] annually. In Vietnam, the amount of GGBFS and fly ash released annually is about 1.12 and 16.4 million tons, respectively [5]. The experimental program is conducted based on six steps as follows: (i) Select raw materials; (ii) Calculate the mix proportions; (iii) Trial batch, then make any necessary adjustments; (iv) Prepare the specimens; (v) Conduct the tests; and (vi) Find out the results and make conclusions.

As a result, GGBFS and fly ash both function as supplementary cementitious materials (SCMs) in place of Portland cement, which is well-known for contributing significantly to man-made CO_2 emissions [6-8] and accounting for a staggering proportion of 6-7% of all CO_2 emissions [9]. Because calcium compounds are readily available, cement is susceptible to acid attack. Additionally, because calcium compounds dissolve in an acidic environment, the structures become more porous and disintegrate more quickly [10]. Cement has also been shown to be of worse quality due to environmental dangers like acidic/ sulfate conditions when this material is used in marine structures. Due to the pozzolanic reaction of fly ash and GGBFS, the presence of these SCMs will contribute to enhancing the durability of mortar to chemical attacks [11].

2. Experimental details

2.1. Characteristics of raw materials

This study used ternary binder materials of grade-40 Portland cement supplied by Nghi Son Cement Company, GGBFS of type S95 from Hoa Phat Steel Company, and fly ash of type F from Tra Vinh coal-fired thermal power plant with densities of 3.09, 2.84, and 2.22 g/cm^3, respectively, to prepare mortar specimens. The major chemical compositions of these binder materials are presented in Table 1. The compressive strength (CS) of cement was tested to confirm that it was greater than 40 MPa at 28 days. The gradation curves of all binder materials are shown in Figure 1, while their natural appearance and scanning electron microscope (SEM) images are given in Figure 2.

Table 1. *Major chemical compositions of binder materials*

Compositions (wt.%)	Cement	Fly ash	GGBFS
SiO_2	23.5	59.2	35.9
Fe_2O_3	3.7	6.1	0.3
Al_2O_3	6.0	26.7	13.0
CaO	59.9	1.1	38.1
MgO	2.0	0.9	8.0
Others	4.9	6.0	4.7

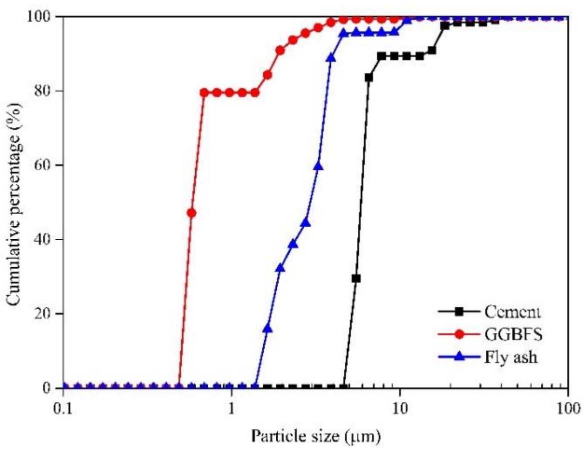
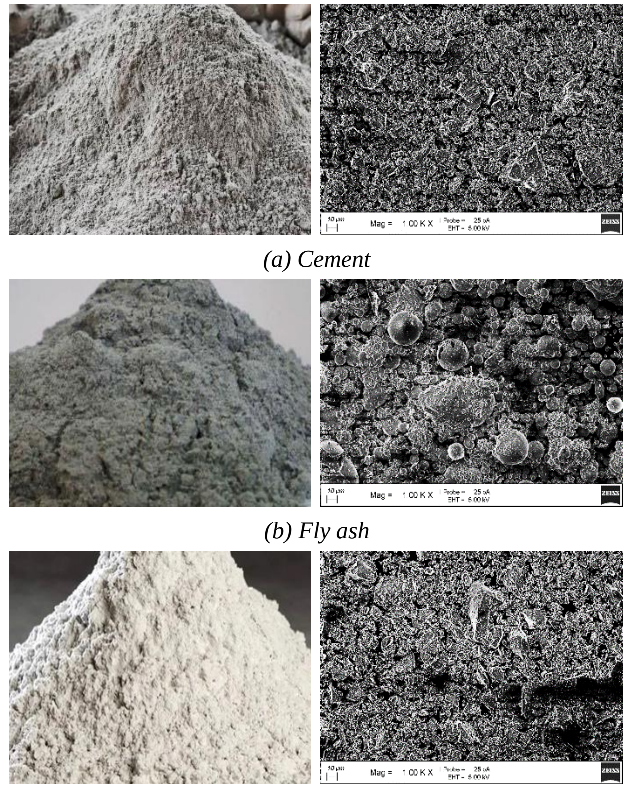


Figure 1. *The gradation curves of cement, fly ash, and GGBFS particles*

According to Figure 1, the particle size of GGBFS is the smallest, followed by fly ash and cement. As stated in a previous study [12], finer particles of SCMs may better participate in the chemical reaction. Additionally, fly ash can be considered to be both a filler material due to its fine particle size as well as an additional cementitious component. Narmluk and Nawa [13] have indicated that fly ash with a high content of SiO_2 can join the pozzolanic reaction to create the secondary calcium-silicate-hydrates (C-S-H) gel, improving the strength and durability of concrete and mortar at the latter ages. As indicated in Table 1, the main compositions of both GGBFS and fly ash are SiO_2 and Al_2O_3, which are crucially important factors for pozzolanic reaction. As shown in Figure 2, the GGBFS particles are irregular, while the fly ash particles are mostly spherical.



(a) Cement

(b) Fly ash

(c) GGBFS

Figure 2. *The natural appearance of binder materials and their SEM micrographs*

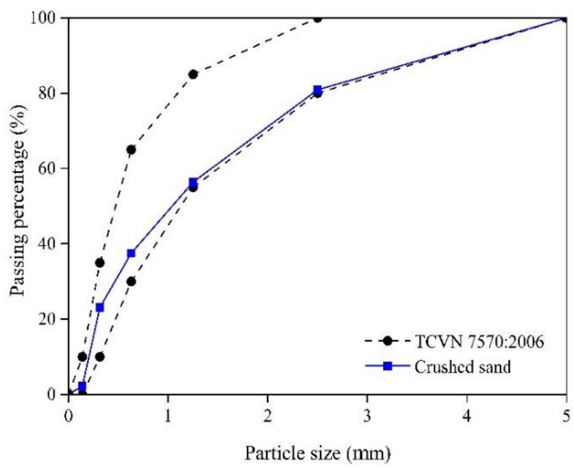


Figure 3. *The particle size distribution of crushed sand*

Crushed sand obtained from a local stone mine with a density of 2803 kg/m^3 was used as fine aggregate. Other features of crushed sand include a fineness modulus of 3.0 and a water absorption (WA) rate of 3.7%. The particle size distribution of this sand is shown in Figure 3 and satisfies the requirement stipulated by TCVN 7570:2006 [14]. The superplasticizer (SP) used in this study is Sika ViscoCrete 3000 of type G. A small amount of SP was utilized to reduce the water content and ensure the desired workability of the mortar mixtures.

2.2. Mixture proportioning

To design the proportions for all mortar mixtures, the idea of a densified mixture design algorithm from a previous study was applied [15]. Firstly, the control mixture without GGBFS was designed with a water/binder (*w/b*) ratio of 0.49, which is denoted as "SL0". It is noticed the selected W/B ratio of 0.49 is obtained through several trials to get the target slump flow of the mixture equal to 200 ± 5 mm. After that, the GGBFS was used to replace 10, 20, and 30% of cement by weight to form other mixtures, denoted as SL1, SL2, and SL3. A densified mixture design approach [15] was used to find that the amount of fly ash was equivalent to 25% of the total amount of SCMs (Table 2). The aggregate-to-binder ratio was fixed to 2.71 for all mixtures. The introduction of a set quantity of fly ash has a significant impact on the reaction. Fly ash may aid in accelerating the hydration of cement in the system [16-18]. SP contents of 0.63 – 0.8 wt.% of total binders were also added to the fresh mixtures to attain the requisite slump flow (200 ± 5 mm).

Table 2. *Material proportions for mortars*

Mortar mixtures	Ingredients (unit: gram)			
	SL0	SL1	SL2	SL3
Cement	1314	1183	1051	920
Fly ash	433	433	433	433
GGBFS	0	131	263	394
Sand	4726	4726	4726	4726
SP	14	13	12	11
Water	858	858	858	858

2.3. Experimental methods

All raw materials listed in Table 2 were prepared. The dry materials including cement, GGBFS, fly ash, and crushed sand were mixed first, then a blend of water and SP was added and continuously mixed until the homogeneous paste was achieved. Then, based on ASTM C1437 [19], C807 [20], and C138 [21], respectively, the flowability, setting time, and unit weight of the fresh mixtures were assessed. After that, the mortar specimens with different dimensions were fabricated using steel molds for hardened mortar property tests. The CS, flexural strength (FS), WA, and DS of the mortars were tested following the guidelines of ASTM C109 [22], ASTM C348 [23], ASTM C1403 [24], and ASTM C490 [25], respectively. The CS was tested at 1, 7, 14, 28, and 56 days, and the FS was checked at 7, 28, and 56 days. In addition, the WA was measured at 28 days, while the DS test was conducted at 3, 7, 14, 28, and 56 days. The average value of at least three measurements was presented in this manuscript.

3. Results and discussion

3.1. Properties of fresh mortar mixtures

Table 3 displays the workability, unit weight, and setting times of mortar mixtures. For the mortar mixture to have the requisite flowability of roughly 200 ± 5 mm, SP was added. It was discovered that as the GGBFS content in the mixtures increased, the SP dosage marginally increased as well. Thus, it is feasible that GGBFS with fine particles requires more water/SP to attain the desired flowability.

Table 3. *Characteristics of fresh mortar mixtures*

Mix ID	Flow diameter (cm)	Fresh unit weight (kg/m^3)	Initial setting time (min)	Final setting time (min)
SL0	20.0	2205	100	340
SL1	20.5	2210	120	365
SL2	20.3	2208	125	370
SL3	20.5	2201	130	390

When the amount of GGBFS increases, the mortar's setting times are proportionately delayed. After being postponed for more than 30 minutes when 30% of the cement was replaced with GGBFS, the induction phase of the SL0 mixture started after 100 min. This also applied to the acceleration phase (between the initial and final settings). Since the acceleration period significantly affects the rate at which the C-S-H gel forms, an extension of the acceleration period's duration may, unfortunately, have a negative impact on the performance of the pozzolanic reaction [26]. As a result, the fresh unit weight values for all mortar combinations measured were about 2200 kg/m^3.

3.2. Compressive strength

Figure 4 illustrates how the hardened mortar changes in CS as the curing times increase. At all testing ages, specimens without GGBFS had higher CS values than the ones with 10%, 20%, and 30% GGBFS by weight of cement substitution. In addition, the amount of GGBFS for each of these data points was scaled back in descending order. The decreased strength of the mortars is due to the slower pozzolanic reaction rate of GGBFS and fly ash compared to Portland cement [27]. At 56-day-old specimens, when the SL1, SL2, and SL3 mixes significantly increased with the increments at roughly 8, 9, and 12%, respectively, there are perceptible gains in CS. This value is above 6% for the GGBFS-free combination. Thus, the inclusion of GGBFS in mortar has a largely negligible impact on the development of early strength but considerably on later ones. Additionally, at 56 days, all of the mortars made for this investigation exhibited CS values that were higher than 45 MPa, a sign of outstanding quality.

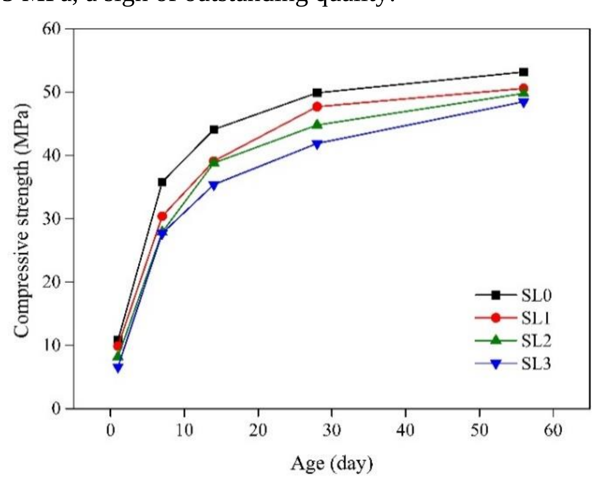


Figure 4. *CS of the mortars*

3.3. Flexural strength

The inclusion of GGBFS in the mortar created for this study has virtually little benefit on the development of FS, even though it is a pozzolanic material associated with strength enhancement and that it contributes significantly to the development of strength (see Figure 5). However, it should be noted that SL3 specimens have virtually the same high FS as SL2 specimens when utilizing a greater percentage of GGBFS (around 30%). At 56 days old, the 10%, 20%, and 30% GGBFS-containing mortar specimens had FS values that were roughly 93, 88, and 87% higher than the non-GGBFS mixture's FS. In an earlier investigation, fly ash and GGBFS were used in mortar mixtures with a *w/b* ratio of 0.5, and the FS of the mortars was less than 3 MPa [28]. This demonstrates that the FS of all mortars used in this study was good. The densified mixture design algorithm [15], which is used to create mortar mixtures, is to blame for this issue.

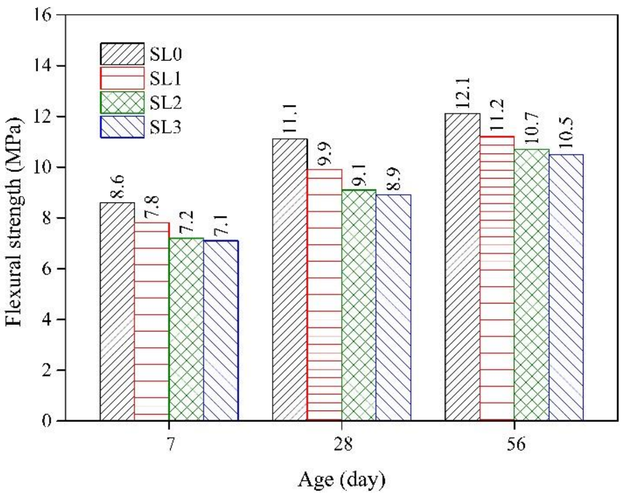


Figure 5. *FS of the mortars*

3.4. Water absorption

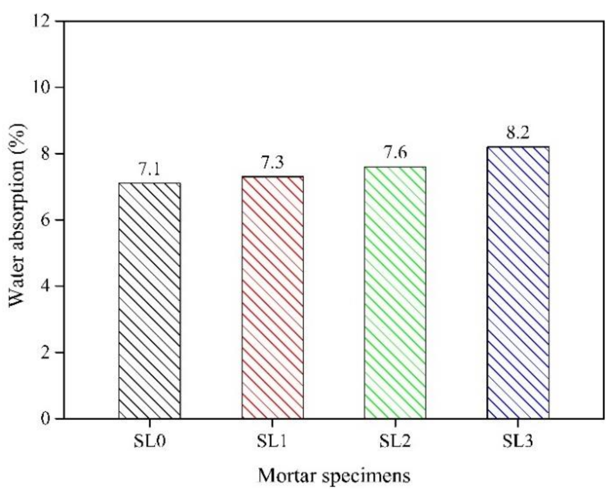


Figure 6. *WA of the mortars*

The rates at which the mortar specimens absorbed water after 28 days are shown in Figure 6. The WA rate of the mortar specimens increases proportionally as GGBFS is added, rising from 7.3% (10% of GGBFS) to 8.2% (30% of GGBFS). The addition of GGBFS to the mortar mixtures marginally accelerated the pace at which the specimens absorbed water when compared to the mix that included no GGBFS (SL0). This might be because of the GGBFS's slower rate of pozzolanic reaction compared to that of cement hydration, especially at the early ages. As a result, limited C-S-H gel was generated in the matrix [29], which increased the number of pores or voids within the mortar matrix and sped up the pace of WA, as shown in Figure 6. The sample with 30% GGBFS (SL3) also exhibited the greatest WA value, 8.2%. The traditional approach was used to create a mortar mixture with *w/b* = 0.4, which produced a WA of 9.1%, higher than the WA of all mortars in this evaluation. Utilizing the design strategy recommended by Chen et al. [15] may have contributed to this finding. By minimizing the amount of void space inside the mortars, this design technique lowers the WA rate.

3.5. Drying shrinkage

Figure 7 demonstrates that using more GGBFS reduced the DS of the mortar specimens. Generally speaking, there is very little variation in the DS values (0.020 – 0.035%) of the mortar specimens. The differences also tend to decrease over time. This leads to the conclusion that the addition of GGBFS to mortar mixtures had a positive impact on the mortars' drying behavior during the shrinkage process, with the effect being more pronounced at older ages. This behavior might be explained by the fact that GGBFS's pozzolanic reaction only requires a fraction of the heat that cement's hydration reaction does [29].

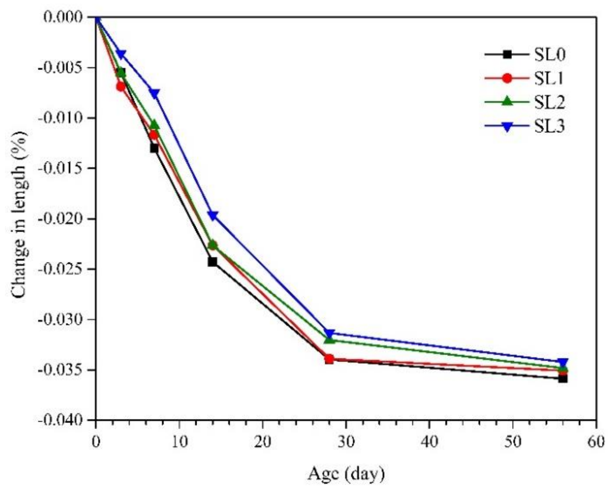


Figure 7. *DS of the mortars*

4. Conclusions

An objective analysis of this research suggests that GGBFS may be used in place of cement in the fabrication of mortar specimens, particularly when using mortar to maintain and protect marine constructions. The following conclusions are possible:

(i) The extended setting time makes it the perfect technique for labor-intensive construction like applying mortar to the restored units.

(ii) GGBFS insignificantly affected the early strength development of the mortar specimens, despite its repute as an SCM. However, GGBFS keeps its quality in the pozzolanic reaction over time. The 56-day-old mortar containing 30% GGBFS was able to provide high CS and

FS values of approximately 49 and 11 MPa.

(iii) The greatest WA rate for the 30% GGBFS-mortar specimens was just 8.2%. Additionally, the addition of GGBFS to the mortar mixture helped to lessen the shrinkage that occurred during the drying process.

(iv) When GGBFS is added to the mortar mixture for the restoration of coastal concrete structures, in particular, C-S-H gel forms from the pozzolanic reaction because GGBFS lessens the mortar's permeability to attack agents like sulfate/ chloride.

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