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COMPARISON OF PHYSICAL AND MECHANICAL PROPERTIES OF COLD BONDED AND SINTERED LIGHTWEIGHT ARTIFICIAL AGGREGATES

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ABSTRACT

Production of artificial aggregate which has the highest volume ingredient in concrete has gained great importance in the last decades. The fundemental cause for this is to reduce harmful environmental impacts. In addition, artificial aggregates are tried to be used to improve some important features of concrete. In the present study, the physical and mechanical properties of two types of artificial aggregates produced by cold bonding and sintering methods were compared. For this purpose, artificial aggregates pelletized and sintered at different temperatures were produced by using fly ash at different percentages. Dry density, specific density, water absorption and crushing strength tests were carried out to investigate the physical and mechanical properties of the produced artificial aggregates. The results showed that the bulk density and density values of sintered Fly ash artificial aggregates have a trend of rising but the water absorption values have a decreasing trend. The minimum and maximum density values were observed as for 50% sintered at 900 ºC and 20 % cold bonded artificial lightweight aggregates respectively. Moreover the highest crushed strength value was measured as 945 N in samples with 50% Fly ash sintered at 900 ºC.

Keywords: *Artificial aggregate, Fly ash, Cold bonded, Sintered, Water absorption, Crushed Strength*

SOĞUK BAĞLAMA VE SİNTERLEME YÖNTEMİ İLE ÜRETİLMİŞ HAFİF YAPAY AGREGALARIN FİZİKSEL VE MEKANİK ÖZELLİKLERİNİN KARŞILAŞTIRILMASI

ÖZET

Beton içerisinde en yüksek hacme sahip olarak yer alan agregaların yapay olarak üretimi son yıllarda çok büyük bir önem kazanmıştır. Bunun başlıca sebebi zararlı çevresel etkileri azaltmaktır. Ayrıca betonun bazı önemli özelliklerini iyileştirmek için de yapay agregalardan faydalanılmaya çalışılmaktadır. Bu çalışmada soğuk bağlama ve sinterleme yöntemi ile üretilmiş iki tür yapay agreganın fiziksel ve mekanik özellikleri kıyaslanmıştır. Bu amaçla farklı oranlarda uçucu kül kullanılarak pelletlenmiş ve farklı sıcaklıklarda sinterlenmiş yapay agregalar üretilmiştir. Üretilen yapay agregaların fiziksel ve mekanik özelliklerini araştırmak için kuru yoğunluk, özgül yoğunluk, su emme ve ezilme mukavemeti deneyleri yapılmıştır. Sonuçlar sinterlenmiş uçucu küllü yapay agregaların yoğunluk ve özgül yoğunluk değerlerinin artan eğilimde ancak su emme değerlerinin azalan eğilimde olduğunu göstermiştir. En yüksek ve en düşük yoğunluk değerleri sırası ile 900 ºC'de %50 sinterlenmiş ve %20 soğuk bağlama ile üretilmiş agregalarda gözlenmiştir. Ayrıca en yüksek ezilme dayanımı 945 N olarak 900 ºC'de sinterlenmiş %50 uçucu küllü numunelerde ölçülmüştür.

Anahtar Kelimeler : *Yapay agrega,Uçucu kül, Soğuk bağlama, Sinterleme, Su emme, Ezilme dayanımı*

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1. Introduction

Aggregates are one of the most important ingredient of concrete that covers approximately 75% of the concrete. It is used multifunctional purposes as a constructional material and found naturally as an inorganic granular material or produced as an artificial aggregate. In the past several decades, artificial aggregate and especially lightweigh aggregate production have become an important study field in construction industry.

The studies related to manufacturing the artificial lightweight aggregates (ALAs), and the manner of using the industrial wastes focused on the compressive and flexural strengths of the composites. At the same time ductility characteristics of artificial lightweight aggregates could be advanced. In the [1] study, it was found that the compressive, splitting, and the flexural strength values were improved using the sintered fly ash (FA) aggregate as a substituted material for the fine aggregates. Cold bonded pelletization manufacturing technique was utilized to produce ALAs [2]. The cold bonding method process is used as to produce ALAs by pelletization. Pelletization procedure is used to produce artificial lightweight coarse aggregate using FA and it relies on the particle sizes and their distribution. There are some other related parameters with the aforementioned method such as; the particle wettability and the moisture content [3]. The usage of artificial aggregates has been studied by many researchers using different mineral admixtures. Bottom ash from municipal solid waste incinerator has been employed by Cioffi et al. [4]. Kockal and Ozturan [5] investigated different types of lightweight fly ash aggregates and discussed the effects of these aggregates on the behavior of concrete mixtures.

The Physico-mechanical and durability properties of ALAs were examined by reference [6]. FA aggregates may be produced by way of adopting pelletization as the system of merging finer particles into a bigger solid material without applying external force which leads in a light weigh product due to the presence of pores [7] and [8]. The properties of the ALAs are directly influenced by the processing parameters and the curing conditions. Pelletization may be conducted through cold bonding or thermal treatment [9].

Sintering method is a thermal hardening technique which implies exposure of pellets to excessive temperatures (usually up to 1200 ºC) in different time periods accordance with the related standart [10, 11 and 12]. 1100℃ was regarded as the optimal sintering temperature to reach high density, low water absorption, and greater strength ALAs by reference [10]. High strength concrete, having very high carbonation resistance, could be achieved using sintered fly ash aggregates [11].

In recent years, there has been growing interest in production of environmental friendly materials in engineering. FA is among the most widely used waste material especially in civil engineering applications. In this study, a framework that considers the significance of the use of FA in three different percentages (20-30 and 50) in the production of cold bonded and sintered ALAs. It is expected that the outcome of this study will be helpful for project managers, engineers, and academicians in selecting sustainable alternate aggregate as a building material for infrastructure projects. The lightweight aggregate production processes have been explained

2. Material and Method

A number of techniques have been developed in lightweight artificial aggregate production. In this study an experimental method was used to produce cold bonded and sintered type of artificial lightweight aggregates. The materials and artificial lightweight aggregate production methods are explained in following sections.

2.1. Materials

2.1.1. Cement

The Portland cement type CEM I 42.5 N was chosen in accordance with ASTM Type I in experimental analysis. It has a Blaine fineness and specific gravity as 3430 cm^2/g and 3.17 respectively. This cement type encloses quite higher quantity of major silicate compounds and has a normal fineness level which is appropriate for preferred setting and harmless release of hydration heat. The chemical compositions of the cement type and FA involved in the present study are shown in Table 1.

2.1.2. Fly Ash (FA)

The FA used in the manufacturing of ALAs has F class type properties. Its specific gravity was 2.25. The specific properties of the F class FA in compliance with ASTM C618-19 [13] and Portland cement type are shown in Table 1.

Table 1 Chemical composition of Portland cement and FA

Chemical composition (%)	Portland Cement	FA
CaO	62.58	4.24
SiO_2	20.25	56.20
Al_2O_3	5.31	20.17
Fe_2O_3	4.04	6.69
MgO	2.82	1.92
SO_3	2.73	0.49
K_2O	0.92	1.89
Na_2O	0.22	0.58
Loss on ignition	3.02	1.78
Specific gravity	3.15	2.25
Blaine Fineness (m^2/kg)	329	287

2.2. Cold bonded Artificial Aggregate

The cold-bonding pelletization technique was carried out to produce the ALA. An electrical pelletizer pan was used in cold bonded artificial aggregate production (Fig.1). The pan has a diameter and depth as 800 mm and 300 mm respectively. This pan was operated to manufacture the ALAs. The pelletizer pan had a horizontal angle and a rotational speed of 45 degrees and 42 rev/min respectively. To manufacture the ALAs, a combination of 20, 30, and 50% FA by weight of cement was utilized as the dry powdered material. Mix identifications 20F80C, 30F70C and 50F50C are designed according to the percentages of FA and cement. For example, 20F80C means that 20% FA and 80% cement. This mixture of powdered material was poured into the pelletization disc and permitted to be blended till a well-mixed material is reached. In a certain amount of water sprayed onto the cement and mixtures which is served as the coagulant and the spherical pellets were completed on the quit of 10-

min in initial step. The pelletization disc with spherical pellets has been allowed to rotate an additional 10 min, by which the stiff and compacted pellets have been manufactured. The manufactured ALAs are shown in Figure 2. Afterward, these pellets have been saved in the plastic bags (with the 70% relative humidity) immediately the manufacturing process finished. The plastic bags were stored under normal curing room temperature (22 ± 2 ℃) 28 days.

Figure 1. Pelletization Disc

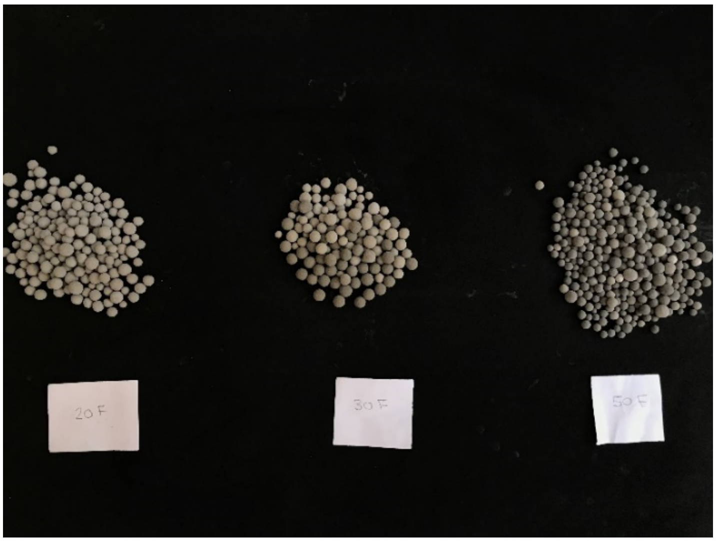

Figure 2. Manufactured cold-bonded ALAs

2.3. Sintered Artificial Aggregate

The effect of sintering on the specific features of the ALAs was produced by heating a series of aggregate samples at three different temperatures of 300, 600, and 900℃. The increasing rate of temperature was set at 10 ℃ per minute (Fig. 3). After sintering for 1 hour, the hot pellets were kept in the oven for being slowly cooled to the room temperature. The sintered pellets were then tested after cooling in terms of particle density, water absorption capacity, specific gravity, and crushing strength. The change in color and shape for each type of cold-bonded and sintered ALAs are clearly seen in Fig. 4.

Figure 3. Sintering process of ALAs

Figure 4. The change in color and shape of cold bonded and sintered ALAs

2.4. Test Methods

The ALAs were sieved by using sieve test analyses. The sieved aggregates larger than 4 mm were utilized in manufacturing process of cementitious composite materials. The sieve analyses results of all aggregates are given in Fig. 5.

The dry density, bulk density, water absorption, and crushing strength tests were carried out to investigate some important physical and mechanical features of the produced aggregate pellets. ASTM 127 standart has been applied to the physical properties of ALAs such as ; density, specific gravity, and water absorption.

The density and water absorption of the artificial aggregate pellets were obtained by measuring the dry weight (*W1*), weight of pellets immersed in water (*W2*), and saturated weight after 24 h immersing in water (*W3*). The following relationships were used for calculations:

$$\text{Density} = \frac{W1}{W2-W3} \tag{1}$$

$$\text{Water absorption (\%)} = \frac{W2-W1}{W1}*100 \tag{2}$$

The crushing strength test was applied on the individual pellets after 28 days curing period finished by placing the pellets between two parallel plates and applying the direct load as shown in Fig. 6. The load was then converted to the crushing strength using the following formula:

$$S = \frac{2.8P_c}{лX^2} \tag{3}$$

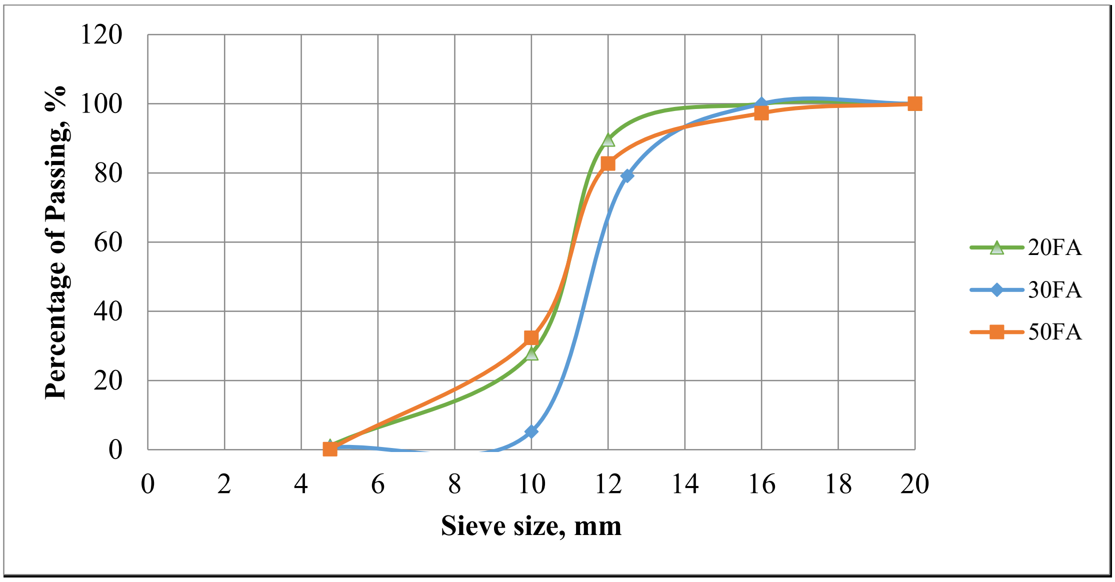

Figure 5. Sieve Sizes of each ALA Types

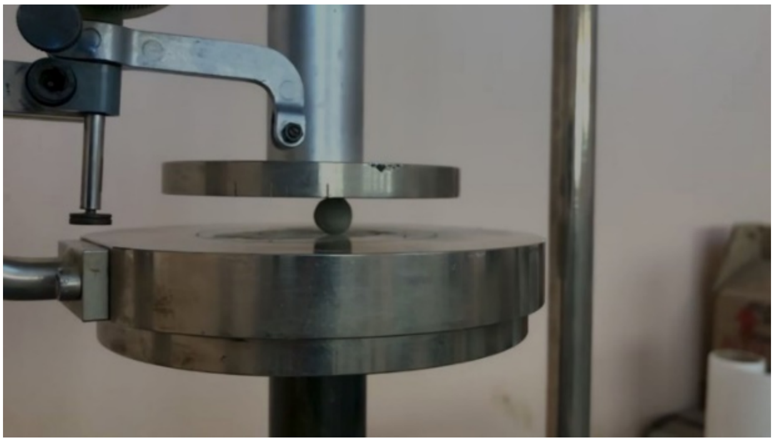

Figure 6. Crushing Strength Test of ALAs

3. Results and Discussions

3.1. Bulk Density

The bulk density results of cold-bonded and sintered ALAs are shown in Fig. 7. The improvement within the density was because of the SiO_2 content in the FA. The SiO_2 content reaction with the $Ca(OH)_2$ causes a hydration response of cement and it contributes a strong extend of calcium silicate hydrate gel (C-S-H). As a result of the chemical reactions, it gives a further reduction in the porosity throughout hydration. Minimum and maximum bulk density values are observed as 912.24 and 1012.2 kg/m^3 for cold bonded and sintered artificial aggregates at 900 °C, respectively. It is a fact that FA continues its puzzolanic activities between 14 and 150 days under normal temperature conditions. The improvements of bulk density values in sintered FA lightweight aggregates are higher than the cold bonded pelletized FA lightweight aggregates (Fig. 7). This is obviously due to the high puzzolanic reaction activities of sintered FA lightweight aggregates under high temperature.

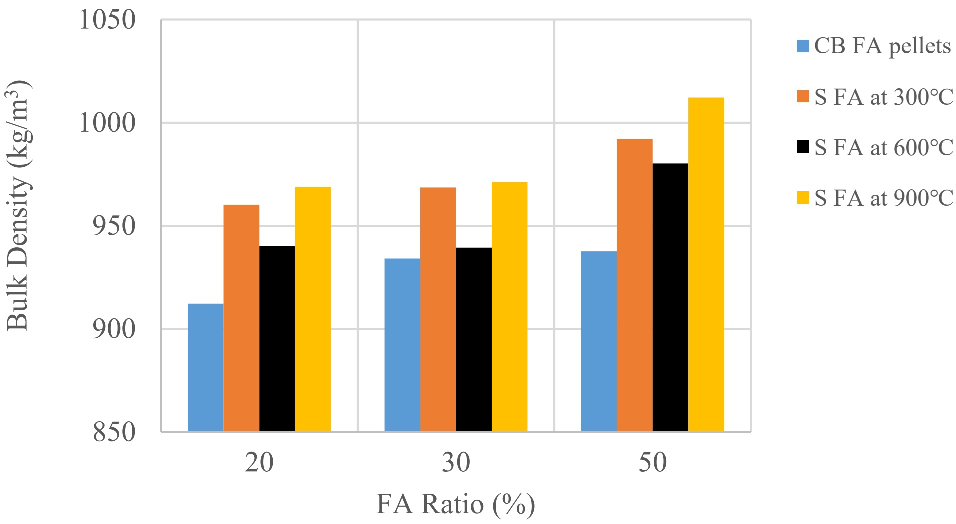

Figure 7. Bulk Density of ALAs

3.2. Water absorption

The water absorption values are shown in Fig. 8. The results also exhibited that 50% FA mix had maximum water absorption equal to 28%. The cement hydration and the pozzolanic reaction of FA generated a denser microstructure due to the higher amounts of the formed C-S-H. A high poro-size causes a higher water absorption percentage. These water absorption results are in accordance with that the bulk density values in which water absorption increases with decreasing bulk density. On the other hand, the water absorption reduces with high temperature of the sintering ALAs (Table 3). The main reason of this result is glassy texture formation on the surface of aggregates at the high temperatures [13]. Furthermore, it is clearly observed that at the higher temperatures of ALAs got smooth with a dense surface. The dense surface formation is due to the gas release and the melting of the raw materials under high temperatures. The high temperatures allow a visible reduction of the water absorption values of sintered FA lightweight aggregates.

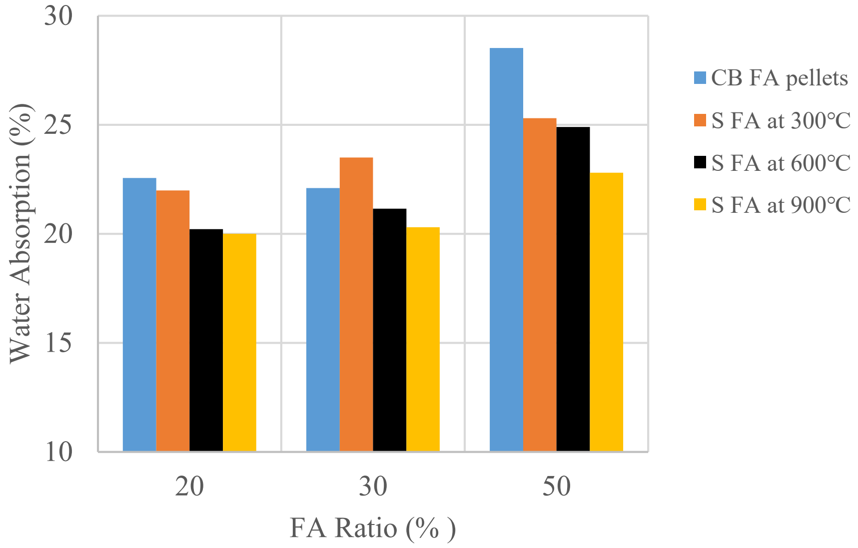

Figure 8. Water Absorption percentages of ALAs

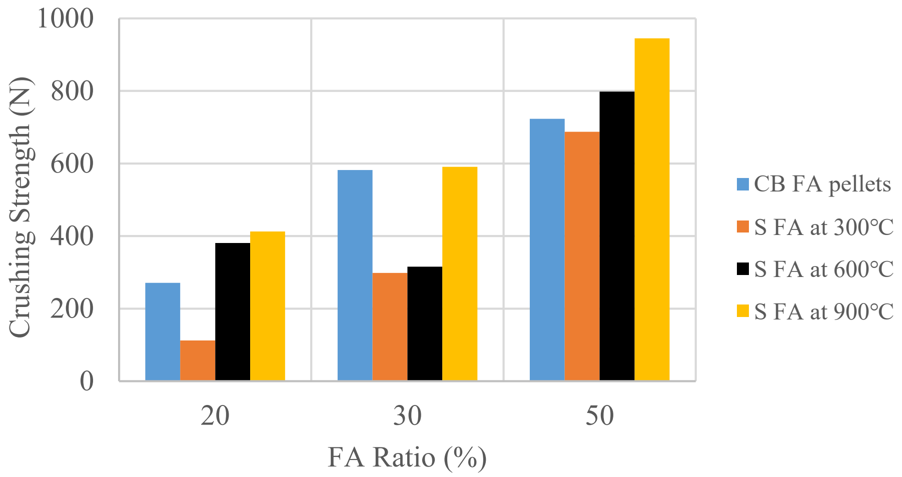

Figure 9. Crushing Strength values of ALAs

3.3. Crushing strength

The crushing strength values of artificial aggregates are shown in Fig. 9. All physical and mechanical results are given in Tables 2 and 3. Portland cement with high percentages of FA lightweight aggregate increases the crushing strength of the artificial lightweight aggregates. The lowest crushing strength has found in the 20% mixture of FA (271.11 N). Addition of 50% FA to the mixture of manufactured aggregates increased the crushing strength by 26% with respect to the crushing strength of the mixture containing 20% FA as seen in Table 2 and Fig. 9. The crushing strength showed significant increase with increasing the temperature. This fact is again related with the increase in puzzolanic activity of FA lightweight artificial aggregates under high temperatures. The 50% FA artificial lightweight aggregate showed crushing strength value as 945 N. The crushing strength results are in a good aggrement with the density results. As shown in Table 2, the highest density of each mixture is also consistent with the highest crushing strength. The enhancement in strength occurred by adding FA with high temperature. The reaction with the interior silicate phase of FA lightweight aggregates allows the hydration reaction and production of additional C-S-H gels [14].

Table 2 Physical properties and mechanical results of cold-bonded ALA

Mix ID	**Specific Gravity**	**Apparent Specific Gravity**	**Density (kg/m^3)**	**Water Absorption (%)**	**Crushing Strength (N)**
20F80C	1.64	2.62	912.24	22.56	271.11
30F70C	1.66	2.62	934.15	22.10	582.14
50F50C	1.43	2.43	937.59	28.52	722.96

Table 3 Physical properties and mechanical results of sintered ALAs

Tests	**Temperature (°C)**	**Mix ID**		
		20F80C	30F70C	50F50C
Bulk Density (kg/m^3)	300	960.2	968.6	992.1
	600	940.2	939.4	980.2
	900	968.8	971.2	1012.2
Water Absorption (%)	300	21.99	23.5	25.3
	600	20.21	21.15	24.9
	900	20	20.3	22.8
Crushing Strength (N)	300	112.3	298.3	687.3
	600	380.87	315.9	798
	900	412.5	590.8	945

4. Conclusions

In this study, FA was selected to be recycled and used in manufacturing two different types of artificial lightweight aggregates; cold pelletized and sintered types. Considering the obtained results, the subsequent conclusions are drawn:

1. All produced aggregate densities were found in the range of 912.24-1012.2 kg/m^3. Therefore, according to BS EN 13055-1 (2002), these materials could be utilized to produce ALA since the densities were less than 2,000 kg/m^3. The maximum density is achieved in the mixture containing 50% FA sintered at 900ºC. On the other hand, the minimum density is observed in mixture containing 20% FA cold-bonded type.
2. The maximum crushing strength is 945 N which belongs to 50% FA sintered at 900ºC. The minimum crushing strength is found in 20% FA cold-bonded type of ALA as 271.11 N.
3. It is found that the water absorption increases by increasing the amount of Portland cement in the mixture. This is due to increased amounts of the hydrated products (C–S–H). Maximum and minimum water absorption values are found 20 % and 28 % for 20% FA sintered at 300 ºC and 50% FA cold-bonded type artificial aggregate, respectively.
4. Sintered aggregates show a decrease in water absorption with increase in the temperature for all the aggregates mixtures. It is mainly because of the glassy texture formations under high temperatures of sintered aggregates.
5. Further experimental works are planned to be carried out using these ALAs to replace with the coarse aggregates in concrete mixtures with different ratios. These studies could help with examining the effects of artificial aggregates on the durability properties of concrete.
6. A detailed comparison of cost analysis of both types of lightweight artificial aggregates are needed as a future study. The cost analysis results could give very useful information for environmental friendly artificial aggregate production.

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