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Effect of the moisture states of artifical fly ash aggregate as a partial river sand replacement on bulk density and mechanical strengths of hardened concrete

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KEYWORDS

Artificial fine fly ash aggregate
Bulk density
Compressive strength
Flexural strength
Slump

ABSTRACT

In this study, artificial fly ash aggregate (FAA) under oven-dry (OD) and natural (N) states was employed for partially replacing natural river sand (RS) to investigate effect of moisture states of FAA on slump of fresh concrete, bulk density and mechanical strengths (i.e., flexural strength and compressive strength) of hardened concrete. The FAA with particle sizes ranging from 1.25 to 5 mm was made from 85% Class-F fly ash, 15% Porland cement, a water-to-binder ratio of 0.21, and cured for 1 day in air and 13 days in water condition. Compared with RS, density and bulk density of FAA were lower by 22.4 and 32.5%, respectively, while water absorption was significantly higher. Based on the particle size distribution results of fine aggregate mixtures (including FAA and RS), replacing RS with FAA at volume ratios of 20 and 40% were selected for producing concrete. The slump of fresh concrete with 20 and 40% replacements of FAA under the N state was higher than that with corresponding replacement of FAA in the OD state and the fresh control concrete without FAA had the highest slump. The use of FAA changed insignificantly bulk density at 28 days of hardened concrete, regardless of FAA moisture states. In contrast, the flexural strength at 28 days of hardened concrete declined when FAA content increased, and the difference in flexural strength of hardened concretes using FAA under different moisture states was in a range from 9.3 to 13.6%. Meanwhile, the compressive strength at 3, 7, and 28 days of hardened concrete tended to increase when using FAA in the OD state and decreased when using FAA in the N state. Consequently, 40% replacement of RS with FAA in OD state can be suggested for the concrete production to limit the exploitation of RS and utilize the most fly ash released from coal-fired power plants, towards sustainable development for the concrete industry.

1. Introduction

A significant demand of concrete use leads to depletion of natural resources such as RS. The natural river sand (RS) plays a role of densifying the concrete and enhancing its shrinkage resistance [1]. The RS is a finite resource and its natural regeneration cannot keep pace with current rate of use in Vietnam. Unless suitable solutions are suggested, this environmental issue will only worsen, leading to potential shortages of RS [2]. Several researchers are continuously exploring new-friendly materials to replace RS, aiming at eliminating environmental impact caused by over-exploitation of RS.

On the other hand, Vietnam is facing a serious environmental concern due to fly ash (FA) released from more than 40 thermal power plants [3]. In 2020, these plants produced over 25 million tons of FA [3]. Several research in terms of using FA as cement substitute in concrete production have been employed. For example, Nguyen et al. [4] identified a 20% FA replacement as an optimal content for commercial concrete properties. This replacement contributes to concrete meeting the desired consistency and compressive strength requirements. However, the utilized amount of FA is insignificant compared with its vast quantities released from coal-fired power plants.

To utilize a huge FA amount, Zhang et al. [5] investigated the use of FA as a replacement for natural RS in mortar. The study showed that replacing 80% of the RS by FA results in the optimal compressive strength at 90 days. Le et al. [6] also investigated the fabrication of fine FA aggregates (FAA) to replace RS at levels of 30% and 40% by volume of fine aggregate. The results showed that the compressive strength of concrete changes insignificantly, regardless of FAA replacement and the concrete with FAA exhibits a faster strength development rate at early ages than the control concrete without FAA.

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On the other hand, Ji et al. [7] found that the use of recycled fine aggregate (RFA) under different moisture states significantly affects the engineering properties of concrete, such as cracking resistance and compressive strength. This study found that the crack resistance of concrete using RFA under surface-saturated dry (SSD) state is enhanced when compared to that using RFA under oven-dried (OD) and air-dried (AD) conditions. Additionally, the compressive strength of concrete using RFA under SSD state at 7 and 28 days is higher than that using the corresponding RFA under OD and AD states, indicating the moisture state of fine aggregate significantly affects the engineering properties of concrete.

Therefore, this study aimed to utilize the most amount of FA to fabricate FAA as partial replacement of RS and examine the effect of FAA moisture states on slump of fresh concrete, bulk density and mechanical strengths (i.e., flexural strength and compressive strength) of hardened concrete, towards sustainable development for the concrete industry.

2. Experiments

2.1. Materials

2.1.1 For FAA fabrication

Cementitious materials used for manufacturing FAA included Porland cement (PC40) and Class-F fly ash conforming to TCVN 2682:2020 [8] and TCVN 10302:2014 [9] with a density of 3.1 and 2.3 g/cm^3, respectively. Chemical compositions of cement and fly ash are shown in Table 1. In addition, tap water meeting the requirement of TCVN 4506:2012 [10] was employed for fabricating the FAA.

Table 1. Chemical compositions of cement and fly ash (% by mass).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	SO_3	LOI
C	22.3	1.8	2.7	65.7	0.1	0.7	1.2	1.6	2.6
FA	64.8	21.7	5.5	1.0	1.7	2.3	3.4	0.1	2.5

C: cement; FA: fly ash; LOI: loss on ignition

2.1.2 For concrete production

A cementitious material used in this study was Portland cement (PC40) which was the same as the cement used for the FAA fabrication as described in section 2.1.1. Natural RS and crushed stone as fine and coarse aggregates, respectively, with physical characteristics meeting requirements specified in TCVN 7570:2006 [11]. Density and bulk density of RS were 2.63 and 1.51 g/cm^3 and those of crushed stone corresponded to 2.74 and 1.48 g/cm^3, respectively. The RS was prepared in the saturated-surface dry (SSD) state before mixing concrete. Particle size distributions of fine and coarse aggregates are given in Figures 1 and 2Figure , respectively. Additionally, the artificial FAA was used to replace partially RS for concrete production. A mixture proportion, fabrication process, and engineering properties of FAA are described in sections 2.2.1, 2.3.1, and 3.1, respectively.

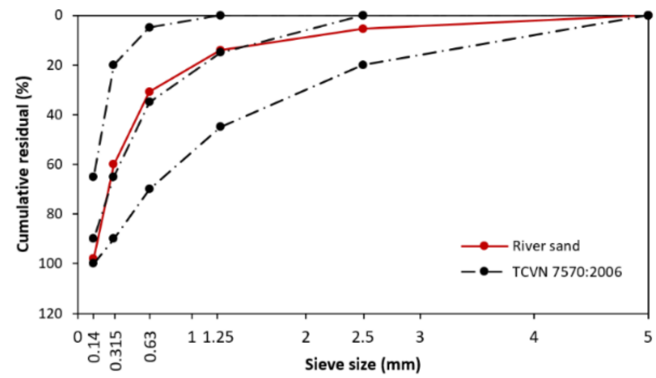

Figure 1. Particle size distribution of natural river sand compared with TCVN 7570:2006. [11]

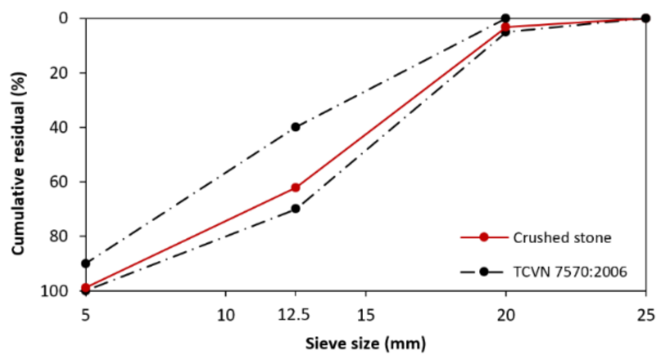

Figure 2. Particle size distribution of crushed stone compared with TCVN 7570:2006. [11]

2.2. Mixture proportions

2.2.1 FAA

The FAA was made from 85% Class-F fly ash and 15% Portland cement according to previous research of Gesoğlu et al. [12] and Nguyen and Ho [13]. A water-to-binder ratio for FAA fabrication was 0.21 following to trial experiments with the amounts of Class-F fly ash and Portland cement as shown in Table 2.

Table 2. Mixture proportion of FAA.

Fly ash (kg)	Cement (kg)	Water (L)
1282	226	317

2.2.2 Concrete

A mixture proportion for the control concrete without FAA was determined according to ACI 211 [14] to have a designed slump of 12±2 cm and a 28-day compressive strength of 35 MPa. Based on the particle size distribution results of fine aggregate mixtures (including FAA and RS) as shown in section 3.1, replacing RS with FAA at volume ratios of 20 and 40% were selected for producing concrete. Two moisture states of FAA were OD and natural (N) states. The specific mixture proportions of concretes are listed in Table 3. According to Table 3, notation of concrete mixture proportions is xFy in which x is percentage of FAA replacement, F is FAA, and y is moisture state of FAA.

Table 3. Mixture proportions of the concretes

Mixture proportion	%FAA	Unit: kg/m^3				
		Water	Porland cement	Fine aggregate	FAA	Coarse aggregate
0F	0	208	328	774	0	1032
20FOD	20	208	328	620	115	1032
40FOD	40	208	328	465	230	1032
20FN	20	208	328	620	115	1032
40FN	40	208	328	465	230	1032

2.3. Production processes

2.3.1 FAA

The raw materials (i.e., Portland cement and Class-F fly ash) after quantifying by using a technical balance, were mixed thoroughly for 2 minutes (i.e., 120 seconds) in a mechanical mixer to reach the uniform-dry mixture. After that, the dry mixture was thoroughly mixed by using a pelletizer along with tap water sprayed regularly until the complete formation of FAA particles having a size ranging from 1.25 to 5.0 mm. After pelletizing, the FAA was cured in air condition for 1 day and thereby cured in water condition for next 13 days to test engineering properties of FAA. Figure 3 describes the process of making FAA.

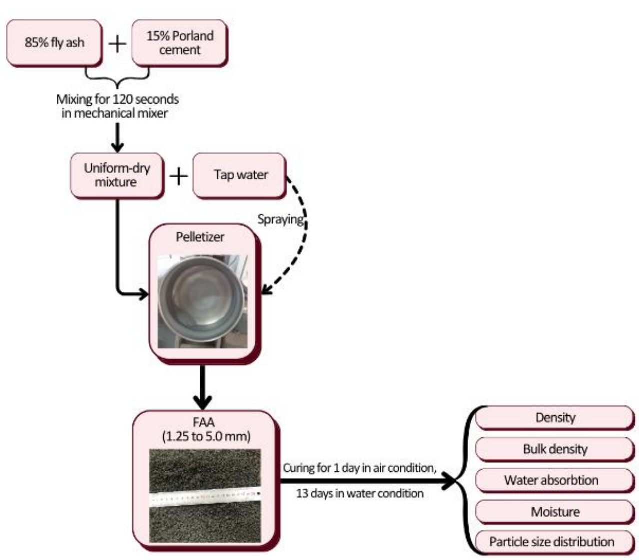

Figure 3. Process of making FAA

2.3.2 Concrete

A procedure of making concrete was done within six steps as follows: (1) quantifying all materials by a technical balance; (2) after mixing cement and fine aggregate (RS or a mixture of RS and FAA) for the first 30 seconds, water was added to the mixer and mixed for further 30 seconds at high speed in order to achieve a uniform fresh mortar; (3) adding crushed stone to mix for 60 seconds; (4) mixing all the components for the last 180 seconds to achieve a uniform fresh concrete and immediately testing the consistency of fresh concrete and casting concrete specimens; (5) the specimens were all cured in air condition for 20±4 hours; and (6) all the specimens were demolded and then cured in normal water condition at 27±2 °C until testing properties at designated ages as described in section 2.4.2.

2.4. Test methods

2.4.1 Properties of FAA

Engineering properties of FAA including density, bulk density, water absorption, moisture, and particle size distributions of FAA were measured following TCVN 7572:2006 [15]. In addition, particle size distribution of various mixtures including RS and FAA, in which FAA was replaced RS at various ratios of 0, 10, 20, 30, 40, and 50% by volume of fine aggregate to determine their fineness modulus and optimum particle size distributions.

2.4.2 Properties of concrete

The slump of fresh concrete was tested according to TCVN 3106:2022 [16] with the steps as follows: (1) moistening the inside of the Abram cone and putting it on a smooth level; (2) filling the cone with a fresh concrete corresponding to each mixture proportion as shown in Table 3, within 3 layers and tamping 25 times for each layer by using a steel rod to help the fresh concrete fully settle and allow any air to escape; (3) scraping off excess concrete and slowly lifting the cone away from the fresh concrete; (4) putting the cone beside the fresh concrete; and (5) measuring the slump of fresh concrete.

Bulk density of hardened concrete at 28 days was tested according to TCVN 3115:2022 [17]. After water curing for 27 days, cubic concrete specimens were taken out from the water bath for removing the surface moisture with air condition. The cubic concrete specimens then were weighed and their dimensions were measured to calculate the volume based on their shape. Bulk density value of concrete is an average value of three samples calculated through a ratio of mass-to-volume.

Mechanical strengths of concrete included the flexural strength at 28 days, and compressive strength at 3, 7, and 28 days corresponding to each mixture proportion as shown in **Table 3**. The flexural strength test was done according to TCVN 3119:2022 [18] with a uniform load at a rate range of 50–10 N/s until fracture. Meanwhile, a loading rate for testing compressive strength according to TCVN 3118:2022 [19] was in a range from 400 to 600 N/s until failure occurred. Each strength value was an average of three samples corresponding to each mixture proportion at each age.

3. Results and discussion

3.1. Engineering properties of FAA

Table 4 describes the engineering properties of FAA including density, bulk density, water absorption, and moisture. Compared with RS, density and bulk density of FAA were lower by 22.4 and 32.5%, respectively, while water absorption of FAA was significantly higher than that of RS. The results aligned with previous research of Luu et al. [20] who observed that both the density and bulk density of FAA were lower than those of RS.

Table 4. Engineering properties of FAA and RS

Engineering properties	FAA	RS
Density (g/cm^3)	2.04	2.63
Bulk density (g/cm^3)	1.02	1.51
Water absorption (%)	16.21	2.33
Moisture (%)	15.61	-

-: no experiment

Figure 4 shows fineness modulus of fine aggregate mixtures including FAA and RS which was replaced with FAA at various ratios of 0 (0FAA), 10 (10FAA), 20 (20FAA), 30 (30FAA), 40 (40FAA), and 50% (50FAA) by volume of fine aggregate. The fineness modulus of fine aggregate mixture increased from 2.08 to 3.19 when the FAA amount increased from 0 to 50% by volume of fine aggregate. This was because of the coarser particle sizes of FAA which was controlled to be between 1.25 and 5 mm during the fabrication process as described in section 2.3.1, than those of RS.

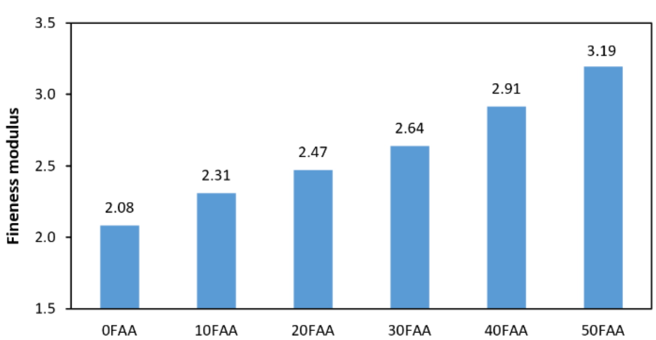

Figure 4. Fineness modulus of fine aggregate mixtures including FAA and RS replaced with FAA at 0 (0FAA), 10 (10FAA), 20 (20FAA), 30 (30FAA), 40 (40FAA), and 50% (50FAA) by volume of fine aggregate.

Figure 5 displays the particle size distributions of fine aggregate mixtures including FAA and RS which was replaced with FAA at 0 (0FAA), 10 (10FAA), 20 (20FAA), 30 (30FAA), 40 (40FAA), and 50% (50FAA) by volume, comparing to TCVN 7570:2006 [11].

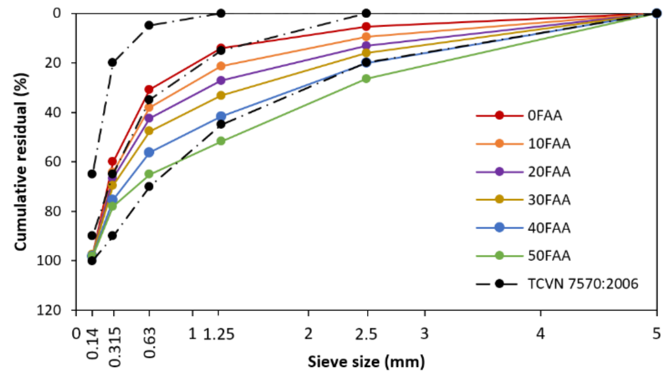

Figure 5. Particle size distribution of fine aggregate mixtures including FAA and RS replaced with FAA at 0 (0FAA), 10 (10FAA), 20 (20FAA), 30 (30FAA), 40 (40FAA), and 50% (50FAA) by volume, comparing with TCVN 7570:2006 [11].

The replacements of RS with FAA in the range from 10% to 40% by volume proved to be within the allowable limits for fine aggregate having coarse size according to TCVN 7570:2006 [11]. Therefore, this study decided to research the effect of artificial FAA replacement at volume ratios of 20% and 40% on the slump of fresh concrete, the bulk density, and mechanical strengths of hardened concrete up to 28 days.

3.2. Engineering properties of concrete

3.2.1 Slump of fresh concrete

Figure 6 describes slump of fresh concretes with 0, 20, and 40% replacements of FAA under OD and N states. The slump of fresh control concrete without FAA (0F) was 12.0 cm, meeting the designed slump in a range of 12±2 cm. The slump of fresh concrete declined when the FAA replacement increased, regardless of moisture states. The use of FAA under N state increased the slump value when compared with that of FAA under OD state. Specifically, the slump of fresh concretes with 20 and 40% replacements of RS with FAA under OD state corresponded to 9.0 and 5.0 cm, which was lower by 25.0 and 58.3%, respectively, when compared with that of fresh control concrete without FAA (0F). Meanwhile, the fresh concrete with 20 and 40% replacements of RS with FAA under N state exhibited slump values of 10.5 and 7.0 cm, respectively. These values were lower by 12.5 and 41.7%, respectively, when compared to the fresh control concrete without FAA (0F). The workability of fresh concrete decreased as the FAA amount increased because of moisture states including OD and N of FAA which absorbed a part of mixing water of fresh concrete. The difference in slump value of fresh concrete using FAA in different state was due to the inherent moisture content of FAA under N state. The FAA under N state already contained some water, while that under OD state did not have water, leading to FAA under OD state which greatly absorbed mixing water.

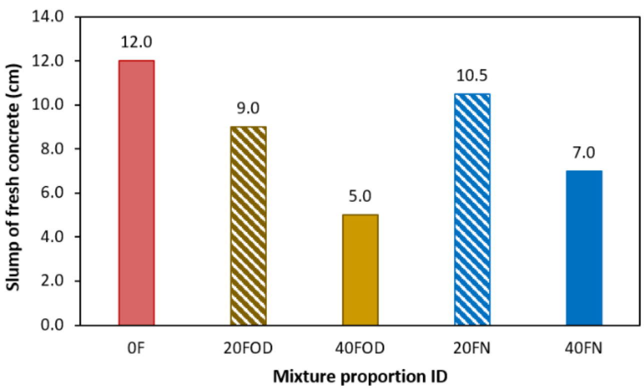

Figure 6. Slump of fresh concretes with 0, 20, and 40% replacements of FAA under OD and N states.

3.2.2. Bulk density of concrete

Figure 7 shows bulk density at 28 days of hardened concretes with 0, 20, and 40% replacements of FAA under OD and N states. The bulk density at 28 days of hardened concretes with 0, 20, and 40% replacements of FAA under OD and N states were in a range from 2450 to 2541 kg/m^3, indicating all the concretes in this study was heavy-weight concretes. Although the bulk density of FAA was lower by 32.5% than that of RS as shown in Table 4, the FAA use had no significant influence on the bulk density of hardened concrete, regardless of moisture states, with a difference of less than 5%. This can be due to the low replacements (i.e., 20 and 40% by volume) of RS with FA while the amounts of the other raw materials such as Portland cement, tap water, and coarse aggregate were kept constant as shown in Table 3.

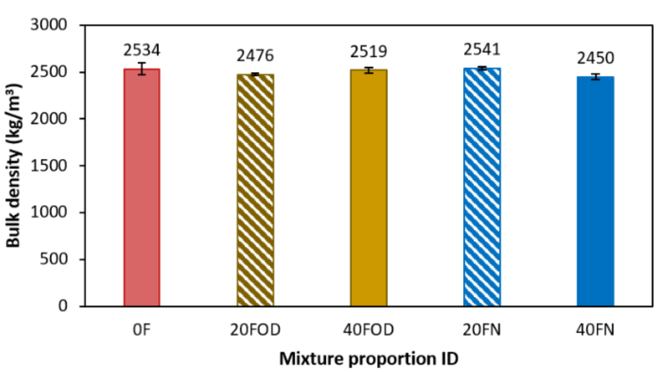

Figure 7. Bulk density at 28 days of hardened concretes with 0, 20, and 40% replacements of FAA under OD and N states.

3.2.3. Mechanical strengths

Figures 8 and 9 display the flexural strength and compressive strength up to 28 days of hardened concretes with 0, 20, and 40% replacements of FAA under OD and N states, respectively. The flexural strength of hardened concrete decreased when the FAA amount increased. Compared with the control concrete without FAA (0F), the replacement of RS with FAA in OD and N states at 20% by volume decreased the flexural strength at 28 days by 18.2 and 25.8%, respectively. At a 40% replacement level, the reductions were 17.7% and 28.9%, respectively. The lower flexural strength of hardened concrete with FAA could be due to the round shape of FAA particles reducing the bonding capacity of aggregate in the matrix. Additionally, the flexural strength of hardened concretes using FAA under OD state was higher by 9.3–13.6% than that using FAA under N state, indicating the moisture state of FAA contributed to flexural strength of hardened concrete.

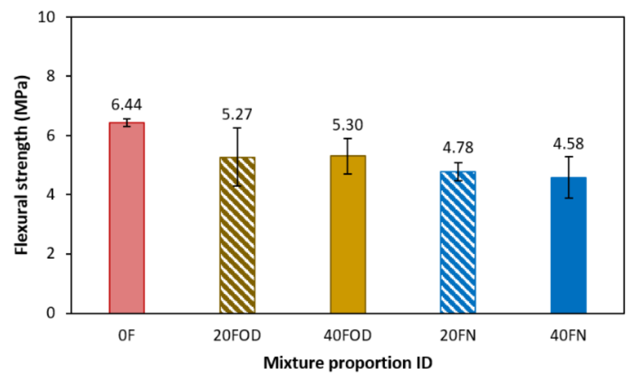

Figure 8. Flexural strength at 28 days of hardened concretes with 0, 20, and 40% replacements of FAA under OD and N states.

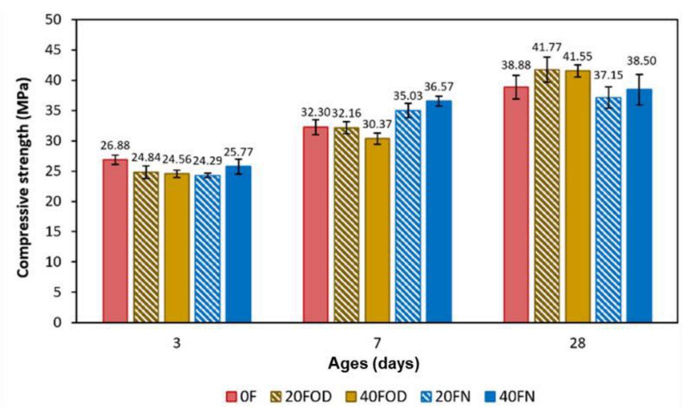

Figure 9. Compressive strength of hardened concretes with 0, 20, and 40% replacements of FAA under OD and N states at 3, 7, and 28 days.

According to Figure 9, the compressive strength of hardened concrete increased as the curing age increased, confirming that the hydration of Portland cement continuously proceeded with time. At the age of 28 days, compressive strength of control concrete without FAA (0F) was 38.88 MPa, meeting the designed strength of 35 MPa. At 3 days, the compressive strength of hardened concrete with FAA under both OD and N states was lower by 4.1–9.6% than that of control concrete. The lower compressive strength of hardened concrete with FAA could be due to the round shape of FAA reducing the bonding capacity of aggregate in the matrix, similar to flexural strength results. However, at 7 days, the compressive strength of hardened concrete with

FAA under OD state was nearly the same as that of control concrete, while that of hardened concrete with FAA under N state was higher by 8.5–13.2%. At 28 days, the concrete with 20% and 40% replacements of FAA under OD state had compressive strengths reaching 41.77 and 41.55 MPa, increasing approximately 7.4% and 6.9%, respectively. Meanwhile, that with 20% and 40% replacements of FAA under N state showed compressive strengths of 37.15 and 38.5 MPa, decreasing approximately 4.4% and 0.9%, respectively. This result could be attributed to FAA absorbing more mixing water than RS under SSD state. This "pre-absorbed" water in FAA under OD and N states helped the concrete internally cure and improve the compressive strength development. However, FAA under N state did not absorb much mixing water when compared to that under OD state. This extra water in concrete with FAA under N state could evaporate earlier, creating tiny voids and slightly reducing the later compressive strength compared to the concrete with FAA under OD state.

4. Conclusions

The use of FAA decreased the slump of fresh concrete and flexural strength at 28 days of hardened concrete, regardless of various moisture states and FAA replacements. The use of FAA changed insignificantly bulk density at 28 days of hardened concrete, regardless of various moisture states and FAA replacements. The use of FAA significantly affected the compressive strength of hardened concrete up to 28 days.

The use of FAA under the N state contributed to a higher slump of fresh concrete than that of FAA under the OD state. Meanwhile, the use of FAA under the OD state contributed to higher mechanical strengths at 28 days of hardened concrete than that of FAA under the N state.

Consequently, 40% replacement of RS with FAA in OD state can be suggested for the concrete production to limit the exploitation of RS and utilize the most fly ash released from coal-fired power plants, towards sustainable development for the concrete industry.

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