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Potential Use of Fly Ash for Developing Angular-shaped Aggregate

S. Singh*, S. Patel

Department of Civil Engineering, S. V. National Institute of Technology, Surat, Gujarat, India

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ABSTRACT

The prices of aggregate are increasing in India due to the massive demand for natural aggregate for infrastructure development. An attempt has been made to check the feasibility of the past developed technique for developing angular-shaped light-weight fly ash coarse aggregate from three different types of fly ashes. In this study, the effects of binder content, water content and hot water bath curing temperature on the compressive strength of blocks, as well as the impact value of prepared aggregate for fly ash-binder mixes were investigated. A relationship between impact value and compressive strength has also been suggested to predict the impact value of fly ash aggregate based on the compressive strength of block. For making angular-shaped fly ash aggregate, it was found that the fly ash with CaO content of 0.71%-3.85% requires higher binder content and curing temperature than that required for fly ash with CaO content of 10.45%. The resulting lightweight aggregates from three fly ashes have a compacted structure and angular shape for good interlocking. The results of mechanical properties test showed that the aggregate also meets the criteria of Indian code specifications for structural concrete aggregate.

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1. INTRODUCTION

Most of the electricity in India is generated in thermal power plants using coal. 232.56 million tons of fly ash was generated in 2020-21 after the consumption of 686.34 million tons of coal in 202 thermal power stations [1]. In 2016, Ministry of Environment, Forest and Climate Change (MoEF&CC) instructed all thermal power plants to achieve a target of 100% fly ash utilization within five years. However, the 100% fly ash utilization goal could not be achieved within the stipulated timeline. Still, 7.59% of fly ash has remained unutilized, which may harm the environment.

Conversely, the demand for stone aggregate is increasing daily for infrastructure development. Aggregate is the main component, covering more than 80% of raw materials for making concrete and pavements. On the basis of market survey, the nationwide aggregate demand for construction may be between 4,500 and 5,000 million tonnes. The cost of stone aggregates is Rs. 1300 to Rs. 1400 per cubic meter as per Delhi Schedule Rate, Central Public Works Department [2]. This cost continues to rise as a result of rising demand. More aggregate is required for the fast infrastructure development of a country. Mining of natural aggregate leads to severe environmental impacts and consumption of natural resources [3].

The aggregate demand may be fulfilled by producing artificial aggregate from industrial fly ash and locally available resources that can replace mined stone aggregate for construction purposes using simple and appropriate technology. Production of aggregate from fly ash can also help thermal power plants in achieving the target of 100% fly ash utilization. Several advantages of producing fly ash artificial aggregate are natural resource conservation; reducing the amount of energy used in quarrying operations; transforming waste into high-value items; and producing lighter aggregate [4-7].

Raw material mixing, agglomeration and hardening are the main steps for producing fly ash aggregate. Several complicated, costly and time-consuming processes have been developed in the past, most of which are based on the agglomeration by pelletization and hardening by sintering process [8, 9]. Several other

*Corresponding Author Email: ssinghcivil11@gmail.com (S. Singh)

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hardening processes, such as cold bonding and hydrothermal processes, have been developed in the past [5, 10, 11]. The shape of the aggregate is an important factor in governing the strength of concrete. [12]. The pelletization process produces spherical-shaped aggregates with smooth surfaces and the load bearing capacity of these aggregates is reduced due to their low interlocking properties [8].

Most of the literature is focused on developing granular fly ash aggregate by pelletization and sintering. Only a few studies on developing angular-shaped aggregate by water bath curing were reported in the literature, primarily dealing with different binders and hardening techniques. Shahane and Patel [8] developed a technique for producing angular-shaped fly ash aggregate (ASFA) using four simple steps: mixing, compaction, curing and crushing.

This study aims to increase the feasibility of the previously developed technique [8] for producing angular-shaped light-weight coarse aggregates from three types of fly ash using a commercially available binder. This will help in scaling up the utilization of fly ash. The current study is centered on the following novel objectives:

i. To investigate the effects of water bath curing temperature, binder and water content on compressive strength of blocks and impact value of fly ash aggregate.
ii. To provide suitable mix proportion and water bath curing temperature for developing fly ash aggregates from three fly ashes.
iii. To compare the engineering properties of developed fly ash aggregates with the requirements of Indian standards.
iv. To establish an empirical relation for predicting the aggregate impact value from the compressive strength value of blocks.

2. MATERIALS

The physical parameters and chemical constituents of fly ashes are presented in Table 1. Based on the chemical constituents presented in Table 1, all three fly ashes are classified as Class F [13]. Fly ashes with CaO contents of 0.71%, 3.85%, and 10.45% are designated as F1, F2, and F3, respectively. In the present study, the CaO content of F3 fly ash was found higher than that of F1 and F2 fly ash. A combined percentage of 94.39%, 90.24%, and 75.34% of silica, alumina, and iron oxide were found in F1, F2 and F3 fly ashes, respectively. This indicates that a pozzolanic reaction may occur after adding a binder to the fly ashes [14].

The specific gravity of 1.83 to 2.15 and bulk density of 803 to 848 kg/m^3 were found for the fly ashes. The specific gravities of fly ashes were determined as per IS 2720 (Part-III) [15]. The specific gravity of F3 fly ash was found to be less than that of F1 and F2 fly ashes. Commercially available hydrated lime was used as a binder in this study. The particle sizes present in fly ashes were determined using 2.00 mm, 0.425 mm, 0.075 mm and 0.045 mm Indian Standard (IS) sieves.

3. METHODOLOGY

3. 1. Production Process and Experiments

The following steps were followed for carrying out the experimental study-

Step 1. Determination of OMC and MDD of fly ash and fly ash-binder mixes.
Step 2. Preparation of blocks in brick pressing machine to achieve MDD.
Step 3. Curing in hot water bath for hardening of blocks.
Step 4. Determination of compressive strength of the cured blocks.
Step 5. Crushing of fractured blocks (fractured after compressive strength test) in laboratory-scale impact crusher to obtain aggregates.
Step 6. Sieving of aggregates to segregate different sizes of aggregates.
Step 7. Determination of AIV, i.e., aggregate impact value.
Step 8. Check whether AIV is less than 40%; if not, repeat steps from 2 to 7 after varying water bath curing

TABLE 1. Physical and chemical parameters of fly ashes

Physical	**F1**	**F2**	**F3**	**Chemical (%)**	**F1**	**F2**	**F3**
Color	Gray	Gray	Dark Gray	SiO_2	61.91	60.32	44.54
Specific Gravity	2.11	2.15	1.83	Al_2O_3	27.80	25.11	24.70
Bulk Density (kg/m^3)	818	848	803	Fe_2O_3	4.68	4.81	6.10
Sieve size (mm)		**Percentage Finer**		SO_3	0.11	0.35	4.53
2.000	100.0	100.0	100.0	MgO	0.56	1.27	0.62
0.425	99.5	99.4	99.7	CaO	0.71	3.85	10.45
0.075	81.5	77.3	87.7	Na_2O	0.10	0.15	0.55
0.045	61.0	46.7	63.9	P_2O_5	0.35	0.17	0.40

temperature, binder content and water content, until AIV and crushing value become less than 40%. If yes, then move to step 9.

Step 9. Determination of typical physical properties of fly ash aggregate.

For developing angular-shaped fly ash aggregate (ASFA), the following parameters were adopted for all fly ashes to check the feasibility of the previously developed process [8]: (i) dry mixing of 96% fly ash and 4% lime and then thoroughly wet mixing after addition of water conforming to optimum moisture content; (ii) preparation of rectangular blocks of size 200 mm × 100 mm × 70 mm considering maximum dry density of fly ash-binder mixes and then samples were kept at a temperature of 50°C in oven for 6-7 hours; (iii) then kept for curing in water bath for 3 days under 75°C temperature; and (iv) crushing of cured blocks after keeping cured samples at ambient temperature for 1 day.

After performing compressive strength tests, the fractured blocks were crushed in a laboratory-scale impact crusher to obtain aggregates. The segregation of different sizes of aggregates was carried out by sieving aggregates through different Indian Standard sieves. For large-scale production, fly ash blocks can be crushed in an industrial crusher to obtain fly ash aggregates.

The binder content is mentioned in percentage by dry weight. Binder and water content percentages are with respect to the total dry weight of raw material. The blocks were pressed to their maximum density to obtain high-strength and densely-structured fly ash aggregate, which required determining the water content for molding the blocks. Optimum moisture content (OMC) and maximum dry density (MDD) of fly ash-binder mixes were determined by conducting a modified compaction test [16]. Then blocks were prepared in a brick-pressing machine by applying a pressing force of 350 kN. Green blocks were kept for accelerated curing in the water bath under specified temperature.

The compressive strength test was then performed on the cured blocks as per IS 3495 (Part-1) [17]. Three identical specimens were prepared for each study and compressive strength test was performed by applying axial load at a uniform rate of 14 N/mm^2 per minute till failure occurred. The mean value was taken as the strength value of the tests performed.

Different trials by varying water bath curing temperature and binder content were also carried out for the fly ashes, where the parameters adopted in the process failed to develop an aggregate impact value lower than 40%. Further improvement in strength was achieved by varying water content. The strength in aggregate may be due to formation of cementitious and binding gels [18].

Figure 1 shows the process for developing angular-shaped fly ash aggregate (ASFA) in the laboratory.

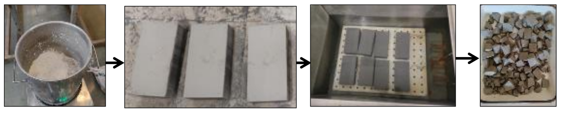

Figure 1. Process for developing angular-shaped fly ash aggregate

3. 2. Physical Tests on Fly Ash Aggregates

Different physical tests were conducted on aggregates developed by finalized mix, water content and curing temperature for three fly ashes. Loose bulk density, specific gravity and water absorption were determined for ASFA of size 6.3 mm to 20 mm as per IS 2386 (Part III) [15].

Aggregates must be tough and strong enough to withstand disintegration caused by sudden and gradually applied load. Aggregate impact value (AIV) and crushing value of aggregates were determined as per IS 2386 (Part IV) [19]. The durability test for ASFA was also carried out as per IS 2386 (Part V) [20] in sodium sulphate solution for five alternate wetting and drying cycles.

4. RESULTS AND DISCUSSION

4. 1. Compaction Test Results

A modified proctor test was conducted and OMC & MDD values of fly ash and fly ash-binder mixes were found. OMC & MDD values of F1, F2 and F3 fly ashes were 18.9%, 1.34 g/ cm^3; 19%, 1.35 g/ cm^3 and 25.6%, 1.38 g/cm^3. OMC in the range of 18.5% to 19.0%, 18.0%-19.0% and 25.4%-25.5%, while MDD in the range of 1.38 g/ cm^3-1.41 g/ cm^3, 1.40 g/ cm^3-1.42 g/ cm^3 and 1.37 g/ cm^3-1.38 g/ cm^3 were found for F1, F2 and F3 fly ash-binder mixes, respectively. Blocks were prepared for different fly ash-binder mixes at their respective OMC and MDD.

4. 2. Results for Three Fly Ashes Following the Previous Mix and Curing Parameters

Initially, the mix proportions and water bath curing parameters following literature [8] were trialed to check the feasibility of the suggested parameters for three new fly ashes. Table 2 shows the compressive strength of blocks and AIV of aggregates prepared for 96% fly ash+4% lime (named F1+4L, F2+4L and F3+4L) for all three fly ashes.

TABLE 2. Compressive strength and AIV results of fly ashes following the previous mix and curing parameters

Mix	Compressive Strength (MPa)	AIV (%)	Target AIV (%)
F1+4L	6.2	51.0	
F2+4L	7.1	50.8	<40%
F3+4L	22.1	27.5	

The highest compressive strength of 22.1 MPa and AIV of 27.5% was found for F3+4L. The AIV for F3+4L was found below the permissible limit mentioned in IS 9142 [23] for aggregate to be used in structural concrete, while the AIVs of F1+4L and F2+4L were found above the permissible limit. This shows that the mix proportion and curing temperature mentioned in the literature [8] are unsuitable for F1 and F2 fly ashes. This may be due to the low percentage of CaO in F1 and F2 fly ashes. More trials were conducted to find the suitable mix proportion and curing temperature for making ASFA from F1 & F2 fly ashes.

4. 3. Influence of Temperature on AIV and Compressive Strength Figure 2 shows the influence of water bath curing temperature on the compressive strength of blocks and AIV of aggregates prepared for F1+4L and F2+4L mixes. The compressive strength is increasing and AIV is decreasing with the temperature. The compressive strength was found to be decreased by 6%-8% on lowering the temperature from 75°C to 65°C, while the compressive strength was found to be increased by 53% on increasing the temperature from 75°C to 95°C in F1+4L & F2+4L mixes. The increase in compressive strength value may be due to an increase in the rate of pozzolanic reaction with the increase in temperature. Low curing temperatures are not favorable for early strength development because of the slower rate of pozzolanic reaction at low temperatures [21].

The lowest AIV of 47.6% and 46% were found for F1+4L and F2+4L at 95°C curing temperature. The impact values obtained were more than 40%. This proves that 4% binder is insufficient for developing high strength aggregate with F1 and F2 fly ashes, even at higher curing temperatures.

4. 4. Effect of Binder Content Due to the presence of low percentage of CaO in F1 and F2 fly ashes, the fly ashes have very low or no cementitious properties. A suitable amount of binder is required to improve the strength of aggregates. Figure 3 shows that as the binder content increases, so does the compressive strength of blocks of F1 and F2 fly ashes. More binders will provide more calcium for the reaction. Binder content of more than 14% was found suitable to make ASFA with AIV less than 40%.

Impact values of 35.6% and 34.8% were found to be highest for aggregates of F1+18%L and F2+18%L, respectively, prepared after curing at 95°C in the water bath for 3 days. Fly ash with low CaO content demanded a relatively higher binder content in the mix and accelerated curing to achieve sufficient strength [22]. As the AIV for 14% binder was found to be just touching the maximum permissible AIV limit, 16% -18% binder was chosen for further study.

4. 5. Effect of Water Content Further study was carried out by varying the water content as water content plays a vital role in gaining strength. Figure 4 shows the effect of water content on the compressive strength of blocks and AIV of aggregate prepared for OMC to OMC-8%. Lime of 16%-18% and curing temperature of 95°C were chosen for F1 and F2 fly ashes, while lime of 4% and curing temperature of 75°C was chosen for F3 fly ash.

It was found that on lowering the water content from OMC to OMC-4%, the compressive strength increases while AIV decreases for all mixes, which indicates that water content equal to OMC-4% is on the dry side of the OMC resulting in higher strength. Further decrease in water content was leading to decrease in strength of aggregate because the void space between fly ash particles increases as water content decreases, resulting in a loosely packed material and thus a decrease in aggregate strength.

Compressive strength was found to be improved by 4.1%-7.1%, while AIV was found to be lowered by

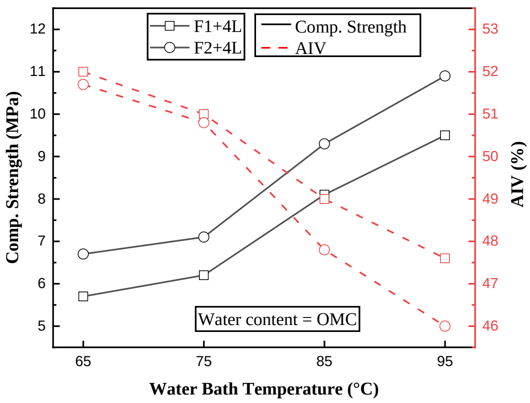

Figure 2. Influence of curing temperature on AIV and compressive strength AIV for F1+4L and F2+4L mixes

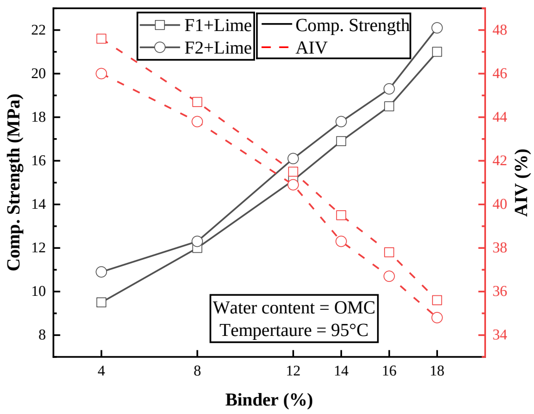

Figure 3. Variation in compressive strength and impact value with binder

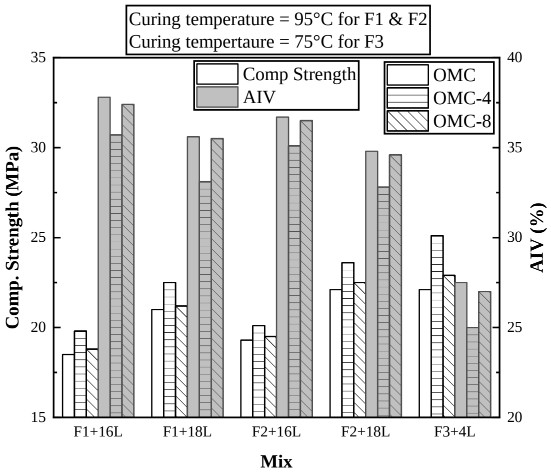

Figure 4. Effect of water content on compressive strength and impact value

4.3%-7.0% on lowering water content from OMC to OMC-4% for mentioned mixes of F1 and F2 fly ashes. An increment of 13.5% in compressive strength and a decrement of 9.1% in AIV was found for F3+4L mix.

4. 6. Abrasion Value Results Los Angeles abrasion test was also carried out for ASFA prepared from F1+16L, F1+18L, F2+16L, F2+18L and F3+4L mixes by taking water content equal to OMC-4%. This test was carried out to check whether prepared ASFA at OMC-4% water content, fulfill the requirement of abrasion value as per IS codes [23, 25]. Table 3 shows the abrasion values for different mixes of F1, F2 and F3 fly ashes. Abrasion values for F1+18L, F2+18L and F3+4L were found below the maximum permissible limit of IS code [23]. This indicates that 18% lime is suitable for preparing ASFA from F1 and F2 fly ash and 4% lime is suitable for F3 fly ash.

4. 7. Empirical Relation between Compressive Strength and Aggregate Impact Value Additionally, efforts have been made to establish empirical relations for predicting the aggregate impact value of ASFA from the compressive strength value of blocks of different mixes. The compressive strength (q)

TABLE 3. Comparison of abrasion value for different mix

Mix	AIV (%)	Abrasion Value (%)	Target Abrasion Value (%) [23]
F1+16L	35.7	42.8	
F1+18L	33.1	38.0	
F2+16L	35.1	42.1	<40%
F2+18L	32.8	38.2	
F3+4L	25.0	33.2	

of blocks and aggregate impact value (AIV) of ASFA depends on several critical leading parameters, like fly ash-binder mix proportion, binder type, curing temperature and water content. By multiple regression analysis, the empirical correlation for predicting AIV using compressive strength for 29 samples is presented as follows:

$$AIV = -12.1\,q + 59.4 \quad (1)$$

where, AIV is impact value of aggregate in %, q is compressive strength of block in MPa, and R^2 is coefficient of correlation. The linear model is found to fit the experimental data best with R^2 value of 0.94, indicating that the fitness of the model is good.

Plot (Figure 5) of actual and predicted values indicates an excellent fit for AIV and compressive strength. The established empirical relation (Equation (1)) is a linear model that considers compressive strength as the independent variable. This independent variable can represent the cumulative influence of the parameters that control the aggregate impact value of ASFA. The analysis of variance (ANOVA) of the regression parameters of the predicted AIV by linear model is also summarized in Table 4 with the F-test. ANOVA shows that the selected linear model adequately represented the data obtained. The p-value less than 0.05 indicate that model terms are statistically significant at the 95% confidence level.

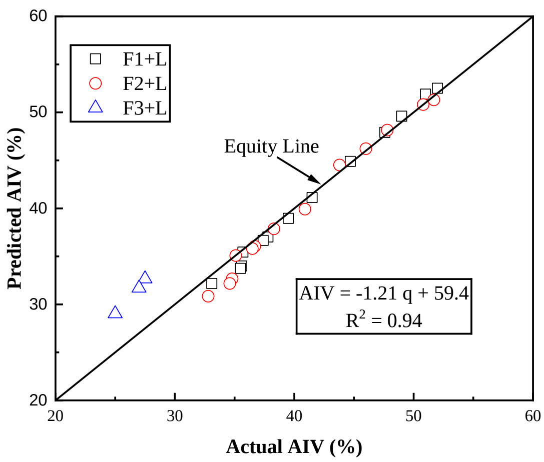

Figure 5. Comparison of predicted AIV with actual AIV

TABLE 4. ANOVA for AIV prediction by linear model

Source	df*	Sum of squares	Mean squares	F value	p-value
Regression	1	1524.2	1524.2	448.5	<0.05
Residual Error	27	91.7	3.4		
Total	28	1615.9			

*df = degree of freedom

4. 8. Comparison of Properties with Standards

Table 5 displays the results of laboratory tests on the physical and mechanical properties of fly ash aggregates. The dry loose bulk densities of fly ash aggregates are below the maximum value of IS 9142 (Part II) [23], which fulfills the requirement of dry loose bulk density of lightweight aggregate for structural concrete.

23.1%, 24.6% and 25.0% of water absorption were found for fly ash aggregates of F1+18L, F2+18L and F3+4L mixes, respectively. Due to the high water absorption of fly ash aggregates, more water will be absorbed by the aggregate in the early stages, enabling the concrete to withstand moisture loss in later stages. This absorbed water contributes to the internal curing of the concrete, making it more resistant to the lack of curing than natural aggregate concretes [24].

ALFC aggregates were found to have a satisfactory crushing value, meeting the requirement of IS 9142 (Part-II) [23] for structural concrete aggregates. The results of the soundness tests also revealed that the five-day dry weight of the fly ash aggregates of the finalised mixes was greater than 90% of the initial dry weight of the aggregates.This implies that weight loss during wetting and drying cycles preserves aggregate integrity regarding resistance to deterioration cycles. This is based on the assumption that stronger aggregate bonding is caused by the formation of binding gels, which results in high strength retention even after continuous wetting and drying cycles.

The wet aggregate impact values are reported in Table 5 because the water absorptions of ASFA of all three fly ashes were found higher than 2%. The impact, crushing, abrasion and soundness value of ASFA were found to be quite adequate, meeting the criteria of IS 383 [25] for application in non-wearing surfaces of concrete and IS 9142 (Part-II) [23] for application as lightweight aggregate in structural concrete. For using fly ash aggregate in concrete, pre-soaking is essential before concrete mixing in order to compensate for its high water absorption value.

TABLE 5. Typical properties of fly ash aggregates

Parameters	F1+18L	F2+18L	F3+4L	IS 383* [25]	IS 9142(II) [23]
Loose Bulk Density (kg/m^3)	872	880	755	-	≤ 950
Water absorption	23.1%	24.6%	25.0%	≤ 2%	≤ 18%
Impact value	33.1%	32.8%	25.0%	≤ 45%	≤ 40%
Crushing Value	42.5%	42.2%	31.1%	-	≤ 45%
Abrasion Value	38%	38%	33%	≤ 50%	≤ 40%
Soundness Value	8.2%	8.8%	9.2%	≤ 12%	≤ 12%

* Non-wearing surfaces

5. CONCLUSIONS

Engineering properties of angular-shaped aggregate developed from F1, F2 and F3 fly ashes under hot water bath curing were examined and compared. The following conclusions can be drawn:

1. It is found that high curing temperature and high binder content are required for developing angular-shaped fly ash aggregate from F1 and F2 fly ashes in comparison to F3 fly ash. 18% lime and 95°C water bath curing temperature for developing aggregate from F1 and F2 fly ashes, while 4% lime and 75°C water bath curing temperature for developing aggregate from F3 fly ash are found to be sufficient.
2. It is found that fly ash aggregates of F3 fly ash are quite stronger than fly ash aggregates of F1 and F2 fly ashes. Impact value of less than 40%, crushing value of less than 45%, abrasion value of less than 40% and soundness value of less than 12% were found for developed aggregates from all three fly ashes. These values are fulfilling the required specifications of IS 383 for aggregates to be used in non-wearing surfaces of concrete and specifications of IS 9142 (Part-II) for lightweight aggregates to be used in concrete.
3. Water absorptions of more than 20% are found for aggregates of three fly ashes. Pre-soaking is essential before mixing and using in order to compensate for its high water absorption value.
4. A linear correlation (AIV = -1.21q + 59.4) has been developed, which is found quite well for predicting the aggregate impact value (AIV) using compressive strength (q) of blocks.

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Persian Abstract

چکیده

توسعه زیرساخت ها. تلاشی برای بررسی امکان‌سنجی تکنیک توسعه‌یافته گذشته برای تولید دانه‌های درشت خاکستر بادی سبک وزن زاویه‌دار از سه نوع مختلف خاکستر بادی انجام شده است. در این مطالعه، تأثیر محتوای بایندر، محتوای آب و دمای پخت حمام آب داغ بر مقاومت فشاری بلوک‌ها و همچنین ارزش ضربه‌ای سنگدانه‌های آماده‌شده برای مخلوط‌های خاکستر بایندر مورد بررسی قرار گرفت. یک رابطه بین ارزش ضربه و مقاومت فشاری نیز برای پیش‌بینی ارزش ضربه خاکستر بادی بر اساس مقاومت فشاری بلوک پیشنهاد شده است. برای ساخت دانه های خاکستر بادی زاویه ای، مشخص شد که خاکستر بادی با محتوای ٪3.85 - ٪0.71 CaO به محتوای چسب و دمای پخت بالاتری نسبت به خاکستر بادی با محتوای ٪10.45 CaO نیاز دارد. سنگدانه های سبک وزن حاصل از سه خاکستر بادی دارای ساختار فشرده و شکل زاویه ای برای در هم قفل شدن خوب هستند. نتایج آزمایش خواص مکانیکی نشان داد که سنگدانه با معیارهای آیین نامه هندی برای سنگدانه های بتن سازه ای نیز مطابقت دارد.