STRENGTH, DURABILITY, AND MICROSTRUCTURE OF HIGH-STRENGTH MORTARS INCORPORATING VARIOUS GROUND GRANULATED BLAST FURNACE SLAG CONTENTS

ĐÁNH GIÁ CƯỜNG ĐỘ, ĐỘ BỀN VÀ VI CẤU TRÚC CỦA VỮA CƯỜNG ĐỘ CAO SỬ DỤNG CÁC HÀM LƯỢNG XỈ LÒ CAO NGHIỀN MỊN KHÁC NHAU

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Abstract - For resource efficiency as well as recycling industrial solid wastes, this study investigates the use of ground granulated blast furnace slag (GGBFS) in the production of high-strength mortars. The GGBFS contents used are 0%, 12%, 24%, 36%, and 48% of the total binder content. The changes in the engineering properties of the mortars with various GGBFS contents were examined through compressive strength, flexural strength, ultrasonic pulse velocity (UPV), rapid chloride ion penetration (RCPT), thermal conductivity, and microstructure tests. Obtained results indicate that the strength and durability of the mortars increased with the use of 12% and 24% GGBFS, meanwhile the use of 36% and 48% GGBFS resulted in a reduction in the mortar properties. However, all the mortars produced in this study exhibited good quality with high strength, a UPV value of higher than 4300 m/s, and excellent resistance to chloride attack.

Key words - High-strength mortar; ground granulated blast furnace slag; compressive strength; flexural strength; rapid chloride ion penetration; ultrasonic pulse velocity.

Tóm tắt - Để sử dụng hiệu quả các nguồn tài nguyên cũng như tái sử dụng các phế thải rắn trong công nghiệp, nghiên cứu này sử dụng xỉ lò cao nghiền mịn (XLCNM) trong sản xuất vữa cường độ cao. Hàm lượng XLCNM được sử dụng tương ứng với 0%, 12%, 24%, 36% và 48% so với tổng hàm lượng chất kết dính. Sự thay đổi các đặc tính kỹ thuật của vữa đối với các hàm lượng XLCNM khác nhau được nghiên cứu thông qua các thí nghiệm cường độ chịu nén, cường độ chịu uốn, vận tốc truyền xung siêu âm, độ thẩm thấu ion Clo, độ truyền nhiệt, và vi cấu trúc. Kết quả nghiên cứu chỉ ra rằng, cường độ và độ bền của các mẫu vữa tăng khi sử dụng 12% hoặc 24% XLCNM, trong khi sử dụng 36% hoặc 48% XLCNM làm giảm chất lượng của vữa. Tuy nhiên, tất cả các mẫu vữa trong nghiên cứu đều có chất lượng tốt với cường độ cao, vận tốc truyền xung siêu âm qua các mẫu vữa lớn hơn 4300 m/s và khả năng chống lại sự xâm thực các ion Clo tốt.

Từ khóa - Vữa cường độ cao; xỉ lò cao nghiền mịn; cường độ chịu nén; cường độ chịu uốn; độ thẩm thấu ion Clo; vận tốc truyền xung siêu âm.

1. Introduction

In recent years, Vietnam has been known as a developing country with rapid industrialization and modernization. Consequently, many construction materials have been consumed for infrastructure construction. In the world, concrete is considered the second most consumed material just after water [1]. It means that a huge quantity of materials such as cement, sand, and stone was exploited. Previous studies [2, 3] have indicated that the production of cement depleted the natural resources and released a large amount of carbon dioxide into the air, causing the greenhouse effect and global warming. As alerted by Ngo and Huynh [4], the reserve of natural sand in Vietnam is not enough for coming years. Thus, the over-exploitation of river sand is popularly occurring, leading to the corrosion of the banks and putting a negative effect on aquatic life. To save the raw materials, construction materials with high strength and good durability are necessary instead of traditional materials with normal strength.

To serve industrialization and modernization, steel is known as an important material in the construction industry. Many iron and steel plants were built in Vietnam over several decades. However, these plants also released a large amount of steel slag as solid industrial waste. If this steel slag was ground to be very fine particles, it can be used as a supplementary binder material. An approximation of 1.2 million tons of ground granulated blasted furnace slag (GGBFS) was created in Vietnam in 2021 [4]. They can be used to replace a part of cement in the production of concrete and mortar.

To use efficiently the natural resources and recycle a part of industrial waste from iron and steel plants, this study is to investigate the use of GGBFS in the production of high-strength mortars. The effect of GGBFS contents on the strength, durability, and microstructure of the mortars was also investigated.

2. Materials and experimental program

2.1. Materials

Table 1 shows the properties of binder materials including cement, silica fume (SF), and GGBFS. Cement type PC40 was sourced from Nghi Son company, while GGBFS type S95 [5] was acquired from Hoa Phat iron and steel plant. The chemical compositions of these materials were determined using X-ray fluorescence analysis. Commercial silica fume named PRO-MIC was provided by IPRO company. It is noticed that SF was used to increase the strength and durability of the mortars [6, 7]. The micrograph of cement, SF, and GGBFS were observed under the scanning electron microscopy (SEM) with a magnification of 1.000 times as shown in Figures 1-3. As observed in Figures 1-3, the SF and GGBFS have many smaller particles than the cement.

The natural river sand sourced from the Ma river in Thanh Hoa province was used as fine aggregate. The characterization of sand includes the density of 2.63 T/m^3, the particle size from 0.15 to 0.63 mm, and the water absorption of 0.42%. The commercial superplasticizer (SP) named Sikament R4 with a specific gravity of 1.15 was used to reduce the water content and increase the workability of the mortars. The tap water was used for mixing.

Table 1. *Physical and chemical properties of binder materials*

Items		Cement	SF	GGBFS
Physical properties	Specific gravity	3.12	2.21	2.82
Chemical composition (%)	SiO_2	22.3	90.1	36.9
	Al_2O_3	6.7	1.0	12.4
	Fe_2O_3	4.7	1.0	-
	CaO	55.5	0.4	30.7
	MgO	2.4	1.9	14.8
	Na_2O	0.6	0.3	0.3
	K_2O	0.7	3.2	0.9
	TiO_2	0.7	0.6	0.4
	Loss on ignition	0.5	1.1	0.4

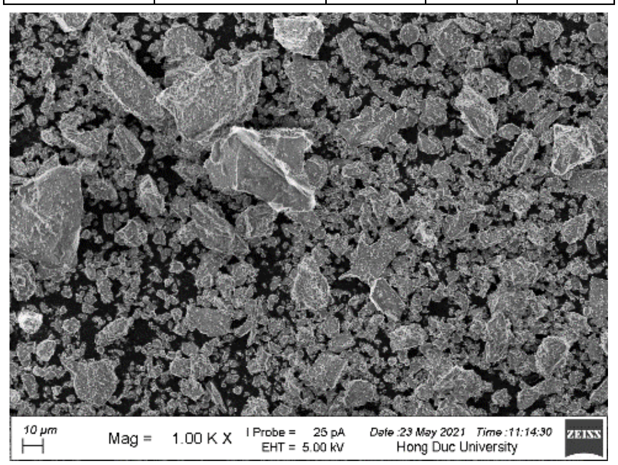

Figure 1. *SEM micrograph of cement*

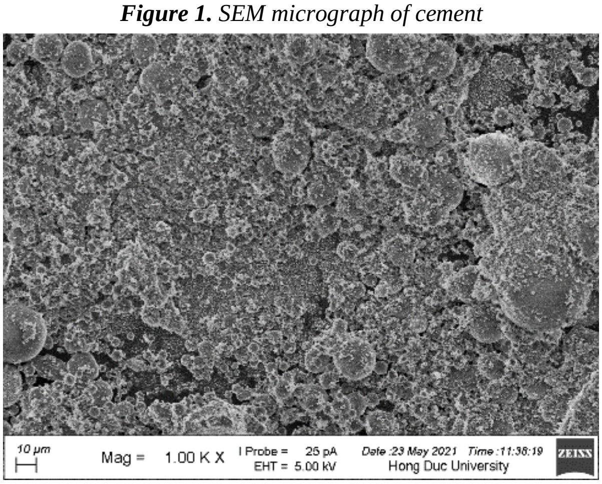

Figure 2. *SEM micrograph of silica fume*

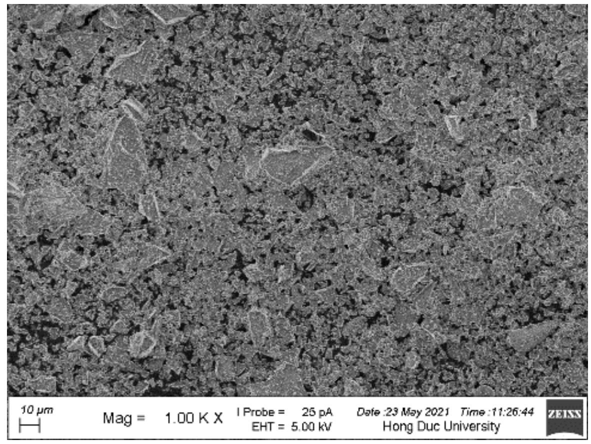

Figure 3. *SEM micrograph of GGBFS*

2.2. Mixture proportion

To enhance the mortar compressive strength, all the mortars were designed with a low water-to-binder ratio of 0.16, and the SF content equals 20% of the total binder by mass. The SP with a dosage of 4% was used to ensure the flow diameter of fresh mortars in the range of 18±2 cm (measurement based on TCVN 3121-2003 [8]. It is noticed that the dosages of SF and SP, and a low water-to-binder ratio were similar to those used in previous studies [9, 10]. The control mixture (M00) was designed first with the binder containing only cement and SF. After that, four other mixtures were designed by using GGBFS to replace 15%, 30%, 45%, and 60% cement by mass. These GGBFS contents are corresponding to 12%, 24%, 36%, and 48% of the total binder by mass, thus these mixtures were denoted as M12, M24, M36, and M48, respectively. It is noticed that a previous study [11] has used GGBFS to replace 20%, 40%, and 60% cement in producing reactive powder concrete. In the present study, the GGBFS replacement level step of 15% was used for a more comprehensive investigation. The sand content is selected equal to the binder content. Table 2 shows the mixed proportions of all the mortars. Due to the lower specific gravity than cement, the mixtures containing GGBFS show a slightly lower unit weight than the control mixture (M00).

Table 2. *Mixture proportions of the mortars*

Mixture	Proportions (kg/m^3)					
	Cement	SF	GGBFS	Sand	Water	SP
M00	868	217	0	1085	174	43
M12	725	213	128	1066	171	43
M24	587	209	254	1048	168	42
M36	453	206	371	1030	165	41
M48	324	203	486	1013	162	40

2.3. Specimen preparation and test programs

Similar to previous studies [9, 10], all dry materials were mixed for 3 minutes. Then a mixture of water and SP was added and mixed continuously until the homogeneous paste was achieved. After checking the flow diameter based on TCVN 3121-2003 [8], the fresh mortar was poured into the steel molds to produce the prismatic samples with dimensions of 40×40×160 mm and the cylinder samples with a diameter of 100 mm and height of

200 mm. These samples were stored in natural condition for 24h, after that they were de-molded and cured in the water until the testing dates.

To assess the effect of GGBFS content on the changes in the mortar properties, compressive strength, flexural strength, ultrasonic pulse velocity (UPV), rapid chloride ion penetration (RCPT), and thermal conductivity were tested. The flexural strength and compressive strength were tested in accordance with TCVN 3121-2003 [8]. The flexural strength was tested first based on the prismatic samples, then a compression test was conducted based on the two half-broken samples of the bending test. The UPV and thermal conductivity were directly measured using hand equipment named MATEST-C369N and ISOMET-2014 based on cylinder samples of 100×200 mm, respectively. The RCPT test was conducted based on the cylinder samples with a height of 50 mm, which was cut from the cylinder samples of 100×200 mm in corroding to TCVN 9337-2012 [12]. Only compressive strength was recorded at 3, 7, 14, 28, and 56 days, others were recorded at 28 and 56 days. The values presented in this paper is the average value of at least three measurements. Small pieces from the compression test were collected for microstructure observation using the scanning electron microscopy (SEM). The equipment used for UPV, RCPT, thermal conductivity, and microstructure tests are illustrated in Figures 4-7.

Figure 4. *UPV test*

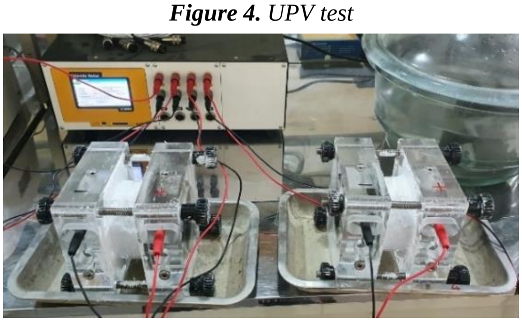

Figure 5. *RPCT test*

Figure 6. *Thermal conductivity test*

Figure 7. *SEM observation*

3. Results and discussion

3.1. Compressive strength

The gaining of the mortar compressive strength versus curing time is shown in Figure 8. It is clear to obverse that the compressive strength of the mortars increased with increasing curing time due to the formation of hydration products during the time. Before 14 days, the compressive strength of the control mixture (M00) exhibited the highest among all the mortars. From 14 days, the compressive strength of the control mixture was lower than those of M12 and M24. This phenomenon is explained by the low pozzolanic reaction of GGBFS at the beginning time and that will strongly happen in the long stage [11, 13]. From 28 days, the mixtures with 12% and 24% GGBFS (M12 and M24) showed higher compressive strength than the control mixture (M00), while the mixtures with 36% and 48% GGBFS (M36 and M48) showed a lower compressive strength than the control mixture (M00). At 56 days, the compressive strength increments are 12% and 5% corresponding to GGBFS contents of 12% and 24%. It means that the use of 12% and 24% GGBFS as supplementary binder material can increase the mortar's compressive strength. As shown in Figures 1-3, the cement, SF, and GGBFS have different particle sizes. GGBFS has many finer particles than cement, which can fulfill the voids between aggregates and other materials. The increase in compressive strength of the mortars containing 12% and 24% GGBFS is attributed to the filling effect and pozzolanic reaction of GGBFS [11, 13]. However, when increasing the GGBFS level to over 24%, a part of GGBFS maybe not join the pozzolanic reaction, leading the compressive strength of these mixtures lower than that of the control mixture.

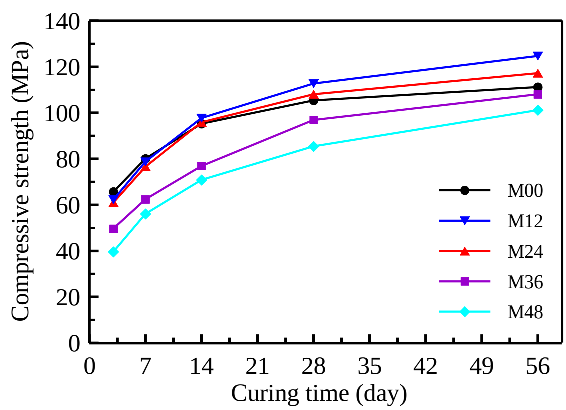

Figure 8. *Compressive strength of the mortars*

At 28 and 56 days, the compressive strength of the mortars in this study ranged from 85.5-112.7 MPa and 101.2-124.7 MPa, respectively. These mortars showed an excellent quality in terms of compressive strength in comparison with traditional mortars. As required by TCVN 4314-2003 [14] and 14TCN 80-2001 [15], the building mortars have a compressive strength of around 1.0-30 MPa, and the hydraulic mortars have a compressive strength of around 5.0-50 MPa, respectively. With super strength, these mortars in the present study can be used for very important projects or used as a repaired material.

3.2. Flexural strength

The flexural strengths of the mortars at 28 and 56 days are shown in Figure 9 with values ranging from 13.0 - 17.3 MPa and 15.8-19.4 MPa, respectively. Similar to compressive strength, the mixture of M12 and M24 showed higher flexural strength than the control mixture, and the mixture of M36 and M48 exhibited a lower flexural strength than the control mixture. This phenomenon is due to the filling effect of very fine particles and the pozzolanic effect of GGBFS [11, 13]. Compared to the normal mortars produced in previous studies [16], all the mortars produced in the present study show excellent flexural strength. With the excellent resistance to bending, the use of these mortars can prevent the appearance of cracks; therefore, they are suitable to be used in hydraulic projects with high proof water requirements.

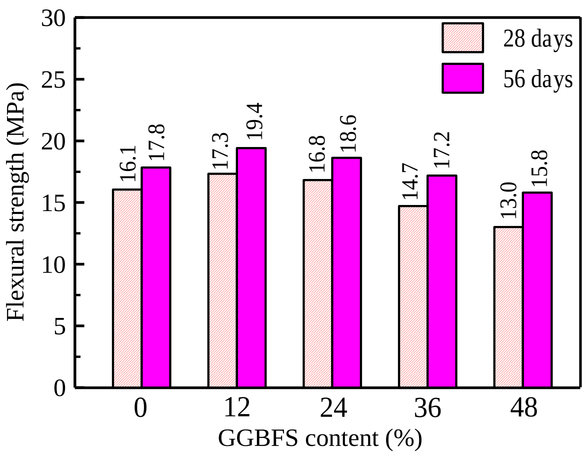

Figure 9. *Flexural strength of the mortars*

3.3. Ultrasonic pulse velocity (UPV)

The durability and the relative quality of concrete and mortars are associated with the voids and cracks inside the mortars. Hence, some studies have used the UPV test to assess the relative quality of concrete and mortars. Figure 10 presents the UPV values passed through the mortar cylinder sample. These values increased with increasing curing time. Along with curing time, the hydration products were generated, thus the density of these mortars was increased, leading to the increment of UPV values. As increasing the GGBFS content, the UPV values decreased. As stated by Bogas et al. [17] and Lafhai et al. [18], the UPV value of concrete and mortars is strongly depended on their density. It is noticed that the GGBFS has lower specific gravity than the cement (Table 1). Thus, when replacing a part of cement with GGBFS, the unit weight of the mortars will be reduced (Table 2). Consequently, the UPV value of the GGBFS mixtures will be lower than the control mixture. However, all the mortars have a 28-day UPV value of higher than 4300 m/s. Based on the study conducted by Khatib et al. [19], a mortar has been considered very good to excellent quality if its UPV value is higher than 4000 m/s. Thus, all mortars in this study can be classified as excellent quality.

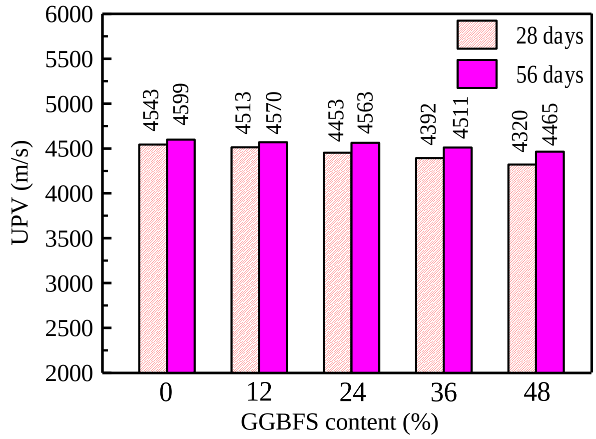

Figure 10. *Ultrasonic pulse velocity of the mortars*

3.4. Rapid Chloride ion penetration

To assess the resistance of the mortars to chloride attack, a rapid chloride ion penetration test was conducted. The resistance of the mortars to chloride attack is presented by the total charges passed through the cylinder sample in 6 hours (RCPT value). If the RCPT value is lower than 1000 coulombs, this mortar is classified as excellent resistance to chemical attack [12]. Figure 11 shows the RCPT values of the mortars. According to Figure 11, mixtures M12 and M24 show a lower RCPT value than the control mixture, while mixtures M36 and M48 show a higher RCPT value than the control mixture. This phenomenon is due to the filling effect and pozzolanic effect of GGBFS as aforementioned [11, 13]. All the mortars show the 28-day RCPT value of significantly lower than 1000 coulombs, indicating excellent resistance to chloride attack. These mortars can be used for very important structures with a high requirement in terms of chemical attack resistance, especially for big projects in coastal areas.

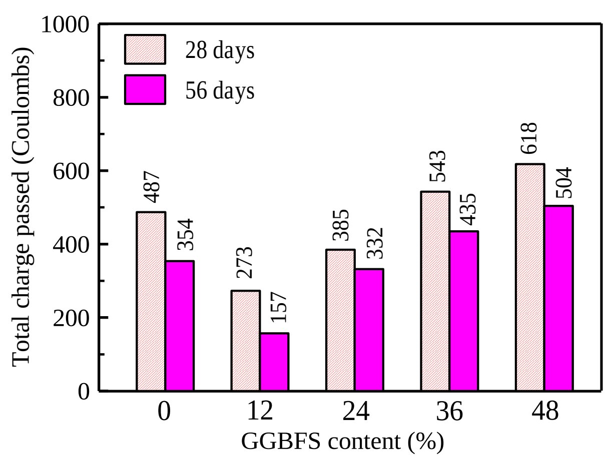

Figure 11. *Rapid chloride ion penetration of the mortars*

3.5. Thermal conductivity

Figure 12 presents the thermal conductivity of the mortars at 28 and 56 days, which ranged from 1.650-2.012 W/m.K and 1.751-2.022 W/m.K, respectively. The thermal conductivity at 28 and 56 days are similar. However, when increasing the GGBFS content, the thermal conductivity of the mortars reduced. This is because the thermal conductivity is related to the dry unit weight [20, 21]. As mentioned above, when the GGBFS replacement level increased, the unit weight of the mortars decreased, resulting in the reduction of thermal conductivity values.

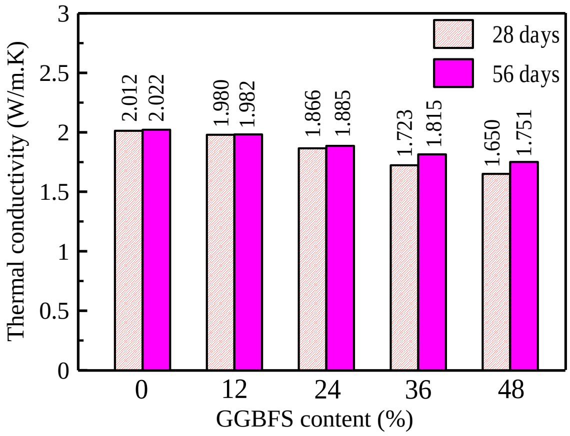

Figure 12. *Thermal conductivity of the mortars*

3.6. SEM observation

Microstructure morphology images of the mortars are shown in Figures 13-17. In general, the microstructure of all mortars produced in this study is quite dense. It is explained for their excellence in terms of strength and durability as presented in the previous sections. The microstructure of M12 shows the most homogenous and densest, followed by M24. This finding explains the increase in strength and durability of M12 and M24 in comparison with the control mixture. When the GGBFS content increases, the microstructure of M36 and M48 is less homogenous with higher porosity. This finding is evidence to explain the degradation properties of M36 and M48 in comparison with the control mixture. The findings from Figures 13 - 17 are related to the changes of the mortars' properties as aforementioned.

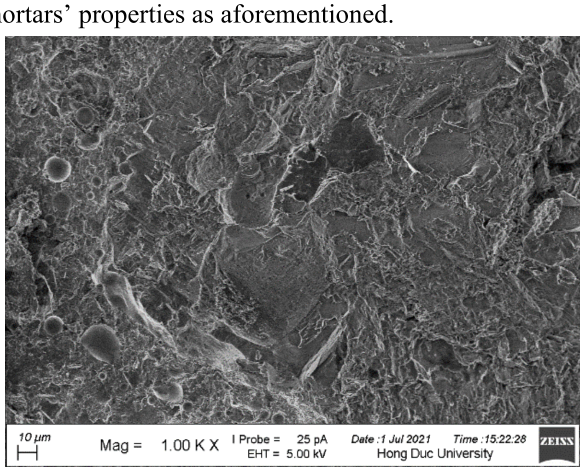

Figure 13. *SEM observation of M00*

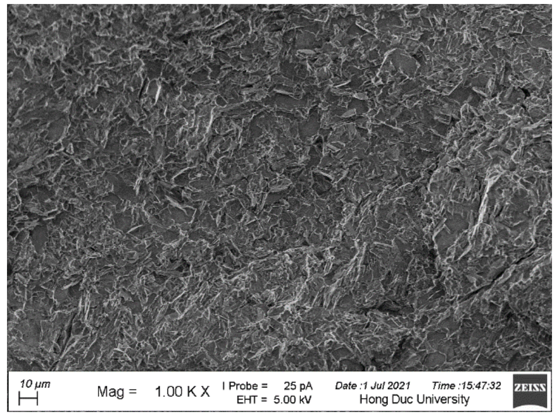

Figure 14. *SEM observation of M12*

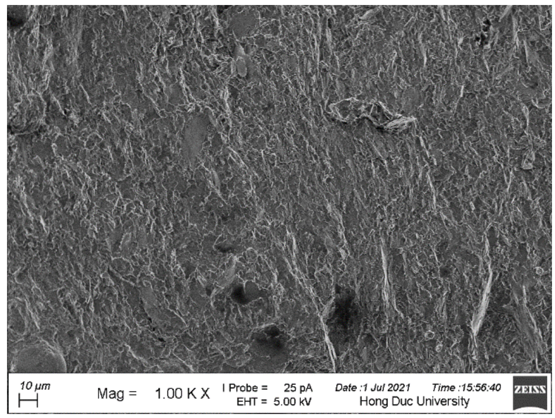

Figure 15. *SEM observation of M24*

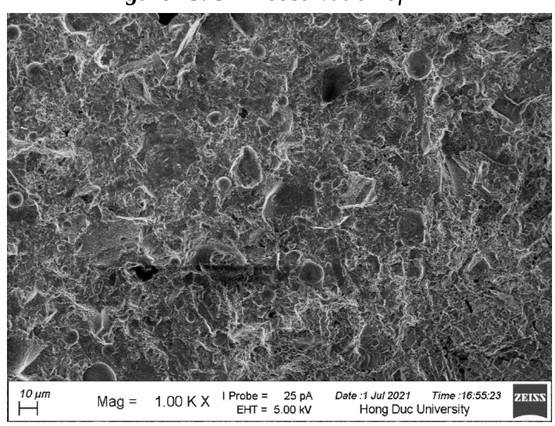

Figure 16. *SEM observation of M36*

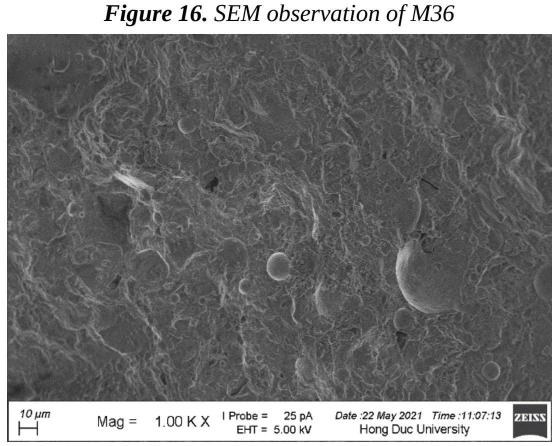

Figure 17. *SEM observation of M48*

4. Conclusions

This paper investigates the effect of GGBFS content on the properties of high-strength mortars. Some brief conclusions can be drawn as follows.

1) At 28 days, all the mortars show excellent compressive strength (85.5-112.7 MPa) and flexural strength (13.0-17.3 MPa). The use of 12% or 24% GGBFS increased in strength and durability of the mortars. However, when the GGBFS replacement level is over 24%, the quality of the mortars is decreased.

2) The relative quality of all the mortars produced in this study is classified as very good to excellent since their UPV values are higher than 4300 m/s.

3) All the mortars show excellent resistance to chloride attack with the RCPT of significantly lower than 1000 coulombs.

4) The microstructure morphology images of all the mortars are quite homogenous and dense. These images demonstrate the high strength and excellent durability of the mortars.

5) This study encourages the recycling of GGBFS, an industrial waste from iron and steel plants, in producing construction materials like high-strength mortars.

6) The above conclusions were drawn based on the use of 12%, 24%, 36%, and 48% GGBFS. Other replacement levels should be investigated in a further study.

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