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BLAST FURNACE SLAG PROPERTIES AT DIFFERENT GRINDING TIMES AND ITS EFFECT ON FOAM CONCRETE COMPRESSIVE AND FLEXURAL STRENGTH

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ABSTRACT

The paper presents the blast furnace slag properties at different grinding times by the dry grinding method. The process of fine grinding blast furnace slag is prepared at different times (10 minutes, 20 minutes, 30 minutes, 40 minutes). The results indicated that the main component in BFS is the amorphous structure defined in about 25÷35 degrees (with the appearance of Akermanite at 31.1, Calcite at 29.2 and Aragonite at 26.4). The results also showed that the compressive strength and activity index of blast furnace slag increased significantly after extending the grinding time from 0-40 minutes (corresponding to compressive strength from 51.2 ÷ 72.1 MPa at 28 days of age and activity index of blast furnace slag from 91.92% -129.44%). The fine grinding process shows that the particle size of blast furnace slag is significantly reduced.

In addition, the paper also presents the effect of finely ground blast furnace slag in 40 minutes on foam concrete properties. Research results show that the use of finely crushed blast furnace slag by the mechanical grinding method to replace sand in foam concrete not only improves the mechanical properties such as compressive strength, flexural strength, the elastic modulus of foam concrete but also protects the environment, reduces product costs.

KEYWORDS

Blast furnace slag, Mechanical properties, Mixtures, Concrete, Mechanical grinding

INTRODUCTION

Blast furnace slag (BFS) is a by-product formed during the production of pig iron. In the process of smelting cast iron, when silicon and aluminium oxides react from barren rock of iron-bearing ore with calcium oxide and magnesium oxide of the flux, a fiery liquid alloy is formed.

Due to the peculiarities of steel and pig iron smelting, since the 19th century, blast furnaces have a by-product in the amount of up to 1 ton of slag per 1 ton of pig iron products, which contributed to the accumulation of a large number of slag dumps, causing the need for their disposal. To date, slags are also mainly taken to landfills, where they accumulate, which leads to a deterioration of the ecological situation. At present, thanks to the development of iron ore beneficiation technology, the yield of BFS is 200–500 kg per 1 ton of cast iron [1].

Currently, worldwide production of BFS is about 0.5 billion tons, while effective utilization rates are still relatively low [2]. Therefore, the reuse of BFS is an urgent issue. The main application area for waste, such as slag is the construction industry. The use of BFS brings excellent benefits such as increasing the durability of concrete, reduce the heat of hydration and saving natural resources [3-5].

The chemical composition of BFS depends on the type and properties of iron ores, coke quality, and the type of cast iron. Blast furnace slags contain CaO, SiO_2, Al_2O_3, MgO, FeO and some other oxides. The chemical composition of blast furnace slags, %, varies within wide limits: CaO 30-49; Al_2O_3 4.5-20; Fe_2O_3 0.3-0.8; SiO_2 33-44; MgO 1.5-15; MnO 0.3-3.0. In recent decades, BFS used as a partial substitute for Cement has increased [6,7]. In there, mechanical grinding improves the blast furnace slag's chemical activation and is interested in many researchers [8,9]. There are two mechanical grinding methods: dry grinding method and a wet grinding method. The wet grinding method has been studied by many scientists [10,11].

Meanwhile, the dry grinding method has been used for traditional Cement. Many experimental studies have been made about BFS performance with a different particle size as a raw material for cement supplements. Norrarat et al. [12] studied the effect of BFS with varying sizes of a particle on the hydration kinetics of Cement. They found that the Cement's water loss rate increased as the BFS size decreased due to its reaction. Wang et al. [13] also studied the effect of the fineness and particle size distribution of BFS on the performance of Cement. They found that the BFS with a higher fineness react with more incredible speed and BFS fraction smaller than 5 microns has an important role in hydration [9,14,15].

As you know, foam concrete is a lightweight concrete with a porous structure obtained by hardening solutions, including binders, fine aggregates, water, additives and a foaming agent. Foam concrete with a density of 400 kg/m^3 to 1700 kg/m^3 is used to manufacture structures (walls, floors), heat and sound insulation of buildings and structures [16,17].

Research on foam concrete using BFS has been interested in many researchers [18-20]. However, there has not been any research on the properties of BFS at different grinding times. Then, using finely ground BFS obtained to produce foam concrete.

Based on the above analysis, the authors have studied the fine grinding blast furnace slag's properties at different times (10, 20, 30, 40 minutes) and its effect on foam concrete properties.

MATERIALS AND METHODS

Materials

The main binder material used in this work was blast furnace slag (BFS). Ordinary Portland Cement (OPC), which meets the requirements of GOST 31108-2016, was used as a binder. The cement compressive strength at the age of 3 days is 27.2 MPa and at the period of 28 days is 46.1 MPa. The experiments are performed according to the standard GOST 310.4-81.

Quartz sand (QS) with a size modulus MK = 3.0 and □ = 2.64 g/cm^3, the sand properties are given in Table 1.

Tab. 1 - The sand properties

Sieve (hole size), mm	5	2.5	1.25	0.63	0.315	0.14
Residues on test sieves, %	0	0	0.83	14.23	73.2	6.28
Full balance, %	0	0	0.83	15.06	88.26	94.54

In this study, superplasticizers (SR5000) were used to improve the performance of concrete mixtures with ρ= 1.1 g/m^3 at a temperature of 25 ± 5°C. Besides, Silica Fume SF-90 (SF90) "Vina Pacific" was used as a binder. Table 2 presents the chemical and physical properties of Portland cement, SF90 and BFS.

This section should describe in detail the study material, procedures and methods used.

Tab. 2 - Properties of OPC, BFS and SF90

Property		SF90	BFS	OPC
Chemical	SiO_2	90.78	36.01	21.98
	Al_2O_3	2.23	13.77	5.31
	Fe_2O_3	2.51	-	3.46
	CaO	0.52	41.05	62.33
	MgO	-	7.36	2.01
	SO_3	-	0.14	-
	Na_2O	0.57	-	0.14
	K_2O	-	0.28	0.62
	Loss on ignition	3.39	1.39	4.15
Physical	Specific gravity (g/m^3)	2.15	2.29	3.12
	Fineness (cm^2/g)	10160	4540	3650

EABASSOC Foaming Agent (United Kingdom) is a highly concentrated, highly efficient liquid used in Foamed Concrete production. Dosage Rate: (0.3 - 0.6) l/m³ with ρ = 1.02 g/cm^3. Mixing water (W) to obtain a concrete mixture, pH = 7.5.

Methods

The activity index of BFS in mortar mixtures was determined by the requirements of the TCVN 11586: 2016 standard;

Compressive and flexural strength of concrete was determined following the requirements of GOST 10180-2012 and TCVN 10303: 2014;

The crystal phases of BFS and blast furnace cement-slag mortar sample were determined by X-ray diffraction (MiniFlex x-ray diffractometer);

Particle shape is determined by device (QUANTA FEG 450);

The Matersizer 3000 laser particle analyzer determined particle size distribution;

The elasticity modulus of samples was determined using cylindrical samples of 150×300 mm. Samples were tested at the age of 28 days following GOST 24452-80 [21]. According to the formula, the elasticity modulus (Es) of each sample is calculated in daN/cm^2.

$$E_s = \frac{\Delta_s}{\Delta_e} = \frac{\sigma_a - \sigma_b}{\varepsilon_a - \varepsilon_b} \tag{1}$$

Where: ε_a - the strain under σ_a; ε_b - the strain under σ_b; σ_a= f'c/3 - the upper loading stress (MPa); σ_b - the basic stress (i.e. 0.5 MPa).

BFS used in work is received from the factory. A production process chart is shown in Figure 1. The BFS is dried in a laboratory oven at T = 100 ± 10°C for 2 hours, then crushed the obtained product in a mill (Model SM500x500, China) in 10, 20, 30 and 40 minutes to obtain BFS in fine powder form (Figure 1).

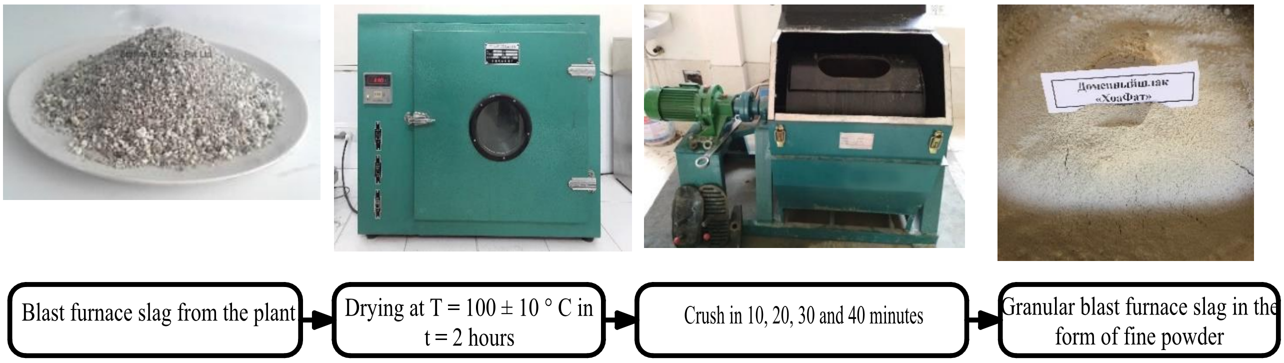

Fig. 1 – Process finely ground BFS

RESULTS AND DISCUSSION

Finely ground blast furnace slag properties

Sieving analysis BFS

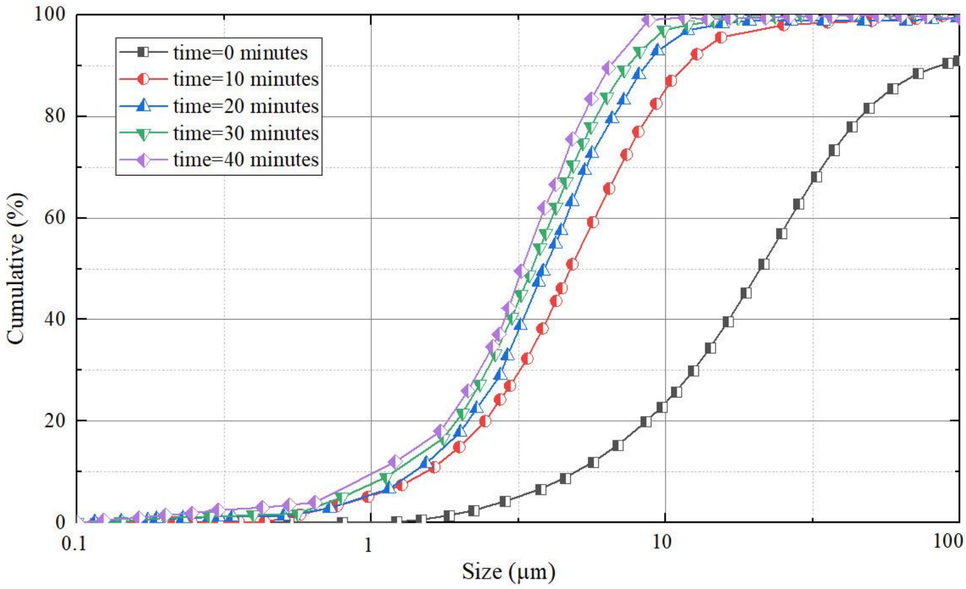

Fig. 2 – Particle size distribution of BFS

The average particle size of BFS, as well as particle size distribution without mechanical activation and after mechanical activation for 10 to 40 minutes by grinding it in a vibrating mill. Which determined using a laser particle analyzer "Coulter LS Particle Size Analyzer" are shown in Figure 2. Figure 2 shows that the obtained BFS is mainly distributed in the range of 1÷100µm. In which the particles with size > 10 µm are about 80%. In addition, fine grinding of BFS at different times (10, 20, 30, 40 minutes) showed a significant improvement in the particle size distribution. Figure 2 also shows that the particle size decreased significantly after grinding for 10 minutes. This was also reported in the study of M. Oner [23]. After 40 min grinding, the particle size did not change much, which can be explained by their aggregation.

XRD of BFS

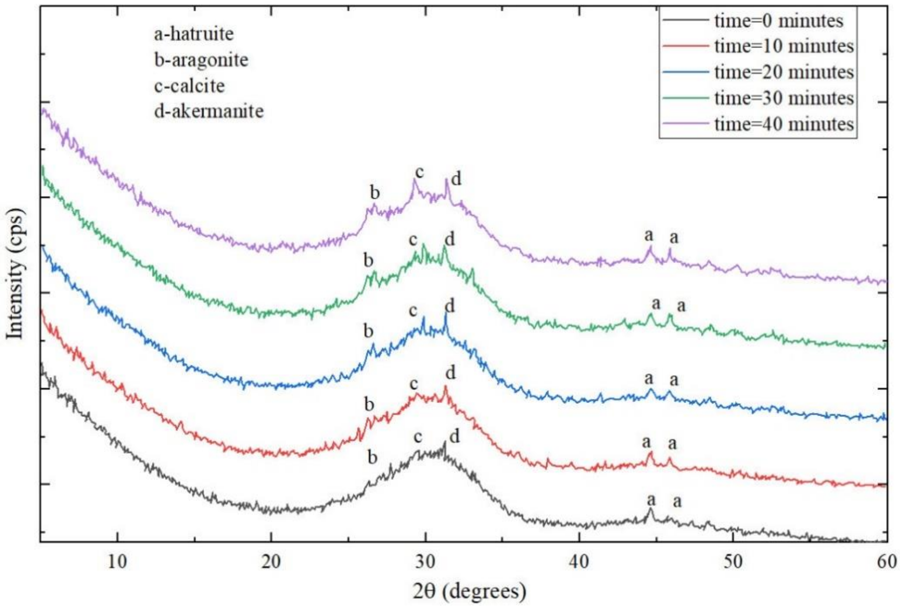

Fig. 3 – XRD samples of BFS at different grinding times

Comparing the finely ground BFS at 10, 20, 30, 40 minutes and BFS is shown in Figure 3. It can be seen that the main component in BFS is the amorphous structure defined in about 25-35 degrees (with the appearance of Akermanite at 31.1, Calcite at 29.2 and Aragonite at 26.4). According to Lei Gan, etc [24], Calcite Aragonite is the structural feature of BFS. In addition, [9] it was reported that the XRD samples of BFS were also present in the presence of Hatruite.

SEM of BFS

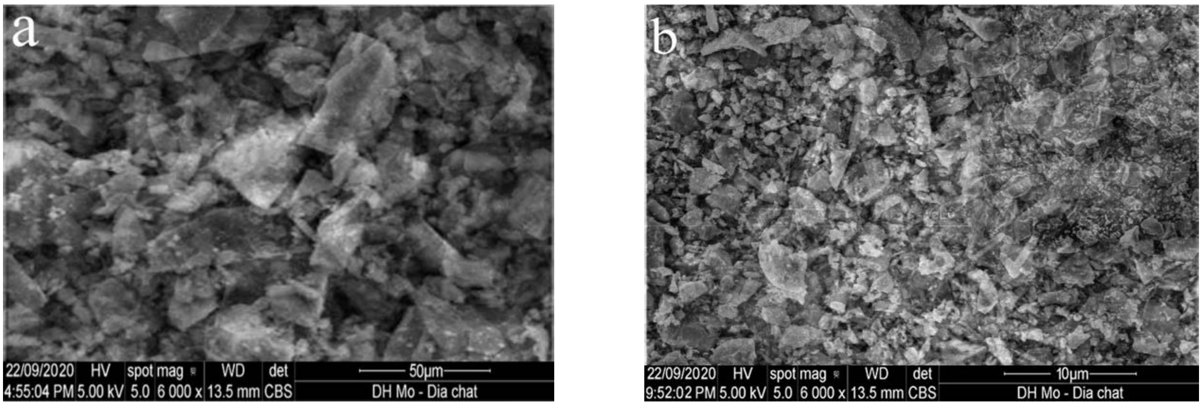

Fig. 4 – SEM of BFS samples at different grinding times: a-0 minutes, b-10 minutes, c-20 minutes, d-30 minutes, e-40 minutes

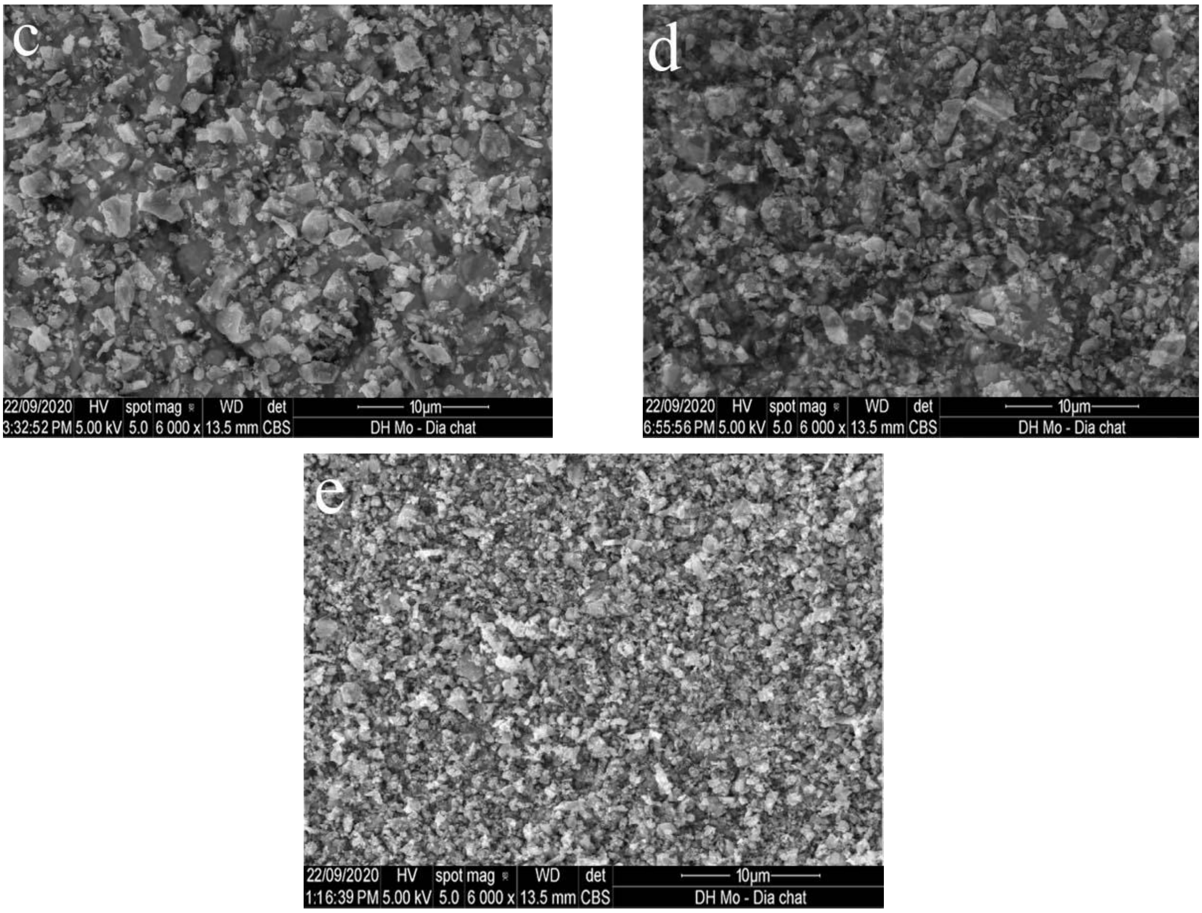

Fig. 4 – SEM of BFS samples at different grinding times: a-0 minutes, b-10 minutes, c-20 minutes, d-30 minutes, e-40 minutes

The change of BFS particle size at different grinding times is shown in Figure 4. It can be seen that the resulting BFS has a dense structure and an uneven shape. The fine grinding process shows that the particle size of BFS is significantly reduced. The impact of the grinding process results leads to BFS particles to break and become smooth.

Mixture proportions

In the present study, the proportions and composition of the mixture are presented in Table 3. Water/binder = 0.5 (binder = Cement + BFS). Mixtures 2, 3, 4 use 50% of finely crushed BFS to replace Cement [22].

Tab. 3 - Mix proportion of BFS -cement mortar

Mix number	BFS grinding time	Cement	Sand	BFS	Water
No-0	100% Cement	513	1539	-	256
No-1	0 minutes (50% Cement – 50%BFS)	256.5	1539	256.5	256
No-2	10 minutes (50% Cement – 50%BFS)	256.5	1539	256.5	256
No-3	20 minutes (50% Cement – 50%BFS)	256.5	1539	256.5	256
No-4	30 minutes (50% Cement – 50%BFS)	256.5	1539	256.5	256
No-5	40 minutes (50% Cement – 50%BFS)	256.5	1539	256.5	256

XRD of blast furnace cement-slag mortar sample

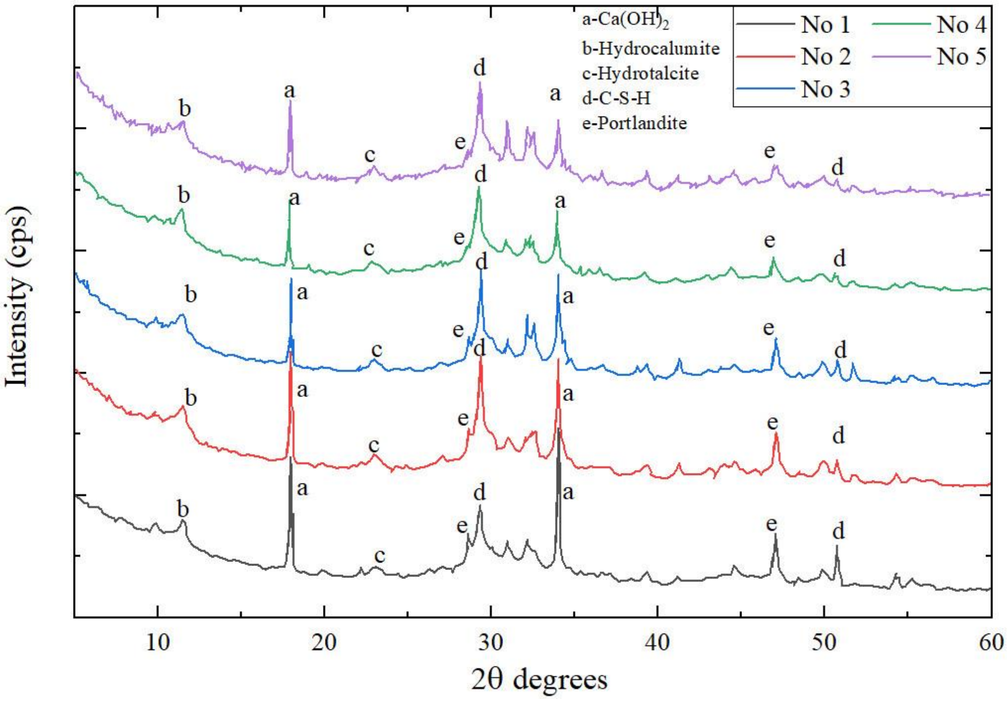

Fig. 5 – XRD of the samples uses BFS for different grinding times

Figure 5 presents XRD results of experimental samples after 28 days of age. This result is to evaluate the effect of finely ground BFS on the reaction processes. Hydration products include C-S-H gel and portlandite derived from Cement due to the carbonation of $Ca(OH)_2$, Hydrotalcite and hydrocalumite due to the reaction of BFS. Therefore, it can be seen that the hydration products are the same for all samples. This study's material composition is the same, only different at BFS grinding time. The $Ca(OH)_2$ content can reflect the blast furnace slag's reactive properties, as shown in Figure 5. In addition, the intensity of $Ca(OH)_2$ decreases significantly as the BFS grinding time increases. This suggests that the BFS grinding process can substantially promote the reactivity of BFS.

Compressive strength

Tab. 4 - Compressive strength of experimental samples

Mix number	Compressive strength (MPa)		
	3 d	7 d	28 d
No-0	24.1	39.2	55.7
No-1	17.9	30.3	51.2
No-2	23.5	39.8	57.3
No-3	34.4	46.1	65.8
No-4	35.4	53.2	68.6
No-5	39.4	61.7	72.1

Table 4 shows that the compressive strength of the concrete sample (No-1) is 17.9, 30.3, 51.2 MPa after 3, 7, 28 days of age. It is lower than the compressive strength of concrete sample (No-0), respectively 24.1, 39.2 and 55.7 MPa. Untreated BFS was shown to have a negative effect on the compressive strength of the concrete at all testing ages. Meanwhile, the effect of increasing concrete strength when extending BFS grinding time occurred in samples (No-2, No-3, No-4, No-5) corresponding to grinding time of 10, 20, 30 and 40 minutes. The compressive strength of the experimental concrete samples has proven that the use of finely ground BFS significantly improves the concrete's strength. This is also confirmed in the study of Dien Vu Kim and etc [17].

Activity index of BFS

The activity index of BFS (I_R,%) is the ratio of a sample's compressive strength made of a cement-sand mortar, where part of the binder - Cement is replaced by BFS (R_2). The compressive strength of the sample control, no-additive cement-sand mortar (R_1). The BFS activity index was calculated using formula (2) given in the TCVN 11586: 2016 standard.

$$I_R = \frac{R_2}{R_1}.100\% \tag{2}$$

where: I_R - activity index of BFS, %; R_1 - compressive strength of control samples made on no additive cement-sand composition at the age of 28 days, MPa; R_2 - compressive strength of samples from cement-sand-BFS mortars at the age of 28 days, MPa.

Figure 6 shows the activity index of the BFS. It can be seen that untreated BFS has a low activity index (91.92%) whereas finely ground BFS has a high activity index (102.87%, 118.13%, 123.16% and 129.44%). This is explained that, due to the finely ground BFS with microparticles, it fills the void and has an excellent pozzolanic effect. This helps to form more hydration products and more compact structure.

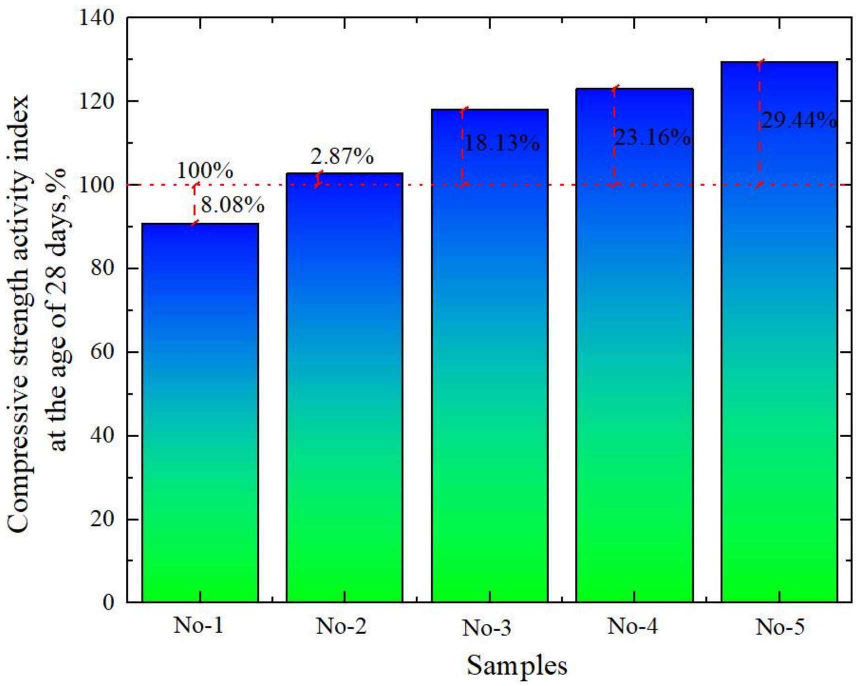

Fig. 6 – Diagram of comparing activity index of BFS

Effect of BFS on foam concrete properties

Foam concrete mix compositions

The purpose of this section is to study two types of foam concrete, produced from QS and BFS finely ground in 40 minutes. Type I with a wet density of 1700 kg/m^3. Type II with a wet density of 900 kg/m^3. The composition of the foam concrete mixture is given in Table 2. According to [25] the amount of fixed cement with the mixture = 1700 kg/m^3 and cement = 350 kg/m^3 with mixes 900 kg/m^3. For Series I-2, II-2 used QS to replacement of 100% BFS [16]. Besides, SF90 and SR5000 have been used to increase strength and reduce water with ratio SF90/OPC = 0.1, SR5000/OPC = 0.015, [26]. The composition of the foam concrete mixture is shown in Table 5.

Tab. 5 - Component foam concrete mixture

Series	Mix number	Component foam concrete mixture, kg/m^3						
		OPC	BFS	QS	SR5000	SF90	W	Foam (l)
Series I	1	450	926	-	4,5	69	271.9	206.92
	2	450	-	926	4,5	69	181.5	206.92
Series II	1	350	356	-	3,5	39	139.5	567.54
	2	350	-	356	3,5	39	104.8	567.54

Mechanical properties of foam concrete

The experimental results of the mechanical properties of foam concrete are presented in Table 6.

Tab. 6 - Results of flexural strength, compressive strength and elastic modulus of foam concrete

Series	Mix number	Compressive strength at different curing times (MPa)					Flexural strength at 28 days (MPa)	Elastic modulus 10^3 (MPa)
		3 - day	7 - day	14 - day	21-day	28 - day		
Series I	1	32.1	39.56	44.11	44.9	45.6	6.74	26.78
	2	22.78	26.96	32.57	33.01	33.34	5.36	21.95
Series II	1	6.76	7.76	8.21	8.55	8.63	1.067	7.71
	2	4.73	5.51	5.69	5.77	5.91	0.824	5.76

Compressive strength of foam concrete

As shown in Figure 7 the use of additives (Silica fume, Superplasticizer) and BFS significantly improves the development of compressive strength in all test periods. This is due to the decrease in water content due to the use of the Superplasticizer and pozzolanic characteristics of SF90 and BFS. In addition, this leads to an improvement in the bonding of aggregates with the less porous interphase formation and better adhesion between the mortar and aggregate mixture.

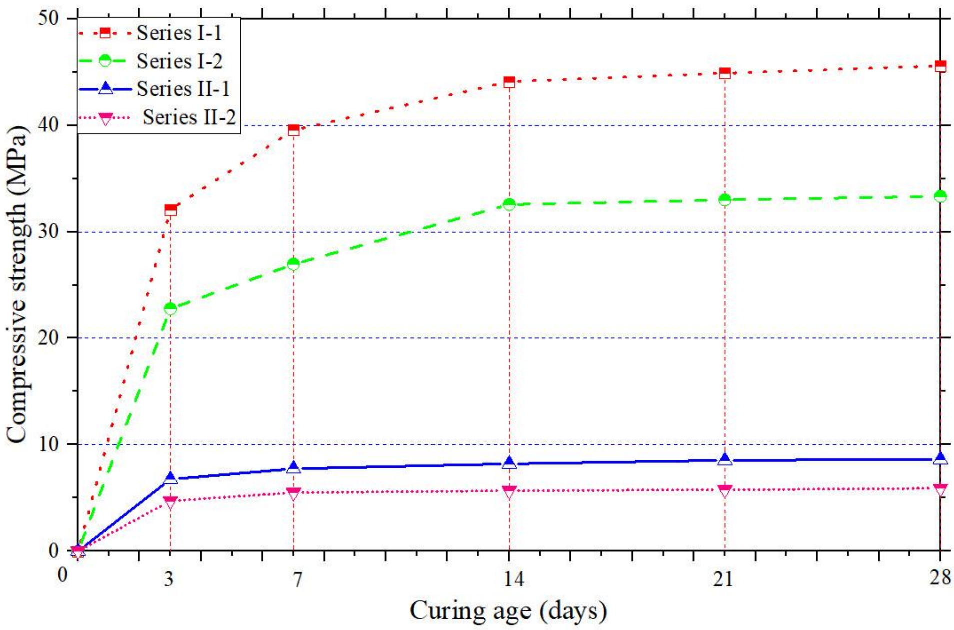

Fig. 7 – Dependences of the strength of foam concrete on the age of the samples

It can be seen from Figure 7 that the compressive strength of Series I-1 and Series II -1 is higher than the strength of Series I -2 and Series II -2. This is because using fine grinding BFS can

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help achieve a more even distribution of air voids, providing a uniform coating on each bubble, thereby preventing the coalescence of bubbles, leading to an increase in strength. In addition, replacing QS with BFS increases both compressive strength and flexural strength. This is because BFS has high pozzolanic activity due to the average content of amorphous SIO_2 in them is 36.01%.

Basically, foam concrete with BFS as a filler material has a higher compressive strength than foam concrete with QS as a filler material. This is also confirmed in the study of Dien Vu Kim, etc. [16].

Flexural strength of foam concrete

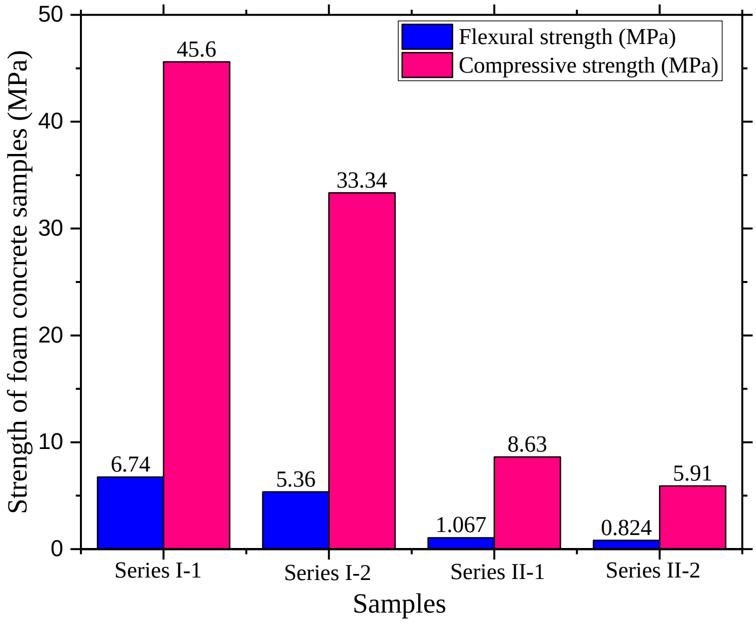

Fig. 8 – Dependences of the strength of foam concrete on the age of the samples

Figure 8 shows the increase in compressive and flexural strength, respectively, depending on the proportions of fine grinding BFS in the foam concrete mixture's compositions. In addition, from Figure 8, it can be seen that with an increase in compressive strength, the flexural strength also increases. This is entirely consistent with the law of the strength development of concrete.

Elastic modulus of foam concrete

The static modulus of elasticity (Es) of the mixtures (Series I-1, Series I-2, Series II-1, Series II-2) was determined using cylindrical samples 150 × 300 mm in size; two samples were tested for each mixture at the age of 28 days following GOST 24452-80 [21][27]. Each sample was equipped with four potentiometers in different quadrants to measure axial deformation, see Figure 9.

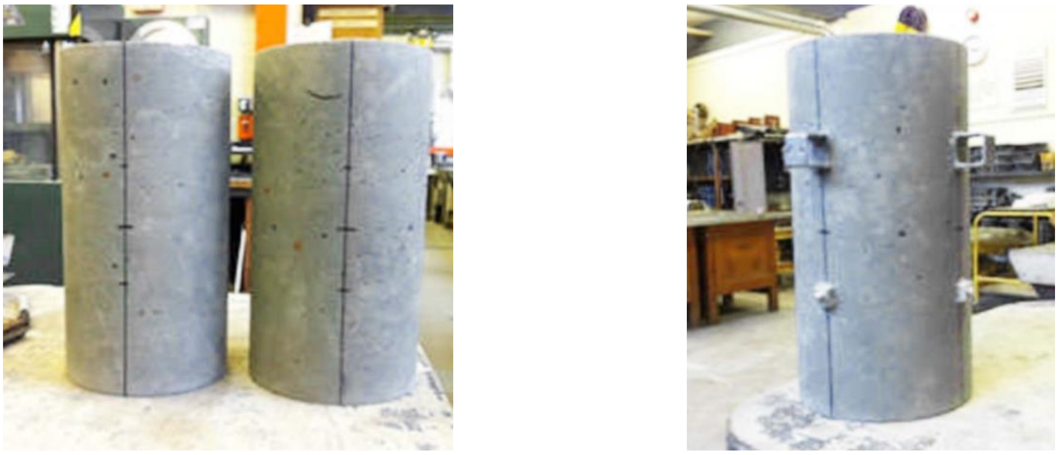

Fig. 9 – Samples for testing elasticity modulus

Figure 10 shows that the modulus of elasticity of the Series I-1and Series II-1 is higher than the Series I-2 and Series II-2. This is directly proportional to the compressive and flexural strength of the foam concrete. Therefore, it can be concluded that when the compressive strength, the flexural strength increases to lead the elastic modulus increases. Compared to the [28] study results, this research result is completely consistent.

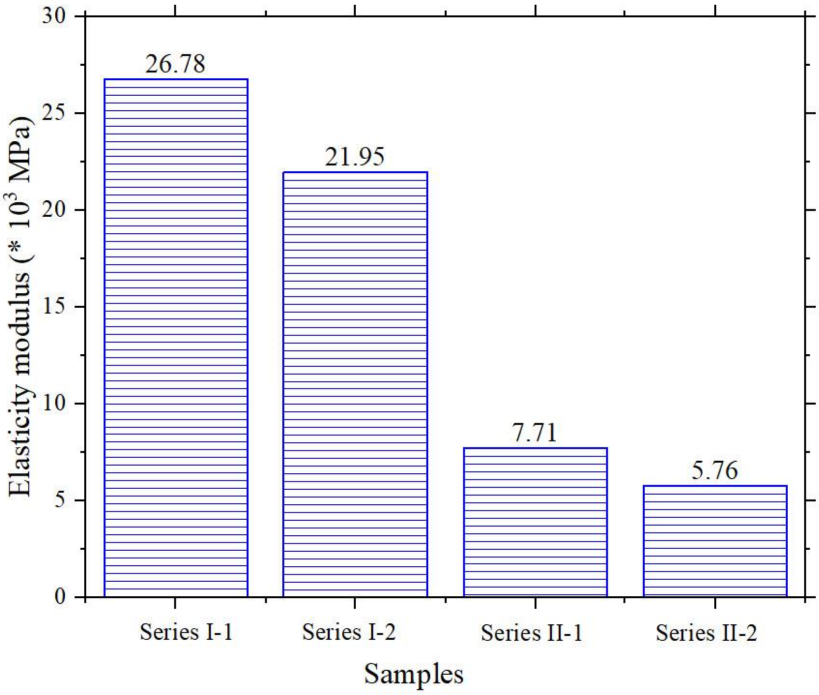

Fig. 10 – Elasticity modulus of foam concrete

CONCLUSIONS

Based on the test results, the following conclusions are drawn:

- Finely ground BFS by mechanical grinding method obtained a minimum average particle size of 5 μm after 40 minutes of treatment. This proves that this method is an effective method for obtaining finely ground BFS. In addition, the fine grinding of BFS after 40 minutes did not affect the particle size much.

- Finely ground BFS by mechanical grinding in 40 minutes with an activity index = 129% can replace activated mineral additives to produce construction mortar and concrete, reducing costs and improving friendly environmental situation.
- The mechanical grinding method can improve the reaction of BFS. The compressive strength increases when the BFS grinding time is extended. Specifically, compressive strength at 28 days increased from 55.7 MPa to 72.1 MPa, corresponding to grinding time from 0-40 minutes.
- The mechanical grinding method results showed that the particle size of BFS decreased significantly. The main constituents of BFS are amorphous structures (Akermanite, Calcite, Aragonite).
- Research results show that the use of finely crushed BFS by the mechanical grinding method to replace QS in foam concrete not only improves the mechanical properties such as compressive strength, flexural strength and elastic modulus of foam concrete. Besides, it can protect the environment, reduce product costs.

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