Pelletized fly ash aggregates use for making eco-friendly concrete

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Abstract. Today Vietnam is facing a seriously environmental challenge in handling fly ash and bottom ash from coal power plants with annual emissions of up to 15 million tons. Using the coal ashes to produce building materials is considered a main solution for this issue. Due to shortage of natural aggregates, using the ashes as aggregates in concretes achieves many benefits. This paper presents research results of pelletizing fly ash to produce an aggregate for concrete. The fly ash aggregates had strength of about 3.1 MPa, apparent specific gravity of 2.1 g/cm³, bulk dry specific gravity of about 1450 kg/m³ and water absorption nearby 22%. The concrete made from a combination of fly ash and bottom ash aggregates had the density of about 2000kg/m³ and the compressive strength of 17.5-46.3 MPa at 28 days. Moreover, the aggregates were also applicable to manufacture ACOTEC wall panel with properties met requirements of TCVN 11524:2016.

1. Introduction
Aggregate is not only an inert filler but also play important roles in contributing to properties of concrete. It usually occupies 60 to 80 percent of the volume in concrete. Nowadays, the demand of aggregates rapidly increases due to construction development while the resources of natural aggregate more and more decrease. Therefore, it is necessary to find new source of aggregate and one of solutions is using wastes to produce artificial materials.

Coal ash is produced from the burning of coal in coal power plants. Fly ash (FA) is a light form of coal ash that floats into the exhaust stacks. Bottom ash (BA) is the heavier portion of coal ash that settles on the ground in the boiler. BA is molten ash that turns into pellets when cooled with water. Coal ash has about 80% FA and 20% BA.

In the fact, the source of FA and BA connect tightly with the development of the coal power plants. Nowadays, there are 19 thermal power plants with capacity total are nearly 14,500MW in Vietnam, so it means that the amount of the coal ash could be around 15 million tons per year. According to the forecasts, the number of this waste will increased to 30 million ton per a year by the 43 plants after 2020 [1].

Many researchers play attention to produce artificial aggregate from fly ash for concrete. The aggregate particle is usually pelletized from a mixture of FA and a binder such as cement or clay. Then the aggregate with cement may be cured by steam or standard temperature-humidity conditions [2] [3] [4]. It is get strength due to hydration process and called non-fired aggregate. In the other way, particles with clay binder would be burned and called fired aggregate. The density of these fly ash
aggregates is usually smaller than that of natural aggregates. That causes significantly reducing density but remains mechanical properties of concrete such as strength, durability, etc. [5] [6] [7].

This research focused on producing a non-fired aggregate from fly ash for ACOTEC wall panel. That product is increasingly used in Vietnam. The research results may promise to an effective application of this aggregate in terms of technique and environment.

2. Material and methods

2.1. Materials

The materials that were used in the study included FA of Pha Lai coal power plant, BA of Mao Khe coal power plant, blended Portland cement PCB40 of Cam Pha cement JSC., and super plasticizing admixture HV313 of BiFi JSC.

Class F fly ash was used confirming to ASTM C 618-19, whose oxides content (SiO₂+Al₂O₃+Fe₂O₃) of 87.8%, 0.1% sulfur trioxide (SO₃) and strength activity index of FA was 84.2% at 28 days. The properties of FA are shown in table 1.

| Properties | Fineness (amount retained when wet-sieved 45μm), % | Strength activity index, % | Water requirement, % | Density, g/cm³ |
|------------|-----------------------------------------------|--------------------------|---------------------|----------------|
| Value      | 23.2                                          | 80.4                     | 84.2                | 96             | 2.23           |
| ASTM C618-19 (class F) | ≤ 34                              | ≥ 75                     | ≥ 75                | ≤ 105          | -              |

The BA from the Mao Khe plant was crushed and sieved to get 1.9 of fineness modulus. This material had apparent specific gravity about 2.42 g/cm³, bulk specific gravity of 1,160 kg/m³ and voids of 47.4%. The crushed BA was used as a fine aggregate to produce concrete.

The blended Portland cement had compressive strength of 43MPa, consistency of 28.5%, and soundness of 1.8mm. Those are met requirements of TCVN 6260: 2009-Portland blended cement-Specifications. The cement was used to make FA aggregates and also used as binder for concrete.

2.2. Methods

Pelletizing is the most effective methods to make the FA aggregate. In fact, there are several ways to pellet FA aggregates such as FA mixing with liquid binder, or FA and cement mixing with semi-wet before feeding to the pelletizer machine, etc. [8]. The method of semi-wet mixing was chosen due to higher effective and easier control to pellet aggregate particles. The detail steps were as below:

- First, powder (FA and cement) were blended then about 70% amount of water was supplied for initial moisture requirement;
- Next, each mixture was fed into pan-type pelletizer;
- Lastly, the 30% amount of water was fed in pelletizing process.
The aggregates were pelleted by a machine (see Figure 1) which has a disk with 1.5m of diameter and 0.3m of depth, 0.5 to 0.8 tons per hour of capacity, and a motor power rating of 5.5kW. The angle of disc could be varied from 40 to 65 degree, and rotation speed of disk can be changed from 15 to 22rpm.

Scanning Electron Microscopic (SEM), chemical analysis, X-ray diffraction analysis were carried out to study the microstructure of the FA aggregates.

3. Results and discussions

3.1. Determine the pelletizing capability of FA aggregates

3.1.1. Effects of pelletizer parameter. The parameters of machine were adjusted to figure out a suitable condition for making the aggregates. A ratio of cement to fly ash (C: FA) at 15: 85 was chosen to test and amount of water was changed during the experiment process. The period of rotation was fixed at 5 minutes, the amount of powder was 5 kilograms, rotation speed was changed from 15 to 22 circle per minute, angle of pan inclined from 22 to 40 degree.

Based on observation, it can be seen that the mixture was not cohesive in condition of slow rotation and small angle of pan. When the angle was increase, the mixture could be pelletized but productivity was low. On the contrary, particle size became bigger but numerous amount of mixture was still not pelletized in condition of fast rotation and small angle. When the angle was raised, not only aggregates were made quickly with smooth surface, equal size, but also productivity was increased. The results
indicated that the most appropriate condition to pelletize was the ratio of water to powder (W/P) at 21%, angle of machine at 40 degrees, and rotation speed at 22 cycles per a minute.

3.1.2. Effects of ratio C: FA and water content. The composition of mixture was varied to investigate the effects of material contents to pelletizing capacity. The ratio C: FA were changed at 10:90, 15:85, 20:80, 30:70 and the ratio W/P was varied in the range of 18-22%. At each mixture, the amount of water was increased gradually. When amount of water was small, the mixture was dry and not cohesive. At the optimum moisture, the pelletized aggregates were smooth, equal size and there was not residual mixture. However, when the amount of water was excessive, particles were wet and cohesive together to increase size. Furthermore, the pelletizing process would fail if water was continuously supplied. The mixtures with the most appropriate content of water is given in Table 2.

| Mix | Cement, % | Fly ash, % | Water, % | Apparent specific gravity, g/cm³ | Dry bulk specific gravity, g/cm³ | Saturated bulk specific gravity, g/cm³ | Absorbed water, % | Crushing force, kN |
|-----|-----------|------------|----------|----------------------------------|---------------------------------|---------------------------------------|------------------|-------------------|
| CP1 | 10        | 90         | 22.0     | 2.04                             | 1.42                            | 1.76                                  | 23.0             | 44.0              |
| CP2 | 15        | 85         | 21.0     | 2.10                             | 1.44                            | 1.74                                  | 21.1             | 57.6              |
| CP3 | 20        | 80         | 20.5     | 2.17                             | 1.46                            | 1.75                                  | 20.1             | 89.6              |
| CP4 | 30        | 70         | 19.5     | 2.21                             | 1.46                            | 1.73                                  | 18.9             | 108.5             |

The results shown that if the C: FA ratio was increased; the required water would decrease. In fact, the amount of cement was 10%, 15%, 20% and 30% so the suitable content of water was 22%, 21%, 20.5% and 19.5%, respectively.

The mixture composition with C: FA= 15:85 and W/P= 21% was chosen to do the next step of experiment due to some following reasons:

- The aggregate particles looked good and pelletized productivity was better;
- Strength of aggregate had good enough met technical requirements of aggregate;
- High amount of fly ash could be used to produce the aggregate.

After pelletizing, the aggregates were cured in room condition and the humidity evaporation was prevented until the testing day. The properties of the aggregates were determined in accordance to TCVN 7572:2006, but the strength of aggregate is determined by BS 812-111:1990. The properties of aggregate are presented in Table 3 and the picture of FA aggregate product is shown in Figure 2.

| Time | Specific gravity, g/cm³ | Dry bulk specific gravity, g/cm³ | Saturated bulk specific gravity, g/cm³ | Absorbed water, % | Crushing force, kN | Crushing strength, MPa |
|------|------------------------|-------------------------------|--------------------------------------|------------------|-------------------|-----------------------|
| 1 day| 2.36                   | 1.59                          | 1.79                                 | 17.3             | 35.0              | 2.0                   |
| 3 days| 2.29                  | 1.54                          | 1.75                                 | 19.6             | 40.8              | 2.3                   |
| 7 days| 2.14                   | 1.46                          | 1.75                                 | 20.1             | 47.3              | 2.7                   |
| 14 days| 2.11                  | 1.42                          | 1.73                                 | 21.4             | 50.6              | 2.9                   |
| 28 days| 2.09                   | 1.43                          | 1.74                                 | 22.1             | 54.2              | 3.1                   |
| 56 days| 2.13                   | 1.44                          | 1.74                                 | 21.9             | 59.5              | 3.4                   |
Figure 2. Pelletized fly ash aggregate

At 28 days, the aggregates were sieved to 3 particle grades including 2.5-5 mm, 5-10 mm and 10-20 mm. The properties testing of each particle size of FA aggregate is presented in Table 4.

| Particle size, mm | Specific gravity, g/cm³ | Dry bulk specific gravity, g/cm³ | Saturated bulk specific gravity, g/cm³ | Absorbed water, % | Bulk specific gravity, g/cm³ | Voids, % | Crushing force, kN | Compressive strength, MPa |
|-------------------|-------------------------|---------------------------------|---------------------------------------|------------------|-------------------------------|--------|-------------------|-------------------------|
| 2.5-5             | 2.14                    | 1.43                            | 1.75                                  | 22.4             | 1.125                         | 21.3    | 37.9              | 2.1                     |
| 5-10              | 2.08                    | 1.41                            | 1.72                                  | 21.8             | 1.100                         | 22.0    | 41.3              | 2.3                     |
| 10-20             | 2.11                    | 1.43                            | 1.74                                  | 23.1             | 1.085                         | 24.1    | 47.9              | 2.7                     |

In Figure 3, the microstructure of the aggregate shows uniform distribution of fly ash in the structure of the aggregate.

Figure 3. SEM images of the FA aggregate

Moreover, the chemical analysis shown that the most of mineral ingredients of the FA aggregate is amorphous phase SiO₂ (68%), and last content were low with different minerals such as quartz, mullite, calcite, etc. The result of X-ray diffraction analysis in Figure 4 also shown the principle crystalline minerals of the aggregate such as quartz, mullite, calcite, etc.
3.2. Using the aggregate to make eco-friendly concrete

In this study, the two methods including volume method and absolute volume method [9] were used to design concrete mixture. That would evaluate the capability of using the fly ash aggregates in concrete. With the purpose to replace all natural aggregates of the concrete by the artificial ones, combinations of FA and BA aggregates were used as coarse and fine aggregates respectively. Composition and some properties of concretes that are given in the table 5 and table 6.

Table 5. Compositions of the concrete mixtures

| Mix. | Cement, kg | Fly ash powder, kg | Coarse sand, kg | Bottom ash aggregate, kg | Fly ash aggregate, kg | Water, kg | Superplasticizer, kg |
|------|------------|--------------------|----------------|--------------------------|----------------------|-----------|----------------------|
| CP1  | 339        | 95                 | 92             | 0                        | 772                  | 286       | 2.71                 |
| CP2  | 318        | 59                 | 394            | 0                        | 792                  | 187       | 1.27                 |
| CP3  | 355        | 66                 | 346            | 0                        | 819                  | 202       | 1.07                 |
| CP4  | 430        | 0                  | 0              | 653                      | 1008                 | 111       | 2.15                 |
| CP5  | 500        | 0                  | 0              | 614                      | 947                  | 129       | 2.50                 |
| CP6  | 437        | 0                  | 0              | 697                      | 792                  | 254       | 2.50                 |
| CP7  | 526        | 0                  | 0              | 625                      | 654                  | 254       | 3.30                 |
| CP8  | 510        | 0                  | 0              | 679                      | 710                  | 250       | 3.00                 |

As shown in Table 6, the concrete had density of about 2000kg/m³ and compressive strength of 17.5-46.3 MPa at 28 days with different content of cement. When the amount of FA aggregates increased, the number of required water decreased. The result indicated that the combination of FA and BA aggregates can replace for natural aggregates effectively.

Table 6. The properties of concretes

| Mix. | Slump, cm | Volume density, kg/m³ | Compressive strength, MPa | Blending strength, MPa |
|------|-----------|------------------------|---------------------------|------------------------|
|      |           |                        | 1 day 3 days 7 days 14 days 28 days 3 days 7 days 14 days |
| CP1  | 7         | -                      | - - - - 31.0 - - - - |

Figure 4. The X-ray diffraction of the fly ash aggregate
3.3. An application of FA aggregates

To evaluate application ability of the fly ash aggregate, it is replaced entire grit of concrete mixture to produce ACOTEC wall panel in a production line of Xuan Mai Concrete company. According to of the ACOTEC technological requirement, size of aggregate must be less than 7 mm, the slump of the fresh concrete is zero. Therefore, other mixture compositions were designed as given in table 7.

| Mix. | Cement, kg | Bottom ash aggregate, kg | Fly ash aggregate, kg | Water, kg | Admixture, kg | Moisture, % |
|------|------------|--------------------------|----------------------|-----------|---------------|-------------|
| A    | 350        | 940                      | 480                  | 110       | 1.75          | 5.3         |
| B    | 350        | 950                      | 520                  | 120       | 1.75          | 5.8         |
| C    | 350        | 900                      | 560                  | 95        | 1.75          | 5.0         |

The dimensions of ACOTEC walls were 3000x 600x 140mm as the length, width and thickness respectively. They had averagely 1150 kg/m$^3$ of density, 160 kg/m$^3$ of weight, 9.1% of absorbed water over 100kg of bearing capacity, and over 25MPa of compressive strength at 28 days. Generally, the properties of the walls made from fly ash and bottom ash aggregates were reached to requirements of the standard TCVN 11524:2016- Precast extrusion concrete hollow core wall panels. The cross section of the ACOTEC panel specimen is shown in Figure 5.

**Figure 5.** Cross section of the ACOTEC wall using coal ash aggregates

4. Conclusions

Based on research results, the following conclusions can be drawn:

- The pelletized fly ash aggregates were successfully produced, and the most appropriate composition of mixture was FA: C: W= 85: 15: 21 by weight. The fly ash aggregate had 3.1 MPa of crushing strength, 1450 kg/m$^3$ of dry bulk specific gravity, and 22% of water absorption at age of 28 days.
- The eco-friendly concrete using fly ash aggregates had about 2000 kg/m$^3$ of density and 17.5-46.3 MPa of compressive strength at 28 days.
- The combination of fly ash aggregates and bottom ash aggregates could be replaced for entire aggregate to produce ACOTEC wall panels with properties met requirement of TCVN 11524:2016.

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