Journal of Science and Technology in Civil Engineering, HUCE, 2024, 18 (3): 19–29

EFFECTS OF CEMENT PASTE VISCOSITY ON THE PROPERTIES OF LIGHTWEIGHT EXPANDED POLYSTYRENE CONCRETE

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Article history:

Received 21/5/2024, Revised 21/6/2024, Accepted 24/6/2024

Abstract

Lightweight expanded polystyrene concrete (EPS-C) offers several advantages, including low density, sound resistance, and good thermal insulation. These characteristics are contributed by the use of expanded polystyrene (EPS) with a closed cellular structure, which is non-absorbent, hydrophobic, and low-density (around 6.9 kg/m³). Since EPS is much lighter than cement paste, the viscosity of the paste plays an important role in directly affecting segregation and the properties of EPS-C mixtures. This paper presents the experimental results of the viscosity and its influence of cement paste on both the segregation of the concrete mixture and the compressive strength of EPS-C. The research revealed that a viscosity of cement paste below 50 mPa.s results in segregation of the concrete mixture. As the viscosity increases, the degree of segregation decreases. However, when the viscosity exceeds 180 mPa.s, using a viscosity-modifying admixture becomes a good solution to prevent segregation in EPS-C mixtures. Therefore, the optimal viscosity range for the binder paste to ensure the concrete mixture does not segregate is between 50 and 180 mPa.s.

Keywords: lightweight concrete; expanded polystyrene concrete (EPS-C); workability; density; viscosity; viscosity modifying admixture (VMA); segregation; compressive strength.

https://doi.org/10.31814/stce.huce2024-18(3)-02

1. Introduction

In recent years, lightweight concrete (LWC) has garnered growing interest for its applications in the construction industry, offshore structures, and large-span bridges. LWC offers the distinct advantage of low density, translating into two major benefits [1–3]. Firstly, it reduces the weight of the building structure, which in turn allows for a reduction in steel bars, ultimately leading to cost savings in construction. Secondly, LWC enhances both sound and thermal insulation of the structure. Among these LWCs, expanded polystyrene concrete (EPS-C) has been a subject of increasing study and holds promising potential for application. The composition of EPS-C typically includes cement, fly ash, sand, expanded polystyrene beads (EPS), water, and chemical admixtures [4–7]. EPS is a type of artificial lightweight aggregate (LWA) with a non-permeable, hydrophobic closed-cell structure and content up to 98% voids. The hydrophobic nature of EPS contributes to the low thermal conductivity of EPS-C [8].

Viscosity is one of the most important properties of cement paste, affecting flowability, deformability, filling ability, resistance to segregation, and ultimately the mechanical properties of concrete [9–11]. This significantly impacts the applicability of EPS-C [12]. Unlike conventional lightweight aggregate (LWA) concrete, which has high water absorption due to large voids in the LWA, EPS-C is not significantly affected by water absorption because EPS beads have a closed-cell structure with

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very low water absorption capacity [4, 13]. However, the ultra-low density of EPS (ranging from 6 to 20 kg/m^3) presents a challenge. Due to this lightweight nature, EPS tends to float to the surface during casting, causing segregation in the concrete mixture. This segregation significantly affects the final properties of the concrete [6, 14, 15]. Various solutions are currently employed to limit segregation in EPS-C mixtures. These solutions include reducing the water-to-binder ratio (w/b), using viscosity-modifying admixtures, incorporating mineral admixtures, or using dispersed fibers. These approaches essentially aim to modify the viscosity of the binder paste or alter the density difference between the EPS particles and the binder paste. However, the adjustment of viscosity to ensure mixture homogeneity remains an area of ongoing research. Despite this, no studies have yet specifically addressed the impact of viscosity indices on the properties of EPS-C. This paper, therefore, focuses on investigating the effects of viscosity on the workability, degree of segregation, and mechanical properties of EPS-C. The experimental results will be used to recommend a viscosity threshold that ensures the homogeneity of the EPS-C mixture.

2. Materials and methods

2.1. Materials

Portland cement PC40 (C) and fly ash (FA) from the Pha Lai thermal power plant were used to produce EPS-C. The physical and mechanical properties of the cement comply with the Vietnamese standard TCVN 2682:2020 [16]. The chemical properties, physical properties and mechanical properties of cement and FA are shown in Table 1 and Table 2, respectively.

Table 1. Chemical compositions of cementitious materials

Material	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	L.O.I
Cement, wt%	20.60	5.13	3.56	63.26	3.07	0.24	0.25	-	1.86
FA, wt%	46.82	12.30	25.29	1.20	1.16	1.09	2.50	0.60	6.65

Note: L.O.I: Loss on Ignition.

Table 2. Properties of cementitious materials

Properties		Unit	Cement	FA
Retained percent on 0.09 mm sieve		%	0.58	-
Retained percent on 0.045 mm sieve		%		23.2
Specific gravity			3.15	2.21
Standard consistency		%	29.5	
Setting time	*Initial*	Minute	115	
	Final	Minute	225	
Strength reactivity index at 28 days		%		85.4
Mean particle size		µm	11.4	
Compressive strength	*3 days*	MPa	29.8	-
	28 days	MPa	52.2	-

EPS was used in all mixtures with a density of 6.9 kg/m^3 and a particle size range of 2.5–5 mm. The properties of EPS are shown in Table 3.

Table 3. Properties of EPS

Properties	Units	Value
Particle size	mm	2.5–5
Bulk density	kg/m^3	4.1
Density	kg/m^3	6.9

Superplasticizer (SP) named ROADCON-SR 5000F, a commercial product from Silkroad, was used to control the viscosity and workability of EPS-C mixtures. The manufacturer lists the following properties of SP:

- Liquid;
- Color: Brown;
- Dosage: 0.3−1.5% per 100 kg binder;
- Density: 1.08 ± 0.02 g/cm^3.

A commercial, powdery viscosity modifying admixture (VMA) was also used in the mixtures. The chemical compound of this VMA is hydroxypropyl cellulose ether, which acts on the cement paste to increase the viscosity, resulting in improved segregation resistance and bleeding resistance of the concrete.

2.2. The composition of EPS-C

This study evaluates the influence of binder paste viscosity on the segregation level and, consequently, the strength of EPS-C. The EPS-C composition consists of two groups: samples with 0% and 20% FA by weight of binder (cement + FA). A water-to-binder (w/b) ratio of 0.25 is used for all mixtures. Superplasticizer (SP) content varies from 0.6% to 1.2% by weight of binder, and viscosity modifying admixture (VMA) content ranges from 0% to 0.075%. The target density of the concrete mixture is between 1400 and 1600 kg/m^3. The EPS content is fixed at 35% by volume of the concrete mixture (350 liters per cubic meter). The absolute volume method will be used to calculate the concrete mix design based on the chosen material proportions. The composition of the EPS-C mixtures is detailed in Table 4.

Table 4. Mix composition of the EPS-C mixture

No	The proportion of materials, wt% of binder				Concrete mixture, kg/m^3					
	w/b	FA	SP	VMA	V_{EPS}, liter	C, kg	FA, kg	SP, kg	VMA, kg	W, kg
Mix1	25	0	0.6	0	350	1154	0	6.9		289
Mix2	25	20	0.6	0	350	924	231	6.9		289
Mix3	25	0	1.0	0	350	1151	0	11.5		288
Mix4	25	20	1.0	0	350	921	230	11.5		288
Mix5	25	0	1.2	0	350	1149	0	13.8		287
Mix6	25	20	1.2	0	350	919	230	13.8		287
Mix7	25	20	1.2	0.025	350	919	230	13.8	0.287	287
Mix8	25	20	1.2	0.050	350	919	230	13.8	0.574	287
Mix9	25	20	1.2	0.075	350	919	230	13.8	0.861	287

2.3. Mixing process of EPS-C mixtures

Cement, water, SP, and FA were measured by weight. EPS beads were measured by volume. The concrete mixture was mixed using an intensive mixer. The process of mixing and manufacturing EPS-C can be shown in Fig. 1.

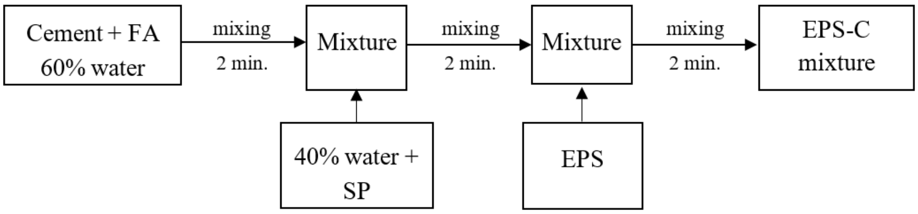


Figure 1. The mixing process of EPS-C mixtures

Casting concrete samples (Fig. 2): After mixing, the concrete mixture was cast in a mold with dimensions of 100×100×100 mm. The concrete was poured into the mold, followed by slight vibration to ensure complete filling, then finishing the samples surface and covering the surface with plastic wrap. After 24 hours, the samples were removed from the mold and cured under standard conditions until the testing age.

Figure 2. Casting and curing the EPS-C

2.4. Methods

The viscosity of the cement paste was measured using a vibrating viscometer SV-10 (Fig. 3) following the procedure described in [17]. This device determines the viscosity of the cement paste by measuring the current required to vibrate two sensor plates at a constant frequency of 30 Hz. The experiment was conducted immediately after mixing the cement paste. The paste was poured

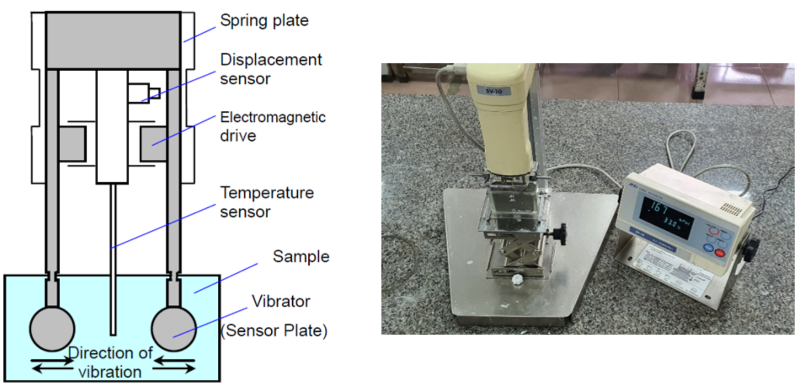


Figure 3. Device for Measuring Viscosity of Cement Paste (Vibrating Viscometer SV-10)

into a measuring cup with a volume of approximately 35–45 ml. The cup was then placed in the measuring position of the device, and the two sensor panels embedded in the sample were adjusted to the designated level line. The meter was turned on to determine the viscosity value. The viscosity of the cement paste mixture was recorded every 15 seconds after starting the machine.

The workability of the EPS-C mixtures was evaluated according to TCVN 3106:2022 [18]. The testing process is shown in Fig. 4.

The compressive strength of EPS-C samples was determined based on the standard TCVN 3118:2022 [19] using 100×100×100 mm samples.

The density of the EPS-C was determined based on the standard TCVN 3115:2022 [20]. The density is denoted by ρ_o.

Figure 4. Determining the slump of the concrete mixture

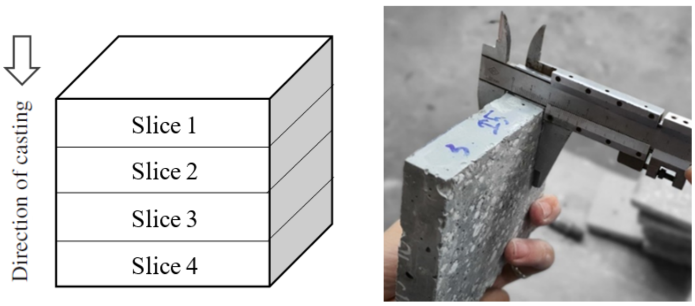


Figure 5. The samples to test segregation

The segregation of EPS-C mixtures was evaluated using a 100×100×100 mm cube sample. To evaluate the segregation, the samples were cut into four horizontal slices along the vertical direction of pouring the concrete, as shown in Fig. 5. The dry density of each slice was determined and assigned symbols ρ_1 (top), ρ_2, ρ_3 and ρ_4 (bottom) accordingly. The specific density for each slice was then calculated using the following formula:

$$K_{SD} = \frac{\rho_o}{\rho_n} \tag{1}$$

in which ρ_o is density of the sample, kg/m^3; ρ_n is density of the slice n ($n = 1 - 4$), kg/m^3.

3. Results and discussions

3.1. Effect of FA, SP, VMA contents on viscosity of cement paste

This research evaluated the effect of FA and SP on the viscosity of cement paste. Two FA contents were used, i.e. 0% and 20% by weight of binder. The SP dosage ranged from 0.6% to 1.2% by weight of binder.

As shown in Fig. 6, the viscosity of the cement paste with 20% FA is significantly lower than that of the control sample without FA. The difference in viscosity depends on the SP content used in the mixtures. Compared to the control sample, the viscosity reductions are 40.9%, 67.8%, and 68.4% for mixtures containing 0.6%, 1.0%, and 1.2% SP by weight of binder, respectively.

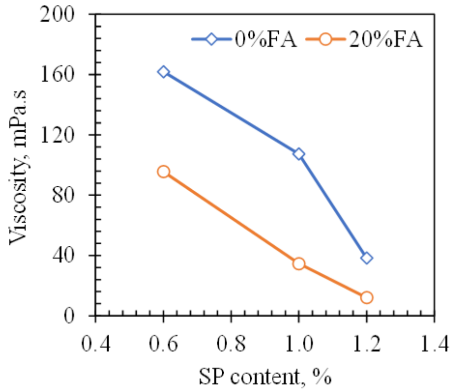


Figure 6. Effect of the SP content on viscosity of cement paste

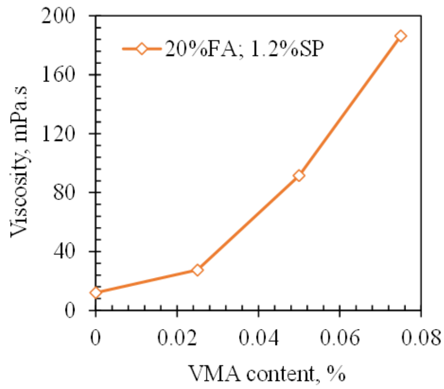


Figure 7. Effect of the VMA content on viscosity of cement paste

In addition, Fig. 7 also illustrates the influence of VMA content on cement paste viscosity. As expected, the addition of VMA increases the viscosity significantly. The viscosity increases from 12.1 mPa.s to 186.5 mPa.s (a 15-fold increase) as the VMA dosage increases from 0% to 0.075% by weight of binder. This confirms that VMA effectively modifies the viscosity of cement paste. VMA functions by increasing the internal friction within the paste, thereby elevating both the yield stress and plastic viscosity [21]. Consequently, the workability of concrete mixtures decreases with VMA addition. The combined effects of FA, SP, and VMA on EPS-C properties are presented in Table 5.

Table 5. The effect of FA, SP, and VMA on properties of EPS-C

Mix	The proportion of cement paste, wt% of binder				Viscosity of cement paste, mPa.s	Properties of EPS-C mixtures		Compressive strength of EPS-C, MPa	
	w/b	FA	SP	VMA		Slump, cm	Density, kg/m^3	7 days	28 days
Mix1	25	0	0.6	0	162.0	6.0	1560	16.6	21.5
Mix2	25	20	0.6	0	95.7	12.5	1466	14.8	19.3
Mix3	25	0	1.0	0	107.4	10.5	1515	15.5	20.4
Mix4	25	20	1.0	0	34.6	19.6	1460	14.0	17.6
Mix5	25	0	1.2	0	38.3	17.5	1520	14.7	18.5
Mix6	25	20	1.2	0	12.1	-	1468	28.6	40.1
Mix7	25	20	1.2	0.025	27.5	-	1485	20.4	33.5
Mix8	25	20	1.2	0.050	91.6	15.3	1480	13.8	18.6
Mix9	25	20	1.2	0.075	186.5	3.5	1502	15.2	20.2

3.2. Effect of viscosity of the cement paste on workability of EPS-C mixtures

Fig. 8 illustrates the relationship between cement paste viscosity and the workability of EPS-C mixtures. It is evident that concrete mixtures with a viscosity below 30 mPa.s exhibit significant segregation (refer to Fig. 9 for visual confirmation). In this low viscosity range, measuring the slump of the concrete mixture becomes impossible.

As the viscosity of the cement paste increases from 30 mPa.s to 50 mPa.s, the slump of the concrete mixture improves, reaching a range of 15−20 cm. Fig. 8 also demonstrates that the addition of FA improves the slump of EPS-C mixtures compared to the control sample without FA. This can be attributed to the spherical shape of FA particles, which acts like ball bearings to reduce friction between particles within the mix. Additionally, the fine FA particles fill the voids between cement particles, releasing some water and increasing the free water content in the mixture. This contributes to a higher viscosity of the cement paste and a significant improvement in the workability of the concrete mixture [10]. However, when the viscosity of the cement paste increases further, from 107.4 mPa.s to 162 mPa.s, the slump of the concrete mixture decreases, dropping from 10.5 cm to 6 cm.

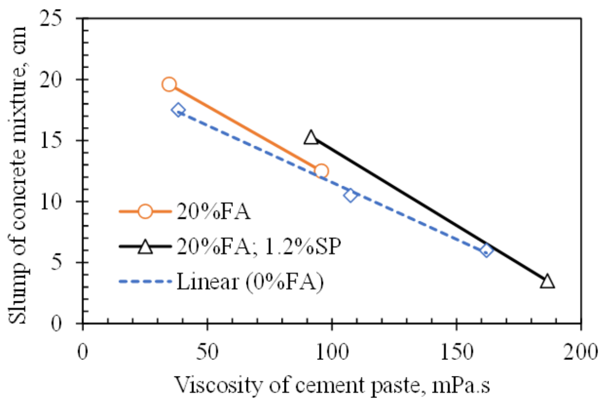


Figure 8. Effect of viscosity of cement paste on the workability of EPS-C mixtures

As shown in Table 5, the VMA content also influences the workability of EPS-C mixtures. Consistent with previous observations, the slump of the concrete mixture could not be measured when the viscosity of the cement paste was below 30 mPa.s, due to segregation in the mixture.

The addition of VMA increases the viscosity of the cement paste, as expected. For instance, with increasing VMA dosage from 0% to 0.075% by weight of binder, the viscosity increases from 12 mPa.s to 186 mPa.s, while the slump of the mixtures decreases from 15 cm to 3.5 cm. This confirms that VMA effectively reduces segregation in the concrete mixture.

However, the effect of VMA on workability is dependent on the dosage. While VMA content up to 0.05% improves the workability of the concrete mixture, further increases beyond 0.05% significantly reduce the slump. This is likely because excessive VMA increases the overall viscosity beyond an optimal level, hindering the movement of particles within the mix.

3.3. Effect of viscosity of cement paste on segregation of EPS-C mixtures

EPS-C is a composite material consisting of cement, water, admixtures, and EPS beads. The significant difference in density between these ingredients makes EPS-C mixtures susceptible to segregation during mixing. The ultra-light EPS beads tend to float on the surface of the concrete mixture. Controlling the viscosity of the mix is crucial for maintaining the homogeneity of EPS-C mixtures.

This study evaluates segregation by comparing the density of four horizontal slices cut by a machine along the vertical casting direction of the concrete sample with the bulk density of the original sample. The specific density (K_{SD}) is calculated for each slice. K_{SD} values below 0.95 or above 1.05 indicate segregation in the concrete [22].

Table 6 and Fig. 9(a) illustrate the influence of viscosity on the density and specific density distribution of the samples. The results indicate that segregation in the concrete mixtures occurs when the viscosity of the cement paste is lower than 50 mPa.s (Mix4 to Mix7), as evidenced by K_{SD} values either below 0.95 or above 1.05. Mix 6, with a cement paste viscosity of 12.1 mPa.s, exhibits the most significant segregation. The density of slices from this sample varies along the vertical casting direction, as shown in Fig. 9(b). EPS beads segregate to the surface, forming a low-density upper slice (K_{SD1} = 0.030), while the cement paste sinks to the bottom, increasing the density of the bottom slice

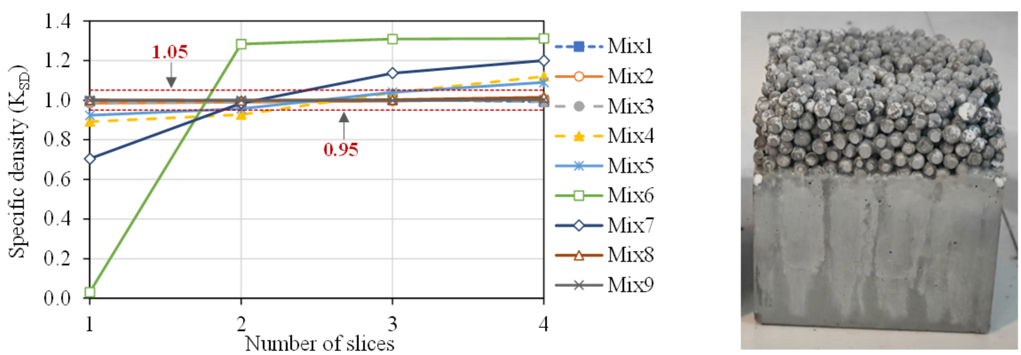
(K_{SD4} = 1.311). This sample clearly demonstrates the high level of segregation that occurs when the cement paste viscosity is insufficient.

Table 6. Specific density of EPS-C

No	Viscosity of cement paste, mPa.s	Density (kg/m^3)					Specific density of slice			
		Slice 1	Slice 2	Slice 3	Slice 4	**Sample density**	Slice 1	Slice 2	Slice 3	Slice 4
Mix1	162.0	1550	1546	1566	1548	**1560**	0.994	0.991	1.004	0.992
Mix2	95.7	1444	1452	1460	1476	**1466**	0.985	0.990	0.996	1.007
Mix3	107.4	1495	1502	1518	1503	**1515**	0.987	0.991	1.002	0.992
Mix4	34.6	1302	1354	1515	1635	**1460**	0.892	0.927	1.038	1.120
Mix5	38.3	1404	1454	1581	1656	**1520**	0.924	0.957	1.040	1.089
Mix6	12.1	44.5	1884	1921	1925	**1468**	0.030	1.283	1.309	1.311
Mix7	27.5	1046	1463	1688	1782	**1485**	0.704	0.985	1.137	1.200
Mix8	91.6	1482	1478	1483	1501	**1480**	1.001	0.999	1.002	1.014
Mix9	186.5	1501	1502	1499	1505	**1502**	0.999	1.000	0.998	1.002

Note: Underline values are outside the acceptable range (either smaller than 0.95 or higher than 1.05).

The addition of VMA effectively reduces this segregation phenomenon. The experimental results show a clear correlation: as the viscosity of cement paste increases with the VMA addition, the degree of segregation in the concrete mixtures tends to decrease correspondingly. This is evidenced in Fig. 9(a), where increasing the VMA dosage from 0.025% to 0.075% leads to an increase in the K_{SD} coefficient from 0.704 to above 0.999.



(a) Specific density of slices

(b) Segregation of Mix6 sample

Figure 9. Effect of viscosity on specific density distribution of EPS-C samples

3.4. Effect of FA, SP, VMA contents on compressive strength of EPS-C

The above experimental results demonstrate that the viscosity of the cement paste significantly influences the distribution of EPS beads, leading to variations in the degree of segregation and density of EPS-C mixtures. As shown in Fig. 10, the compressive strength of EPS-C specimens was evaluated at 7 and 28 days.

For the control mix without FA, a decrease in cement paste viscosity from 162 mPa.s to 107.4 mPa.s has minimal impact on the compressive strength. However, a significant decrease (15.3%) in compressive strength is observed when the viscosity drops to 38.3 mPa.s (Mix 5). This coincides with the high level of segregation observed in Mix6 (cement paste viscosity of 12.1 mPa.s), as indicated by the variation in slice densities in Table 6. The significant segregation in Mix6 likely contributes to the very high resulting compressive strength.

With an increased viscosity of the cement paste up to 95.7 mPa.s (Mix2), as indicated by the K_{SD} values in Table 6, the concrete mixture achieves homogeneity, and the compressive strength of the samples remains comparable to that of the control sample (Mix1). However, for concrete samples experiencing segregation yet exhibiting very high compressive strength, an explanation can be offered. The cement paste, constituting 65% of the sample volume, settles at the bottom, while the EPS beads float to the surface. Consequently, the hardened cement paste bears the load of the concrete, leading to a significant increase in the overall strength of the EPS-C.

The addition of VMA effectively increases the viscosity of the cement paste (over 90 mPa.s for Mix8 and Mix9). This improves the homogeneity of the concrete mixtures and promotes more stable compressive strength values for the EPS-C samples. Notably, when the mixture is homogeneous (as with increased VMA dosage), the compressive strength is not significantly affected by further VMA addition (up to 0.075%).

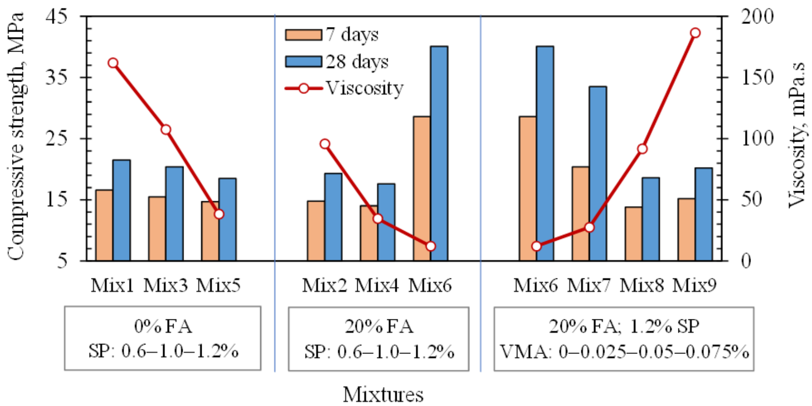


Figure 10. Compressive strength of EPS-C

4. Conclusions

This study investigated the influence of FA, SP, and VMA on the properties of EPS-C. The results highlight the importance of maintaining a suitable cement paste viscosity for achieving homogeneous mixtures. From the research results obtained, some conclusions can be drawn as follows:

- The addition of FA, SP decreases the viscosity of cement paste, while VMA significantly increases it. For instance, using 20% FA with 0.6% SP reduces the viscosity by 60% compared to the control mix. Conversely, VMA content increases the viscosity from 12.1 mPa.s to 186.5 mPa.s (a 15-fold increase) as the dosage increases from 0% to 0.075% by weight of binder. The optimal viscosity range to ensure workability and homogeneity in EPS-C mixtures is between 50 and 180 mPa.s.

- The viscosity of cement paste inversely influences the workability and the segregation of EPS-C mixtures. When the viscosity falls below 30 mPa.s, the slump of the concrete mixture becomes unmeasurable. Conversely, as the viscosity increases from 100 mPa.s to 186 mPa.s, the slump decreases rapidly, dropping from 10 cm to 3.5 cm.

- Segregation in EPS-C mixtures occurs at viscosities of cement paste below 50 mPa.s. The addition of VMA improves the segregation and stability of EPS-C mixtures. The specific density increases from 0.798 to above 0.95 with increasing VMA dosage from 0.025% to 0.075%. The recommended VMA content for optimal performance is between 0.05% and 0.075% by weight of binder.

- The viscosity of cement paste has a significant influence on the compressive strength of EPS-C. A viscosity below 30 mPa.s leads to severe segregation, which can unexpectedly lead to an increase in compressive strength up to 40.1 MPa. In contrast, a similar compressive strength to the control sample can be achieved with a higher viscosity range , from 50 to 180 mPa.s, as demonstrated by the increase in viscosity from 12.1 mPa.s to 95.7 mPa.s.

- The viscosity of cement paste greatly influences the compressive strength of concrete of EPS-C. The viscosity of concrete less than 30 mPa.s causes a significant segregation of the concrete mixture, and resulting in increasing the compressive strength of EPS-C up to 40.1 MPa. By increasing the cement paste viscosity from 12.1 mPa.s to 95.7 mPa.s, EPS-C can be produced with a compressive strength comparable to that of the control sample.

Acknowledgement

This research was financially supported by Hanoi University of Civil Engineering (Grant No. 03.2024-NNCM-ĐHXDHN). The authors gratefully acknowledge this support.

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