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Effect of different binders on cold-bonded artificial lightweight aggregate properties

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Abstract. The present investigation is to identify an optimum mix combination amongst 28 different types of artificial lightweight aggregates by pelletization method with aggregate properties. Artificial aggregates with different combinations were manufactured from fly ash, cement, hydrated lime, ground granulated blast furnace slag (GGBFS), silica fume, metakaolin, sodium bentonite and calcium bentonite, at a standard 17 minutes pelletization time, with 28% of water content on a weight basis. Further, the artificial aggregates were air-dried for 24 hours, followed by hardening through the cold-bonding (water curing) process for 28 days and then testing with different physical and mechanical properties. The results found the lowest impact strength value of 16.5% with a cement-hydrated lime (FCH) mix combination. Moreover, the lowest water absorption of 16.5% and highest individual pellet crushing strength of 36.7 MPa for 12 mm aggregate with a hydrated lime-GGBFS (FHG) mix combination. The results, attained from different binder materials, could be helpful for manufacturing high strength artificial aggregates.

Keywords: metakaolin and ferrochrome ash; aggregates/recycled aggregates; cement; construction materials; fly ash/slag; furnace slag; lightweight aggregate (LWA); silica fume

1. Introduction

Usage of industrial by-products as a building material is an active continuous method to dispose of the by-products and protect the possible resources for next generations (Kisku *et al*. 2017). Fly ash is a coal-based by-product obtained from thermal power plants and GGBFS from the manufacturing of iron are environmental friendly by-products Chore and Joshi (2015). The improper disposal of fly ash will cause water and soil contamination, as a result, disturbs the ecological cycles. Globally USA, China, and few other asian nations jointly utilized about 70% of the coal (Yao *et al*. 2015). As per the Central Electricity Authority of India (2016), 166 million tons of fly ash is generated yearly from 132 different thermal power plants. Around 56% of fly ash is used for manufacturing bricks and tiles, land improvement, mine filling, drainage trench, roads, flyover, agriculture and manufacture of concrete. The unutilized fly ash continues to be a trouble to the public. Higher quality fly ash with lower carbon content is in use as a mineral admixture in cement, concrete and artificial aggregate manufacturing Vali and Bala Murugan (2019). Inferior quality fly ash having high and uneven carbon content is generally utilized in landfilling Chandra and Berntsson (2002).

Utilization of fly ash for the manufacturing of aggregates may reduce the problem of disposal to a greater extent. Typically, 60-80% of the concrete volume occupied by aggregates (Sunil *et al*. 2015, Kurtoglu *et al*. 2018). Replacing natural aggregates by artificial lightweight aggregates will lead to sustainable improvement globally Euro Light Con (1998), Vali and Abdul Rahim (2016). The manufactured aggregates from fly ash will overcome all the problems stated above. Lightweight aggregates (LWA) will be factory-made from fly ash and other binders through different hardening processes like cold-bonding, sintering and Autoclaving or hydrothermal action Central Electricity Authority (2016), Arslan and Baykal (2006), Baykal and Doven (2000), Doven (1998), Vali and Bala Murugan (2017), Gesoglu (2004), Topcu and Uygunogiu (2007), Vali and Bala Murugan (2019), Yao *et al*. (2015), Gesoglu *et al*. (2007), Lo *et al*. (2007). From the different techniques available for hardening of aggregates, the cold-bonding (Water Curing) technique is taken into account to be additional energy efficient than sintering and autoclaving which were an energy demanding techniques. The agglomeration of cement and/or lime as a binder with fly ash or GGBFS was collected at room temperature by utilizing water as coagulant Arslan and Baykal (2006), Baykal and Doven (2000), Doven (1998), Vali and Bala Murugan (2017), Gesoglu (2004), Gesoglu *et al*. (2007). Replacing artificial aggregates in concrete can have many advantages like reduction in self-weight, transportation cost, economical and quicker construction Euro Light Con (1998).

Recently, to utilize the industrial by-products for the manufacturing of LWA by completely different methods and binders. Lo and Cui (2004) gave mechanical properties

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of a structural LWA produced with flyash and clay. Baykal and Doven (2000) noted that the density and strength of the artificial aggregates was greatly influenced by the mechanical aspects like speed and angle of the disc. Hence, the lightweight concrete properties will differ with the mechanical aspects at the time of aggregate manufacturing Doven (1998), Joseph and Ramamurthy (2009). Zhang and Gjorv (1991) reported that the strength of high-performance lightweight concrete could be altered by the density of lightweight aggregates. Ke *et al*. (2009), Torres and Garcia-Ruiz (2009) were conducted to look into how the aggregate form and how its volume fraction influences the properties of lightweight concrete. As a result, the compressive strength of lightweight concrete strongly suffers from the material and binder kind of LWAs additionally as its volume fraction within the entire concrete volume. Gesoglu (2004), Job Thomas and Harilal (2014), Vali and Bala Murugan (2019), (Gesoglu *et al*. 2007, Gesoglu *et al*. 2006, Gesoglu *et al*. 2004) manufactured cold-bonded lightweight aggregates with varying specific gravities of 1.72, 1.80 and 2.43. Water absorption of lightweight aggregates was 27% by weight which was reduced to 3.0 and 18% by treating with slurry of cement, micro silica and water glass on the surface of pellets, correspondingly. Kockal (2008), Kockal and Ozturan (2011), Kockal and Ozturan (2011), Kockal and Ozturan (2010) studied physical and mechanical properties of lightweight concrete made with cold-bonded and sintered lightweight aggregates manufactured with glass powder and bentonite.

The purpose of the current study was to assess the manufacturing and testing for 28 different cold-bonded artificial aggregates produced from various binders was given in Table 2. From 28 mixture combinations, 15 combinations of aggregates became paste while cold-bonding and the remaining 13 combinations were hardened through cold-bonding process for 28 days and tested with different physical and mechanical properties.

Table 1 Chemical and physical characteristics of different binder materials

Observations	C*	HL	FA (F)	GGBFS	SF	MK	SB	CB
Chemical Characteristics								
SiO_2	22.3	0.3	39.4	35	99.88	51.35	43	42.5
Fe_2O_3	3	0.23	18.54	0.95	0.040	1.21	10.6	8.92
Al_2O_3	6.93	0.42	17.9	17.7	0.043	40.31	19.35	9.2
CaO	63.5	69	17.45	41	0.001	0.32	2.8	9.54
MgO	2.54	0.5	2.88	11.3	-	0.11	2.23	6.3
TiO_2	-	-	0.95	-	0.001	2.13	1.77	0.85
Na_2O	-	-	0.28	0.2	0.003	0.06	2.34	-
K_2O	-	-	1.78	-	0.001	0.52	0.74	-
$Ca(OH)_2$	-	91	-	-	-	-	-	-
MnO_2	-	-	0.15	2.7	-	-	-	-
SO_3	1.72	-	1.70	-	-	-	-	-
$CaCO_3$	-	-	-	10	-	-	-	-
P_2O_5	-	-	0.45	0.65	-	-	-	-
Glass content	-	-	-	92	-	-	-	-
Physical Characteristics								
Specific gravity	3.12	2.24	2.12	2.85	2.63	2.6	2.71	2.6
Appearance (powder)	Grey	White	Grey	Off-white	White	Off-white	Light cream	Light cream
Specific surface area (m^2/kg)	290	-	407	409	819	805	-	-
Loss on ignition	0.84	-	1.76	0.26	0.015	2.02	10.27	20.7
pH Value	6.3	12.4	8.36	10.07	6.90	5.1	9.4	6.7
Moisture (%)	-	-	0.5	0.10	0.058	0.7	2.2	-

*C: Cement; HL: Hydrated lime; FA (F): Fly ash (class-F); GGBFS: Ground granulated blast furnace slag; SF: Silica fume; MK: Metakaolin; SB: Sodium bentonite; CB: Calcium bentonite

2. Research significance

It was found from the literature that studies of the properties of cold-bonded artificial lightweight aggregates were limited. Present paper addresses the gap from the past literatures. The properties of artificial aggregates manufactured using various mix combinations with different binder materials was studied and reported.

3. Materials and methodology

3.1 Raw materials used in the manufacturing of artificial lightweight aggregates

Fly ash is the important raw material used in the manufacturing of lightweight aggregates. In this study, low calcium fly ash (class-F) was collected from Ennore thermal power plant. The different types of artificial aggregates were manufactured with various flyash-binder mix combinations. The fly ash bonding with different mix combinations was achieved through different binding materials like cement, hydrated lime, GGBFS, silica fume, metakaolin, sodium bentonite and calcium bentonite as shown in Fig. 1(a). Further, water was sprayed on the materials at the time of pelletization. Details of chemical and physical characteristics of the different materials were given in Table 1.

3.2 Pelletization method

As an issue was experienced in spraying water into a traditional mini-mixer, the drum was replaced by an inverted disc. In the past investigations, it had been determined that the position of pelletizing disc should differ from 35° to 50° with the rotating speed varying from 35 to 50 rpm depending on the size of pelletizer Baykal and Doven (2000), Doven (1998). To fix the inclination angle and speed of pelletizer various trials have been performed with different combinations of operation angles and revolving speed. The manufactured artificial aggregates were released freely from 115 cm rise to find out the convenience of the possible strength of LWAs Doven (1998). Throughout the trials, it has been determined that for low revolving speed with angles greater than 45, the

(a) Different materials used

(b) Disc pelletizer machine c) Fresh Pellets in disc pelletizer

(d) Drying of pellets for 24hrs (e) Cold-bonding (f) Final aggregate for testing

Fig. 1 Manufacturing process of cold-bonded artificial lightweight aggregates

surface walls of the disc are stuck by particles, because of moisture. When the pelletizer operated at angles less than 45 but at higher speeds, the pellets did not have sufficient strength because of huge pores. The quantity of sprayed water utilized at the time of pelletization method has been selected to get rounded pellets through the movement of rotating disc Arslan and Baykal (2006), Baykal and Doven (2000), Doven (1998), Kolimi shaiksha vali and Bala Murugan (2017), Gesoglu (2004), Gesoglu *et al*. (2007). According to the previous studies, the highest strength of pellets will only be attained once all the capillaries are filled with water during the production method. If the water content is less than sufficient, entrapped air voids were produced within the pellets. This reduced the capillary action. On the other hand, too much water leads to a water layer on the outer surface of the pellet spoiling the capillary forces (Gesoglu *et al*. 2007).

In the present study, the disc pelletizer was fabricated with a diameter of 0.5 m and a depth of 0.25 m and connected to the mixer machine. The angle of the disc can be modified among 35° to 50° with a speed of 55 rpm is varied by means of a shaft arrangement named as disc pelletizer machine as shown in Fig. 1(b). The raw materials added into the pelletizer initially for 2 minutes rotate the pelletizer without spraying water for better mixing of raw materials; then water was sprayed, the pellets were produced in the disc within the 8th minute duration and turn into strong pellet after the 11th minute. The pelletization was continued till 17 minutes for extra stiffening of the fresh pellet in pelletizer as shown in Fig. 1(c). The compaction force developed inside the pellets which lead to the production of bigger with irregular size. The aggregate size, shape, and efficiency were altered by the pelletization time because it was noticed that the first 10 minutes the aggregates were produced in good shape and later turns into uneven shape. Thus from the trials, it is concluded that 11 to 17 minutes pelletization time prompts a more stable development of pellets with regular size and greater

Table 2 Mix combination of different artificial lightweight aggregates

Mix No	Mix Type	Binder Content (%)							
		FA (F)	C	HL	GGBFS	SF	MK	SB	CB
1	FC	80	20	-	-	-	-	-	-
2	FHL	80	-	20	-	-	-	-	-
3	FG	80	-	-	20	-	-	-	-
4	FSF	80	-	-	-	20	-	-	-
5	FM	80	-	-	-	-	20	-	-
6	FSB	80	-	-	-	-	-	20	-
7	FCB	80	-	-	-	-	-	-	20
8	FCH	80	10	10	-	-	-	-	-
9	FCG	80	10	-	10	-	-	-	-
10	FCSF	80	10	-	-	10	-	-	-
11	FCM	80	10	-	-	-	10	-	-
12	FCSB	80	10	-	-	-	-	10	-
13	FCCB	80	10	-	-	-	-	-	10
14	FHG	80	-	10	10	-	-	-	-
15	FHSF	80	-	10	-	10	-	-	-
16	FHM	80	-	10	-	-	10	-	-
17	FHSB	80	-	10	-	-	-	10	-
18	FHCB	80	-	10	-	-	-	-	10
19	FGSF	80	-	-	10	10	-	-	-
20	FGM	80	-	-	10	-	10	-	-
21	FGSB	80	-	-	10	-	-	10	-
22	FGCB	80	-	-	10	-	-	-	10
23	FSFM	80	-	-	-	10	10	-	-
24	FMSB	80	-	-	-	-	10	10	-
25	FMCB	80	-	-	-	-	10	-	10
26	FSFSB	80	-	-	-	10	-	10	-
27	FSFCB	80	-	-	-	10	-	-	10
28	FSBCB	80	-	-	-	-	-	10	10

strength index. Hence, for all the mix combinations standard angle of pelletizer was set at 36º with speed of 55 rpm, for attaining the greatest efficiency, 17minutes of pelletization time was fixed. Later, fresh pellets were air-dried for 24 hours as shown in Fig. 1(d) and then kept for hardening through the cold-bonding process by maintaining at room temperature for 28 days as shown in Fig. 1(e) and final aggregate for testing as shown in Fig. 1(f). The entire manufacturing process of cold-bonded artificial lightweight aggregates as shown in Fig. 1.

3.3 Tests on artificial lightweight aggregates

After the curing period, the aggregates were tested with different physical and mechanical properties as follows.

3.3.1 Lightweight aggregate gradation

The artificial lightweight aggregates were taken from subsequent fractions (sieved) 40-20 mm, 20-10 mm, 10-4.75 mm, 4.75-2.36 mm, 2.36-1.18 mm, 1.18-0.6 mm, 0.6-0.3 mm and 0.3-0.15 mm for future investigations for aggregates particle size and shape for concrete as per code IS: 2386-Part I (1963).

Fig. 2 Aggregate impact machine

3.3.2 Efficiency of lightweight aggregates

The efficiency of lightweight aggregates calculated as the ratio of aggregates produced to the total material added in to disc pelletizer.

3.3.3 Specific gravity and Water absorption of lightweight aggregates

The specific gravity values for both the weight of oven-dry pellets in the air, the weight of the pellet with saturated surface dry in both water and air were calculated as saturated surface dry values as per code IS: 2386-Part III (1963). The lightweight aggregates were submerged in water for 24 hours at room temperature to calculate the aggregate water absorption value for concrete as per code IS: 2386-Part III (1963).

3.3.4 Bulk density of lightweight aggregates

The loose and rodded bulk density was calculated by using shoveling and rodding method for concrete as per code IS: 2386-Part III (1963).

3.3.5 Aggregate impact strength of lightweight aggregates

The impact strength of the lightweight aggregates was tested by means of an impact testing apparatus as shown in Fig. 2. The impact value provides approximate calculations of the aggregate resistance due to constant impact loading. The aggregate samples were tested with the support of a hammer blow of 15 times falling from a height of 350 mm and then sample sieved through 2.36 mm size as per code IS: 2386-Part IV (1963). The impact value is defined as the ratio of the weight of fraction passing through 2.36 mm sieve size to the weight of total aggregate and is denoted in percentage and calculated by using Eq. (1).

$$\text{Aggregate Impact Value} = \frac{W2}{W1} \times 100 \quad (1)$$

Where.,

W_1=weight of the fly ash lightweight aggregate sample utilized for testing and

W_2=weight of fractions passing 2.36 mm sieve size.

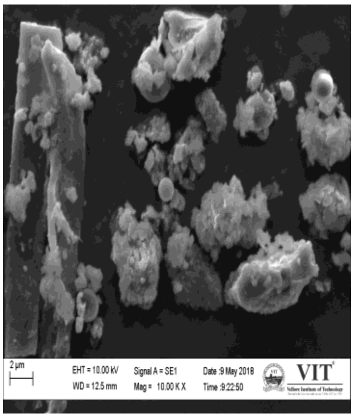
3.3.6 Individual aggregate crushing strength

The crushing strength of individual aggregates tested by

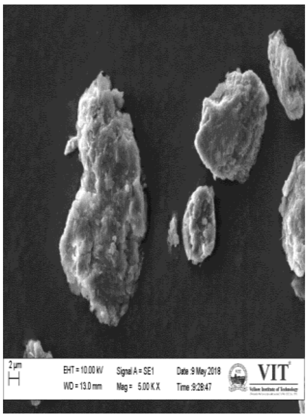
Fig. 3 CBR machine

means of California bearing ratio (CBR) testing apparatus as shown in Fig. 3. The crushing strength of pellets was determined by placing the pellet between the two corresponding plats and loaded diametrically until failure occurred. An average of 20 randomly chosen pellets was tested so as to calculate the average crushing strength for each type of lightweight aggregates. Crushing test was performed on the pellets of different sizes such as 20, 16, 12, 10, 8 and 6 mm by means of a 28 KN capacity load-ring. The individual crushing strength 'σ' was calculated by means of strength index formula as given in Eq. (2).

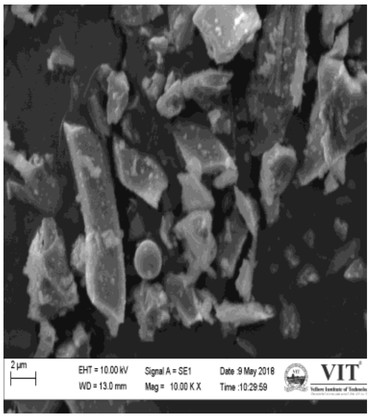
$$\text{Crushing strength '}\sigma\text{'} = \frac{2.8\times P}{\pi\times X^2} \tag{2}$$



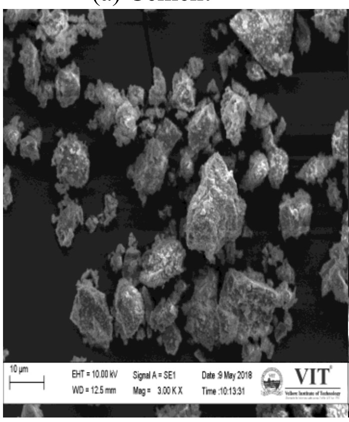
(a) Cement



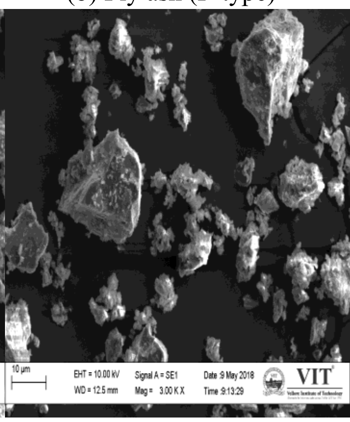
(b) Fly ash (F-type)



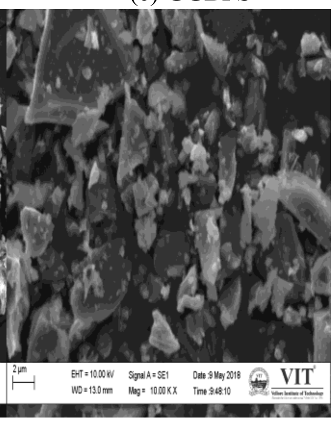
(c) GGBFS



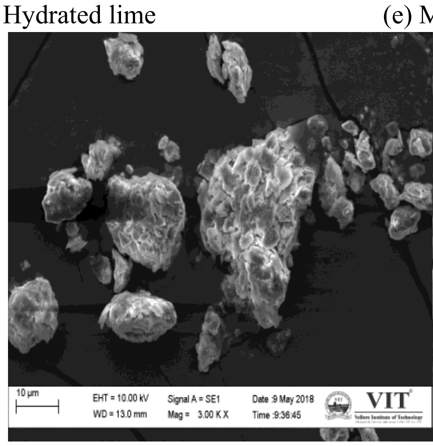
(d) Hydrated lime



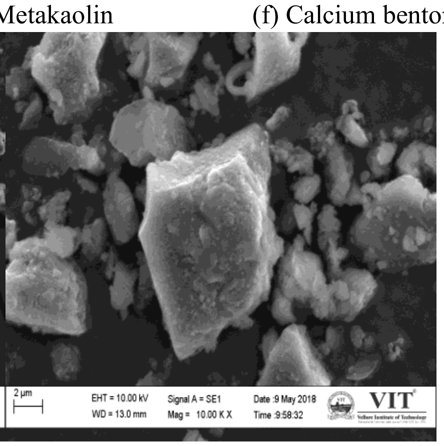
(e) Metakaolin



(f) Calcium bentonite

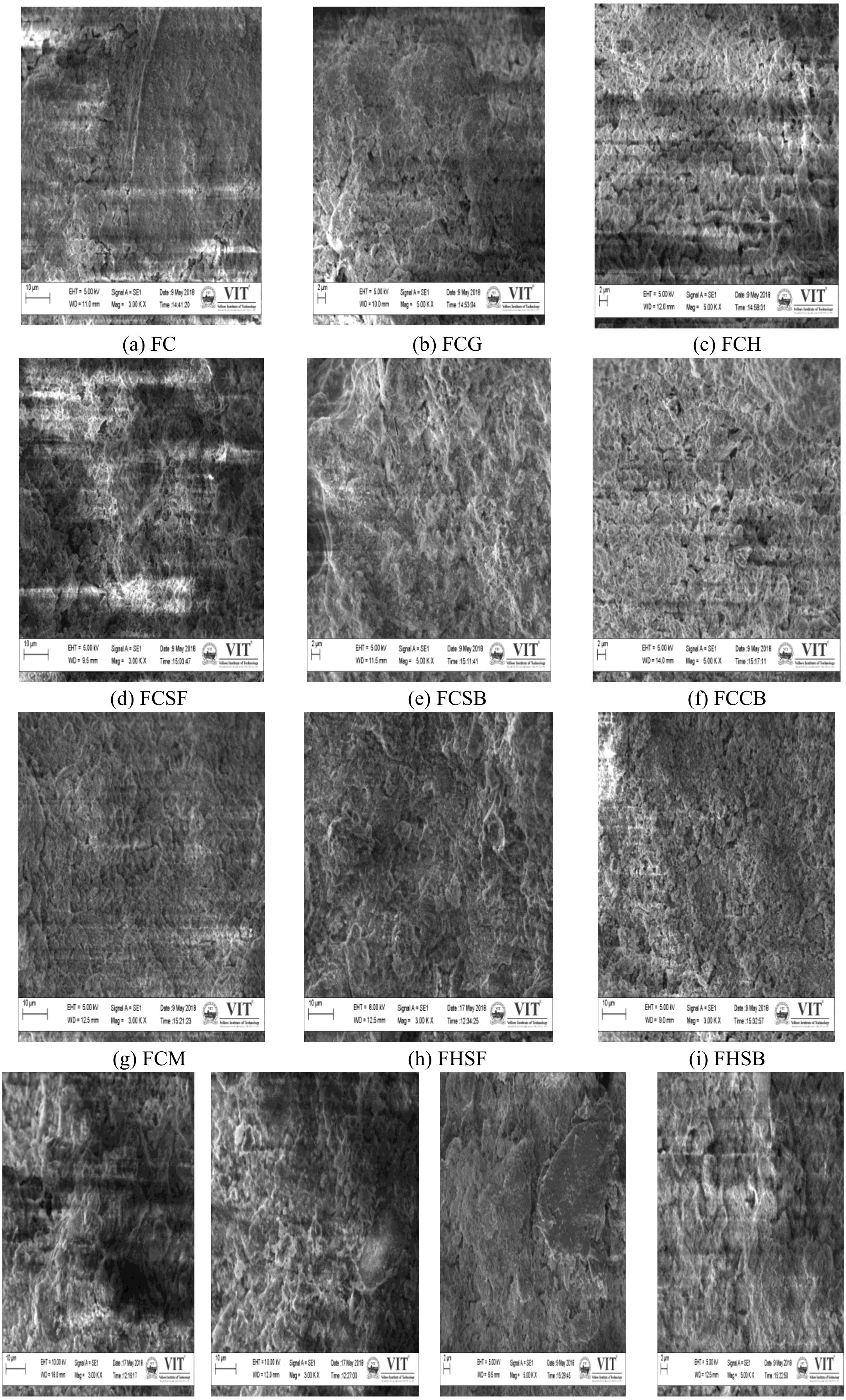


(g) Sodium bentonite



(h) Silica fume

Fig. 4 Grain shape and surface of different binder materials



(a) FC (b) FCG (c) FCH

(d) FCSF (e) FCSB (f) FCCB

(g) FCM (h) FHSF (i) FHSB

(j) FHCB (k) FHM (l) FHG (h) FSFM

Fig. 5 SEM observations of different type of aggregates

Table 3 Characteristics of natural gravel aggregate values

Characteristics of Natural aggregate	
24-hr Water Absorption, %	1.17
Specific Gravity	2.69
Loose Bulk Density, kg/m^3	1469
Rodded Bulk Density, kg/m^3	1574
Aggregate Impact Value, %	9.81
Fineness Modulus	7.47

Where.,

P=failure load and

X=distance between the two plate of the pellet or Diameter of pellet Kockal and Ozturan (2010)

4. Scanning electron microscope (SEM)

4.1 SEM studies of lightweight aggregates

Standard pieces of 1 cm size were kept in an oven for 24 hours at 105±5ºC to eliminate evaporable water content and mounted on alloy stubs and sputter covered before subjecting to the electron beam from a ZEISS EVO/18 SEM studies were carried out with required magnification. The shape and structure of different materials used in the manufacturing of aggregates show different patterns of pores, in general, is uneven, round and disconnected, whereas others were stretched out and interconnected as shown in Fig. 4.

4.2 Microstructure of artificial lightweight aggregates

In this part, the SEM was engaged to explain the microstructure observations of different artificial aggregates as shown in Fig. 5. Wasserman and Bentur (1996) noted that the strength of artificial aggregates depends on physical and chemical interfacial action. The microstructural study recommended that development in the strength of artificial aggregates with hydrated lime and GGBFS binder combination possibly reaction taking place between minerals and calcium hydroxide, therefore results to a solid structure as shown in Fig. 5(i). At the time of hydration, the $Ca(OH)_2$ go in reaction with GGBFS ingredients developing the calcium silicate hydrate (C-S-H), which helps in filling voids.

Aggregates combination with hydrated lime binder shows dense structure compared with aggregate manufactured with cement binder. The large voids are formed in sodium bentonite binder combinations. From all the type of aggregates, the aggregate with combination of hydrated lime and GGBFS binders shows less pore structure which increases the binding capacity.

5. Results and discussions

5.1 Properties of natural gravel aggregate

The shape and surface of aggregate influences the characteristics of the conventional concrete. Artificial aggregates are spherical in shape whereas natural aggregate is an angular in shape. Table 3 present the characteristics of natural gravel aggregate values. Further, the different artificial lightweight aggregates were manufactured and compared with natural aggregates characteristics.

Table 4 Percentage of lightweight aggregates produced with respect to sizes and fineness modulus

Type of aggregate	Percentage of the aggregates produced with respect to sizes (mm)					Fineness modulus
	40	20	10	4.75	2.36	
FC	-	13.43	78.32	7.99	0.23	6.77
FCG	-	12.55	66.8	18.71	1.91	6.48
FCH	-	9.96	74.73	15.19	0.13	6.58
FCSF	-	14.55	76.12	9.14	0.163	6.77
FCSB	-	25.73	72.32	1.81	0.067	7.12
FCCB	-	14.46	74.44	10.96	0.14	6.75
FCM	-	10.31	68.49	20.85	0.35	6.45
FHSF	-	22.29	67.16	10.36	0.175	6.87
FHSB	-	13.43	65.97	20.44	0.134	6.54
FHCB	-	10.98	77.69	11.18	0.133	6.69
FHM	-	10.36	75.13	14.24	0.25	6.58
FHG	-	37.95	53.05	8.83	0.158	7.07
FSFM	-	12.93	78.72	8.13	0.2	6.76

5.2 Properties of artificial lightweight aggregates

5.2.1 Grading of lightweight aggregates

The size and shape of the artificial lightweight aggregate gradation is an essential factor in the mix design of lightweight concrete. Grading of the cold-bonded lightweight aggregates manufactured with different binders was meeting their requirements given in code IS: 9142-Part 2 (2018) and it was calculated as per code IS: 2386-Part I (1963). The percentage passing and size of the aggregate varied and gradation curve for different artificial aggregates are drawn. The percentage of aggregates produced at the time of manufacturing with fineness modulus was given in Table 4. It was noted that primarily at the time of the pelletization method the size of pellets was small, but with the increase in agglomeration with time, the dimensions of the pellets increased. Various trials were conducted to fix the exact pelletization time with desired water content. The fineness modulus of FCSB and FHG artificial aggregate has some closer value with natural aggregate. From the results, it was observed that the artificial aggregates having a round form and the development in size of pellets mainly depends on the type of binder added and the pelletization time.

5.2.2 Production efficiency of lightweight aggregates

The manufacturing efficiency of artificial aggregates mainly depends on the performance of the agglomeration method and binder content added at the time of pelletization. From the investigations, an excellent efficiency of pelletization was found when the angle was positioned at 36° with 55 rpm speed of pelletizer. Hence, in this study for the entire mix combinations fixed angle at 36° with a speed of 55 rpm, greatest efficiency was attained

Table 5 Production efficiency of lightweight aggregates

Type of aggregate	Efficiency of aggregate production (%)		
	Fresh pellets	After 24hrs	Before testing
FC	94.8	88.8	86.2
FCG	88.8	83.5	73.9
FCH	95.5	84.4	88.5
FCSF	94.8	86.6	85.6
FCSB	97.7	77.7	81.2
FCCB	97	87.4	82.8
FCM	97.6	86.7	83
FHSF	96.9	86.8	91.2
FHSB	98.2	83.7	91.9
FHCB	97.3	86.3	91.2
FHM	96.2	86.6	86.9
FHG	90.1	81.8	86.6
FSFM	93.7	87.5	85

with 17 minutes of pelletization time and 28% water content. The efficiency of the aggregates was calculated for the different levels, at the time of manufacturing of aggregate (Fresh pellets), the aggregates were air-dried for 24 hours (Before cold-bonding) and the aggregates before testing (after cold-bonding). The efficiency is different for the different levels with various binding materials were given in Table 5. The efficiency does not depend on the properties of the artificial aggregates. The efficiency of fresh pellets manufactured with hydrated lime and sodium bentonite (FHSB) binder shows the highest efficiency of 98.2% and the lowest efficiency of 88.8% with cement and GGBFS (FCG) binder. The efficiency of 24 hours air-dry pellets with cement (FC) binder exhibit highest at 88.8% and lowest for cement and sodium bentonite (FCSB) binder at 77.7%. However, the aggregates before testing the highest efficiency of 91.9% with hydrated lime and sodium bentonite (FHSB) binder and lowest with cement and GGBFS (FCG) binder at 73.9%. It can be concluded that the use of hydrated lime combination binder shows the highest efficiency compared to that of the cement binder mix combination.

5.2.3 Specific gravity of lightweight aggregates

Based on the investigational results, the specific gravity values of various lightweight aggregates were plotted. From Fig. 6, it was noticed that the specific gravity values of various aggregates vary with different binders. The specific gravity of artificial aggregates with hydrated lime and GGBFS binder (FHG) was noted to be higher as 2.42. Similarly, the least specific gravity was noted for cement and silica fume binder (FCSF) as 1.58. This shows that the performance of hydrated lime and GGBFS binder with fly ash in aggregate manufacturing; Lower specific gravity related to the reduced in stiffness of artificial lightweight aggregates (Gesoglu *et al*. 2004). The specific gravity of natural aggregate was 11% higher than FHG type artificial aggregate given in Table 3.

The specific gravity values are lesser when the primary binder alone was used than the secondary binding material in the aggregate manufacturing. From the results, it was

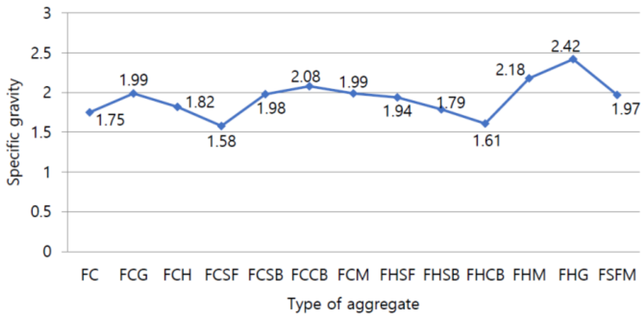


Fig. 6 Specific gravity values of different type of aggregates

concluded that the specific gravity values are higher with a primary binder as hydrated lime than cement and secondary binder with GGBFS and silica fume. Whereas, the specific gravity values are lower with primary binder hydrated lime than cement and secondary binder with sodium bentonite, calcium bentonite, and metakaolin. Overall the specific gravity values were found to be higher with the pozzolanic binding materials, Due to the good packing of fine particles at the time of pelletization.

Gesoglu *et al.* (2004), Manikandan and Ramamurthy (2008), Priyadharshini *et al.* (2011) reported that the specific gravity of artificial aggregates manufactured with the combination of fly ash and cement was between 1.78 to 2.12. In this study, the specific gravity of artificial aggregates manufactured with fly ash, hydrated lime and GGBFS (FHG) was found to be 2.42. The variation in specific gravity may be attributed to the difference in variation in additional binder material, dosage and testing condition.

5.2.4 Bulk density of lightweight aggregates

The results of loose bulk density (L.B.D) and rodded bulk density (R.B.D) of artificial aggregates with different binders were given in Table 6. It is noticed that the higher bulk density was observed for hydrated lime and GGBFS binder (FHG) as 919.4 kg/m^3 and lower bulk density for cement and calcium bentonite binder (FCCB) as 807.2 kg/m^3. All the cold-bonded lightweight aggregates manufactured will be satisfying the loose bulk density values as per code IS: 9142-Part 2 (2018) which was not more than 950 kg/m^3. The bulk density of FHG type artificial aggregate was 40% lesser than natural gravel aggregate which was given in Table 3. From the test results, it was observed that the bulk density was found to be higher when the hydrated lime were used as a primary binder than cement with GGBFS, silica fume, sodium bentonite, calcium bentonite and metakaolin as a secondary binder. The highest percentage increase in bulk density of 10.65% occurs for sodium bentonite and the lowest percentage increase of 1.95% for GGBFS as secondary binder and cement, hydrated lime as primary binder. The results shows that highest bulk density occurred due to better pore structure while pelletization which results in lower water absorption (Chi *et al*. 2003).

Chi *et al.* (2003) and Priyadharshini *et al.* (2011) reported that the bulk density of artificial aggregates was between 972 kg/m^3 to 1247 kg/m^3, the corresponding

Table 6 Bulk density values of lightweight aggregates

Type of aggregate	Bulk density (kg/m^3)	
	L.B.D	R.B.D
FC	863.8	901.5
FCG	901.8	937.4
FCH	864.5	908.5
FCSF	847	882.1
FCSB	811.8	848.7
FCCB	807.2	843.8
FCM	808.6	852.2
FHSF	899.4	932.8
FHSB	898.3	933.8
FHCB	879	917.6
FHM	838.9	891.6
FHG	919.4	948.3
FSFM	856.5	895.4

highest bulk density obtained in the present study for FHG aggregate is 919 kg/m^3. The much variation in bulk density values with above literature is because of usage of different binder materials.

5.2.5 Water absorption of lightweight aggregates

Based on the experimental results, the 24 hours water absorption values of various artificial aggregates were plotted in Fig. 7. As per code IS: 9142-Part 2 (2018), water absorption of artificial aggregates should not more than 18%. In the present study lowest water absorption was observed for hydrated lime and GGBFS binder (FHG) as 16.5% which is satisfying the demands as per code. And higher water absorption of 35.1% for hydrated lime and sodium bentonite binder (FHSB). This was due to the higher porosity in the aggregates manufactured with hydrated lime and sodium bentonite binder. It was recognized from the test results that the water absorption values of different aggregates follow the porosity and examined that aggregate porosity decreased by the addition of binding materials with fly ash. Higher water absorption with high porosity connected with the decreased in stiffness of artificial aggregates which leads to high shrinkage in lightweight concrete (Gesoglu *et al*. 2004). Water absorption values of all the artificial aggregates were very much higher when compared with natural aggregate which was given in Table 3. From all the artificial aggregates, aggregates manufactured with hydrated lime and GGBFS binder shows a significant reduction in water absorption. As a result, pozzolanic reaction among mineral admixture with calcium hydroxide (C-H) in the presence of water leads to additional C-S-H, which helps in developing the solid structure.

Chi *et al*. (2003), Gesoglu *et al*. (2004), Manikandan and Ramamurthy (2008) and Mehmet Gesoglu *et al*. (2015) reported that the water absorption of cold-bonded artificial aggregates manufactured with the combination of fly ash and cement was between 17% to 24%. In present study, the lowest water absorption of cold-bonded artificial aggregates manufactured with fly ash, hydrated lime and GGBFS (FHG) was found 16.5%. The variation in water absorption

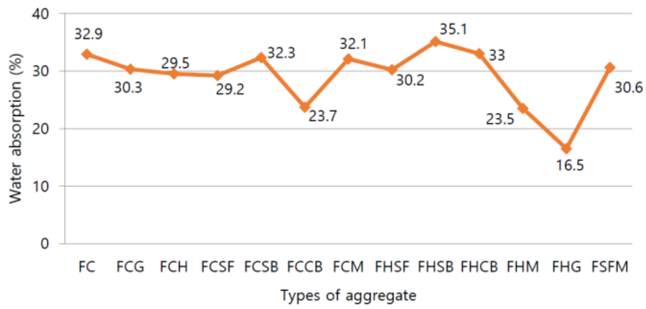


Fig. 7 Water absorption of different type of aggregates

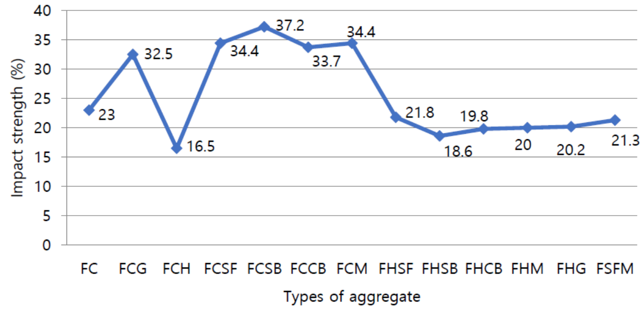


Fig. 8 Aggregate impact strength values of different type of aggregates

results in packing of particles which produces a better micro-structural formation at the time of aggregate manufacturing.

5.2.6 Impact strength of lightweight aggregates

Impact strength test results of artificial aggregates manufactured with various binders as shown in Fig. 8. It was observed that the lowest impact strength for cement and hydrated lime binder (FCH) as 16.5% and highest impact strength for cement and sodium bentonite binder (FCSB) as 37.2%. From Table 3 the natural aggregate impact value is lesser than FCH artificial aggregate. Also, it was seen that the impact values are lower for the aggregates manufactured with hydrated lime binder combination than cement binder. The impact strength of all the aggregates manufactured in the present study was not exceeding 40% by weight which satisfies the structural specification as per code IS: 2386-Part IV (1963) and IS: 9142-Part 2 (2018). Further, it was noted that the impact strength depends on the binder added at the time of pelletization which was responsible for improving properties with development of microstructure as well.

Priyadharshini *et al*. (2011) noted that the impact strength of artificial aggregates was 25.4%, the subsequent impact strength achieved in the present study for FCH aggregate was 16.5%. The impact strength achieved in this study justifies with the test data of (Priyadharshini *et al*. 2011).

5.2.7 Individual pellet crushing strength of artificial aggregates

The experimental results on the individual artificial aggregate crushing strength were given in Table 7. Also, it was noticed that irrespective of various mix combinations,

Table 7 Individual pellet crushing strength test results of lightweight aggregates

Type of aggregate	Pellet crushing strength (MPa)					
	20 mm	16 mm	12 mm	10 mm	8 mm	6 mm
FC	19.6	23.7	24.1	25.2	30.6	45.8
FCG	12.9	16.9	17.3	22.31	23.7	27.7
FCH	19.2	19.7	24	26.7	29.5	34.7
FCSF	6.9	7.6	8.7	8.91	11.1	13.6
FCSB	6.7	6.9	8	8.9	11.9	16.3
FCCB	5.8	6.9	8.7	9.9	13.9	19.8
FCM	7.1	7.7	10.2	10.8	11.5	16
FHSF	22.8	23.3	25.5	28.5	33.4	46.5
FHSB	17.5	18.8	19.2	19.8	21	22.2
FHCB	17.3	18.8	19.2	21.4	22.4	24.7
FHM	17.5	19.5	21.2	22.9	26.9	27.2
FHG	35.9	36.6	36.7	44.6	45.9	47
FSFM	18.2	21.9	22.9	24	29.9	43.3

for the small size aggregate (6 mm) gives maximum strength compared to large size aggregate (8, 10, 12, 16 and 20 mm) respectively. The highest individual 12 mm aggregate crushing strength of 36.7 MPa for hydrated lime and GGBFS binder (FHG) and the lowest crushing strength of 8 MPa for cement and sodium bentonite binder (FCSB). From the investigations, the crushing strength of pellets was higher for aggregates manufactured with hydrated lime combination with pozzolanic binder materials like GGBFS and silica fume. However, GGBFS is a hydraulic substance that hardens itself within the existence of water. Also, high CaO substance in the GGBFS is activated by the hydrated lime utilized in the manufacturing of aggregates that reports for the higher pellet crushing strength. Furthermore, the capillary force produced at the time of the pelletization method with decreasing void ratio gives rise to stronger GGBFS and hydrated lime aggregates. As a result, the fineness of binders had exposed the nearest packing of particles which leading to greater efficiency in terms of strength, inter-particle bonding and filler effect (Gesoglu *et al*. 2004, Chi *et al*. 2003, Le Anh-tuan Bui *et al*. 2012 and Yaragal *et al*. 2016).

Chi *et al*. (2003) noticed that the crushing strength for 10 mm artificial aggregates was 8.57 MPa, the following crushing strength attained in the present study for FCH 10 mm aggregate was 26.7 MPa. The crushing strength attained in this study justifies with the test data of (Chi *et al*. 2003).

6. Conclusions

Based on the experimental study of various cold-bonded artificial aggregates following conclusions were drawn.

• The production efficiency of artificial aggregates mainly depends on type of binder material, water content and pelletization time.

• The artificial aggregates manufactured with hydrated lime binder mix combination shows better results than cement binder mix combination.

• The FHG and FCH type artificial aggregates shows good results, in terms of highest efficiency, higher specific gravity, lower water absorption, lower impact strength and highest individual pellet crushing strength.

• The results obtained from artificial aggregates were consistent with comparative results of natural gravel aggregate. Hence, it may conclude that, artificial aggregates can be used for the production of structural lightweight concrete.

• Finally, the utilization of industrial by-products like fly ash and GGBFS in the manufacturing of artificial aggregates is an alternate potential constituent in concrete and sustainable for disposal problems.

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