PROPERTIES OF GLASS FIBER REINFORCED COLD-BONDED ARTIFICIAL LIGHTWEIGHT AGGREGATES WITH DIFFERENT BINDERS

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Increased construction activities, leads in deficiency of conventional building materials. To overcome the problem now a day's different techniques have been used to benefit industrial by-products which are available in large quantities. Manufacturing of artificial lightweight aggregates by pelletization method is one important technique to substitute natural aggregates in concrete. The present study examines the manufacturing of twenty one (21) different types of artificial aggregates from industrial by-products with the addition of glass fibers at a fixed 17min pelletization time, along with 28% of water content. Manufactured fresh pellets were air-dried for 24 hours and later hardening of aggregates through cold-bonding technique (Water Curing) at room temperature for 28 days and tested with different aggregate properties. The study results that the highest individual aggregate compressive strength of 48.1MPa was observed for 12mm F21 aggregate. The lowest impact strength of 13.3% for F16 aggregate. Similarly, the lowest water absorption of 16.3% was noticed for F14 aggregate. The impact of binders with fibers in the manufacturing of aggregates was noted to be an essential factor for attaining high strength artificial aggregates.

Keywords: *pelletization method, cold-bonded fiber-reinforced artificial lightweight aggregates, alkali-resistant glass fiber, physical and mechanical properties, SEM.*

1. Introduction

With the increase in the development of the construction industry globally, scarcity of conventional construction materials occurred, whichmade it essential to increase in advanced construction materials. The economic manufacturing process for attaining manufactured aggregates with fly ash could be feasible material for the future construction industry to overcome the problems. The large-scale manufacturing, of artificial aggregates by pelletization is a capable technology. Pelletization is one method that predicts the production of balls from a powdery substance with extra stable round pellets [1]. Lightweight concrete manufactured from artificial aggregates or natural lightweight aggregate [2-9] has potential in the production of prefabricated concrete elements. Lightweight aggregate concrete has major advantages over convention concrete like reduced dead load of the entire structure, greater thermal resistance with better sound-proof nature, insulation material and manufacturing of lightweight blocks [10-15]. In recent years, investigations have been carried out for the manufacturing of various kinds of cold bonded fly ash lightweight aggregates. The benefits of manufacturing artificial aggregate are that it doesn't exhaust ordinary resources and furthermore to stop the damages in construction industries [16, 17]. The ordinary concrete is costly when compared to artificial lightweight concrete [18-20]. From the past reports, information regarding manufacturing methods with parameters impact on properties of artificial aggregates is limited and therefore efficient analysis is needed in this area. Consistent needs for tougher and lighter materials provide the motivation of adjusting and improving the aggregate properties. Therefore, the material could be identified as weak and susceptible to brittle failure. The properties of brittle materials such as concrete can be increased by reinforcement of fibers generally. Different aspects affect the benefit and quantity of fiber-reinforcement.

In the presentstudy, cold-bonded fiber-reinforced lightweight aggregate was manufactured and tested with different physical and mechanical properties. The different types of aggregates were manufactured with different binder materials added with different percentages of glass fiber (0%, 0.17% and 0.34%) by the total weight of materials at the time of pelletization. In this study, the impact of glass fibers on the properties of aggregate was noted with feasible strengthening mechanism are set further and discussed.

2. Experimental Study

2.1. Materials used

The F-Type fly ashwas chosen in the manufacturing of artificial aggregates which is classified as per ASTM C618-19. The fly ash

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Table 1

Chemical and physical properties of different binder materials utilized in this study

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

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

aggregate bonding was attained through binding materials like cement (OPC-53grade), hydrated lime, silica fume, sodium bentonite, calcium bentonite, metakaolin, and steel slag. Alkali resistant glass fiber added at different percentages by the total weight of the material. Water was sprayed on materials at the time of pelletization. Detail chemical and physical characteristics of different materials are given in Table 1.

2.1.1. Alkali Resistant glass fiber

Alkali Resistant glass fibers were added to the manufacturing of artificial lightweight aggregates and characteristics are given in Table 2. It is a lightweight and high tensile material, which is evaluated as per ASTM C1579 [21].

2.2. Manufacturing of artificial lightweight aggregates (Pelletization method)

Fiber-reinforced lightweight aggregates were manufactured by pelletization method as shown in Fig. 1. The disc pelletizer was fabricated with a diameter of 500mm and 250mm depth. Based on different trials to attain maximum efficiency in the manufacturing of aggregates inclination angle and speed was fixed at $36^0$and 55rpm with fixed 17 minutes pelletization time. Around 28% of water was sprayed over the materials for the duration of the first 8 minutes to get the spherical balls, additional 9 minutes was allotted to extra stiffening of the pellets to enhance bonding.

Table 2

Physical characteristics of Alkali resistant glass fiber

Characteristics of Alkali resistant glass fiber		
Characteristics	Units	Values
Specific gravity	-	2.68
Density	kg/m^3	845
Elastic modulus	GPa	72
Tensile strength	MPa	1700
Filament diameter	microns	14
Length	mm	12
Loss on ignition	%	1.16
Moisture content	%	0.5

In total 21 combinations, from F1 to F21 types of lightweight aggregates were manufactured with and without glass fibers from various binder materials. From F1 to F7 mix combinations aggregates manufactured without fiber and the remaining F8 to F21 mix combinations alkali-resistant glass fiberwas added with 0.17% and 0.34% with same mix combinations are specified in Table 3. In the beginning, base material fly ash with binders was added in the disc pelletizer and mixed homogeneously for 2 minutes and then fibers were added and mixed for another 1 minute; then required 28% of water is sprayed within the disc and pelletization continued. During this method, initially, the pellets are small as the duration increases the pellets size increase and stops at some point in time. Finally, after the completion of pelletization, the fresh pellets were collected from the disc. After manufacturing, the fresh pellets

Table 3

Mix combinations of various lightweight aggregates manufactured with and without glass fiber

Mix ID	Type of aggregate	Binder content (%)								Glass fiber content (%)
		FA (F)	C	HL	SF	SB	CB	MK	GGBFS	
F1	FC	80	20	-	-	-	-	-	-	0.0
F2	FCH	80	10	10	-	-	-	-	-	0.0
F3	FHSF	80	-	10	10	-	-	-	-	0.0
F4	FHSB	80	-	10	-	10	-	-	-	0.0
F5	FHCB	80	-	10	-	-	10	-	-	0.0
F6	FHM	80	-	10	-	-	-	10	-	0.0
F7	FHG	80	-	10	-	-	-	-	10	0.0
F8	FC1	80	20	-	-	-	-	-	-	0.17
F9	FCH1	80	10	10	-	-	-	-	-	0.17
F10	FHSF1	80	-	10	10	-	-	-	-	0.17
F11	FHSB1	80	-	10	-	10	-	-	-	0.17
F12	FHCB1	80	-	10	-	-	10	-	-	0.17
F13	FHM1	80	-	10	-	-	-	10	-	0.17
F14	FHG1	80	-	10	-	-	-	-	10	0.17
F15	FC2	80	20	-	-	-	-	-	-	0.34
F16	FCH2	80	10	10	-	-	-	-	-	0.34
F17	FHSF2	80	-	10	10	-	-	-	-	0.34
F18	FHSB2	80	-	10	-	10	-	-	-	0.34
F19	FHCB2	80	-	10	-	-	10	-	-	0.34
F20	FHM2	80	-	10	-	-	-	10	-	0.34
F21	FHG2	80	-	10	-	-	-	-	10	0.34

(a). Different materials (b). Glass fiber (c). Disc pelletizer

(d). Air-dry for 24hrs (e). Cold-bonding (f). Final aggregate

Fig. 1 - The Manufacturing process of artificial lightweight aggregates.

were air-dried for 24hours and subsequent hardening of pellets through a cold-bonding technique (Water Curing) for 28 days at room temperature around 23^{0}C as shown in Fig. 1.

2.3. Tests conducted on artificial lightweight aggregates

After the curing period, the artificial aggregates were sieved into size fractions varying from 20mm to 2.36mm as per IS: 2386-(Part I)-1963 [23]. The efficiency of the aggregates produced was noted; later the various properties of artificial aggregates were tested for specific gravity, water absorption, bulk density, impact strength and the compressive strength of individual pellets. The specific gravity and water absorption tests were conducted as per IS: 2386-(Part III)-1963 [24]. The bulk density was conducted as per IS: 2386-(Part III)-1963 [24]. The impact strength test was performed as per IS: 2386-(Part IV)-1963 [25] as shown in Figure 2. The compressive strength of individual artificial aggregates tested by means of California bearing ratio (CBR) testing apparatus is shown in Figure 3. The individual compressive strength 'σ' was measured in N/mm^2 (or) MPaand calculated by means of strength index formula given in Equation 1 [26].

Individual compressive strength 'σ'= $\frac{2.8 \times P}{\pi \times d^2}$(1)

Where P =failure load and

d = distance between the two platesor diameter of the pellet

Fig. 2 - Aggregate impact test apparatus.

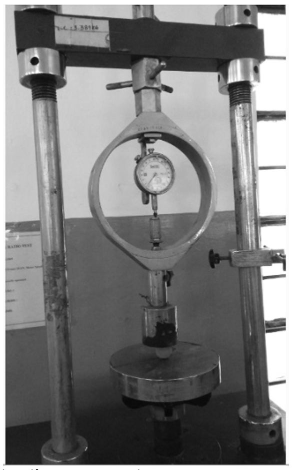

Fig. 3 - CBR testing apparatus.

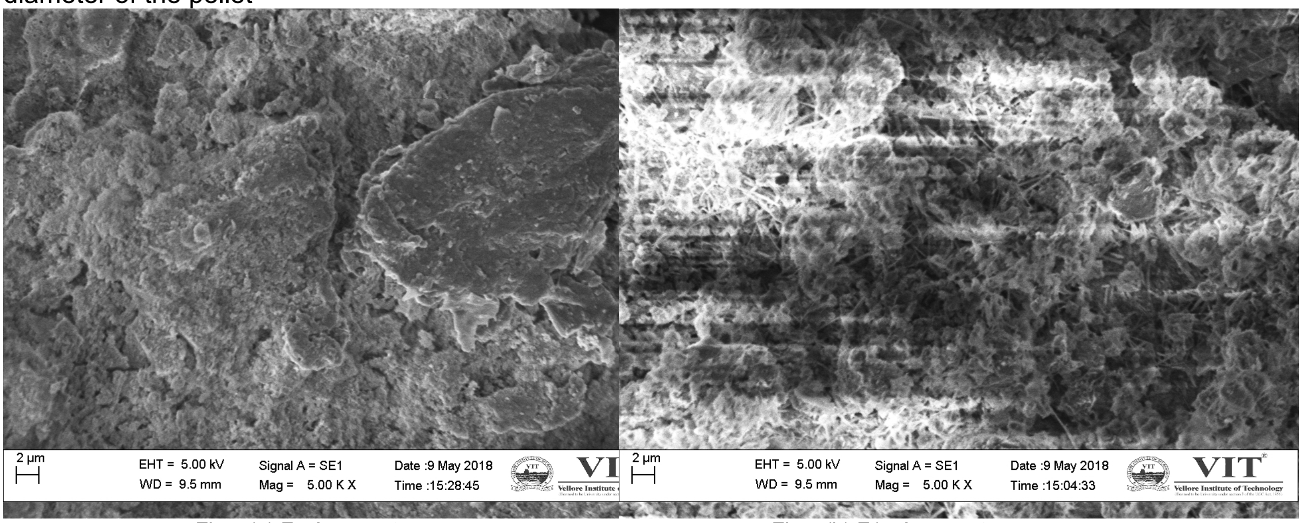

Fig.4 (a) F7 Aggregate

Fig.4 (b) F14 Aggregate

Fig. 4 - SEM observations of fiber-reinforced aggregates with 5KX magnification

2.4. Scanning electron microscope (SEM) studies of artificial lightweight aggregates

SEM studies were performed on the breaking surface of artificial aggregates with a standard size of 1cm were kept in an oven for 24hours at 105 ± 5^{0}C to eliminate evaporable water content and mounted on alloy stubs and sputter physical and chemical interfacial action [27]. covered (If sample is not electrically conducting, it will require carbon or gold coating, generally samples are coated with carbon to get clear images) before subjecting to the electron beam from a ZEISS EVO/18 with required magnification. In this part, the SEM was engaged to explain the microstructure of artificial lightweight aggregates. Strength of artificial aggregates depends on

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 (portlandite), therefore results to a solid structure as shown in Figure.4(a). 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 for filling voids. Crystals of calcium hydroxide (portlandite), long with slender needles of ettringite and crystals of C-S-H as shown in Figure. 4 (b) with 5KX magnification. Aggregates combination with hydrated lime binder shows dense structure compared with aggregate manufacture with cement. From all the type of aggregates, the aggregate with a combination of hydrated lime and GGBFS binders with 0.17% fiber shows less pore structure.

3. Results and Discussions

3.1. Properties of Natural gravel aggregate

Artificial lightweight aggregates are spherical in shape whereas natural aggregate is angular in shape. Table 4 shows the characteristics of natural gravel aggregate as per Indian Standards. Further, the different artificial lightweight aggregates were manufactured and compared with natural gravel aggregate.

Table 4

Characteristics of Natural gravel aggregate

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

3.2. Properties of Artificial lightweight aggregates

3.2.1. Grading of fiber-reinforced artificial lightweight aggregates

The size and shape of the artificial aggregate gradation is the most important factor in the mix design of lightweight concrete. Grading of the cold-bonded aggregates manufactured with the addition of glass fibers areachievingtheir requirements as per IS: 9142 (Part 2) – 2018 [22] and it was calculated as per IS: 2386 (Part I) – 1963 [23]. The percentage of aggregates produced with respect to sizes at the time of manufacturing with fineness modulus is given in Table 5. It can be noticed 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 have been conducted to fix the pelletization time and water content. Usually, it is noticed that the manufacturing of pellets mainly depends on the type of binder added and the pelletization time. With the addition of glass fibers, the size of the aggregates will differ compared with reference aggregate without fibers. Hence, it is observed that fineness modulus values.

Table 5

Percentage of artificial aggregates produced with respect to sizes and Fineness modulus

Mix ID	Percentage of the aggregates produced with respect to sizes (mm)				Fineness modulus
	20	10	4.75	2.36	
F1	13.43	78.32	7.99	0.23	6.77
F2	9.96	74.73	15.19	0.13	6.59
F3	22.29	67.16	10.36	0.175	6.87
F4	13.43	65.97	20.44	0.134	6.54
F5	10.98	77.69	11.18	0.133	6.70
F6	10.36	75.13	14.24	0.25	6.59
F7	37.95	53.05	8.83	0.158	7.07
F8	8.57	78.93	12.2	0.3	6.60
F9	10.87	77.24	11.55	0.33	6.56
F10	3.67	79.37	16.48	0.48	6.36
F11	4.5	76.35	18.58	0.57	6.32
F12	3.32	59.7	36.38	0.6	5.91
F13	4.68	78.33	16.39	0.6	6.37
F14	5.1	80.37	14.07	0.47	6.44
F15	8.15	79.72	11.71	0.42	6.59
F16	5.62	80.97	13.03	0.38	6.47
F17	5.72	77.38	16.36	0.53	6.38
F18	4.8	77.28	17.15	0.77	6.35
F19	4.45	60.68	34.03	0.83	5.96
F20	4.77	80.66	14.11	0.45	6.42
F21	5.58	80.52	13.43	0.47	6.46

3.2.2. Manufacturing efficiency of artificial lightweight aggregates

The efficiency of the pelletization method was visually noticed and determined in step with the quantity of the ultimate product that is a lightweight aggregate. The manufacturing efficiency of fiber-reinforced artificial aggregates mainly depends on the performance of the pelletization method and binder content added at the time of pelletization. From the investigations, excellent efficiency of pelletization was found when the angle was positioned at 36^0angles with 55rpm speed of pelletizer. The manufacturing efficiency of different aggregates is shown in Figure. 5 - 7. Hence, for the entire study angle of $36^0$with a speed of 55rpm was maintained, for attaining the greatest efficiency with 17min of pelletization time. Mainly, the lightweight aggregate production depends on the binder material and water content added at the time of pelletization. The efficiency differs for different levels, which is from fresh pellets to pellets before testing. Efficiency also

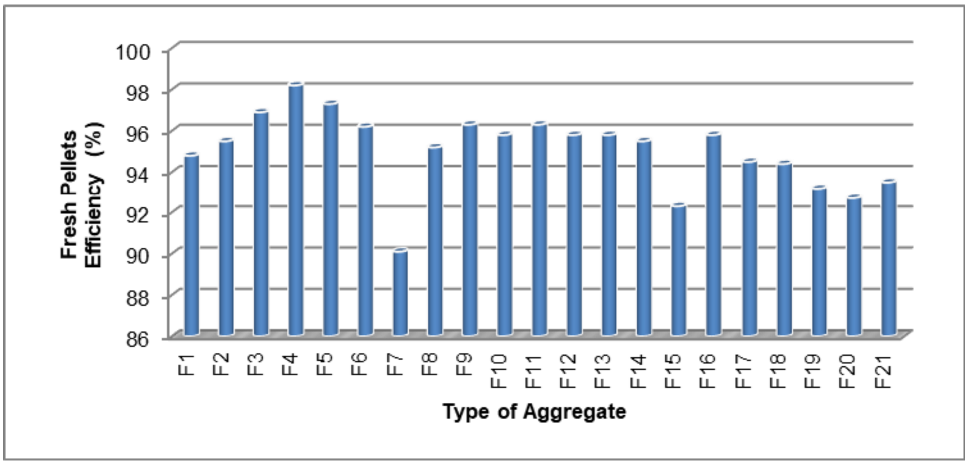

Fig. 5 Production efficiency of fresh pellets

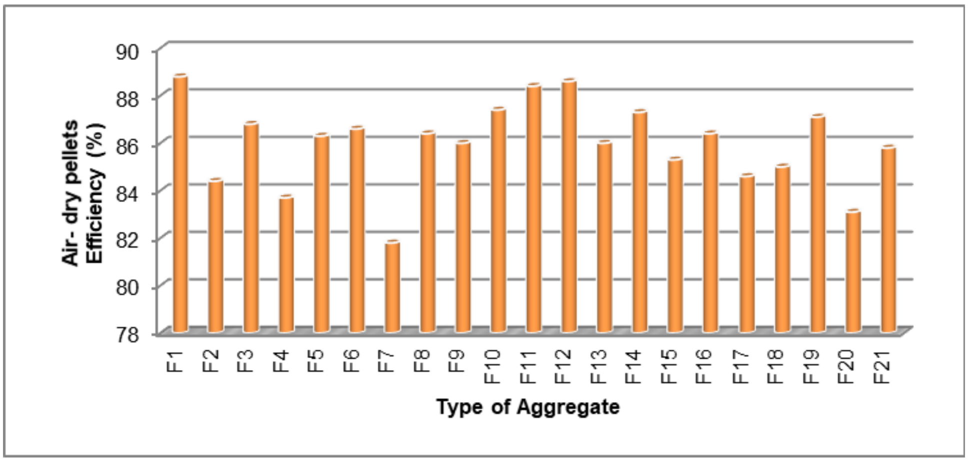

Fig. 6 Production efficiency of air-dry pellets

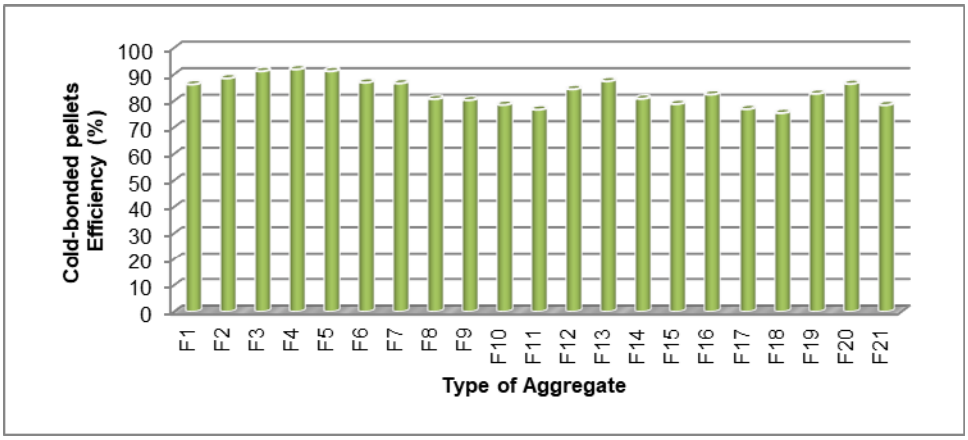

Fig. 7 Production efficiency of cold-bonded pellets

depends on the environmental condition at the time of pelletization, in case of full hot water demand is more and in cold conditions the material may form lumps which decrease the efficiency. Hence, the manufacturing of aggregates to be done at room temperature to overcome environmental effects. In the case of fresh pellets,the maximum efficiency was observed for F4 aggregate and similarly, minimum efficiency for F18 aggregate before testing. An excellent bonding efficiency in the stable production of pellets was observed with the addition of a binder and glass fiber in the fly ash. The efficiency of aggregate production does not depend on the characteristics of the aggregates.

3.2.3. Specific Gravity of artificial lightweight aggregates

Specific gravity value plays major role in the mix design of lightweight concrete. Based on the results, the specific gravity values of different

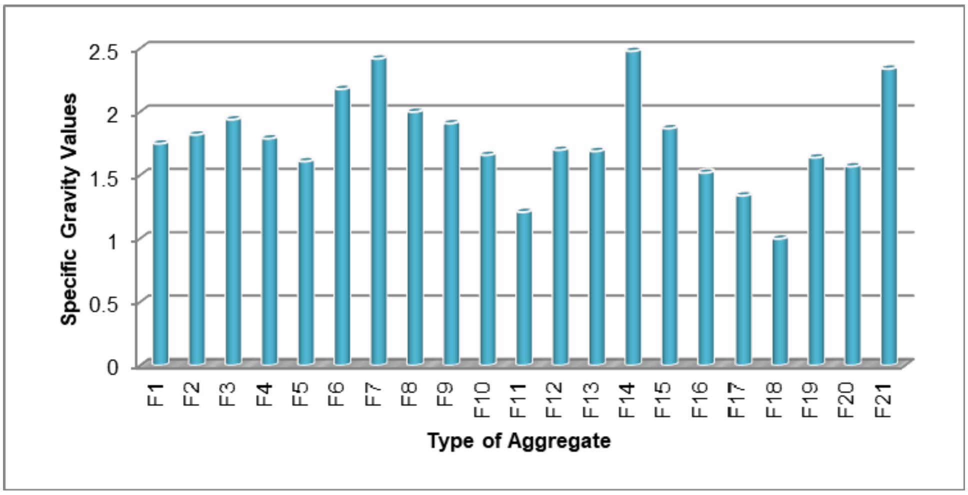

Fig. 8 Specific gravity values of different artificial aggregates

artificial aggregates are given in Figure. 8. Specific gravity values of aggregates manufactured with hydrated lime - GGBFS binder with 0.17% fiber (F14) was observed to be higher as 2.48, which are more than 2.12 in which artificial aggregates manufactured with fly ash, cement, and lime binder [28].Similarly, the least specific gravity was noted for hydrated lime – sodium bentonite binder with 0.34% fiber (F18) as 1.0. From the Figure, it is clear for the F14 type aggregate addition of 0.17% glass fibers the specific gravity values increase again addition the values getting decreased. This shows the influence of the addition of hydrated lime - GGBFS binder with 0.17% glass fibers in aggregate manufacturing, Lower specific gravity related to the reduced stiffness of artificial lightweight aggregates [29]. The specific gravity of natural aggregate is given in Table 4which is 8.4% higher than F14 type artificial aggregate, which is almost closer to the natural gravel aggregate value. The increase in specific gravity values was noticed for the cement (FC), hydrated lime – calcium bentonite (FHCB) binder. Whereas a decrease in specific gravity values was observed for hydrated lime – silica fume (FHSF), hydrated lime – sodium bentonite (FHSB) and hydrated lime – metakaolin (FHM) binder combination. For hydrated lime – cement (FCH) and hydrated lime – GGBFS (FHG) binder, the specific gravity values are increasedfor 0.17% fibers and for 0.34% fibers specific gravity value decreases.

3.2.4. Water absorption of artificial lightweight aggregates

The 24hours water absorption values of various artificial aggregates manufactured with and without glass fibers as shown in Figure. 9. It is observed that the lowest water absorption was obtained for hydrated lime - GGBFS binder with 0.17% fibres (F14) as 16.3% which is less than 18% as per IS: 9142 (Part 2) – 2018 [22] and the highest water absorption value was obtained for hydrated lime – sodium bentonite binder with 0.34% fibers (F18) as 36.5%. More water absorption has the ability to lead to greater porosity. From the results, it is concluded that the

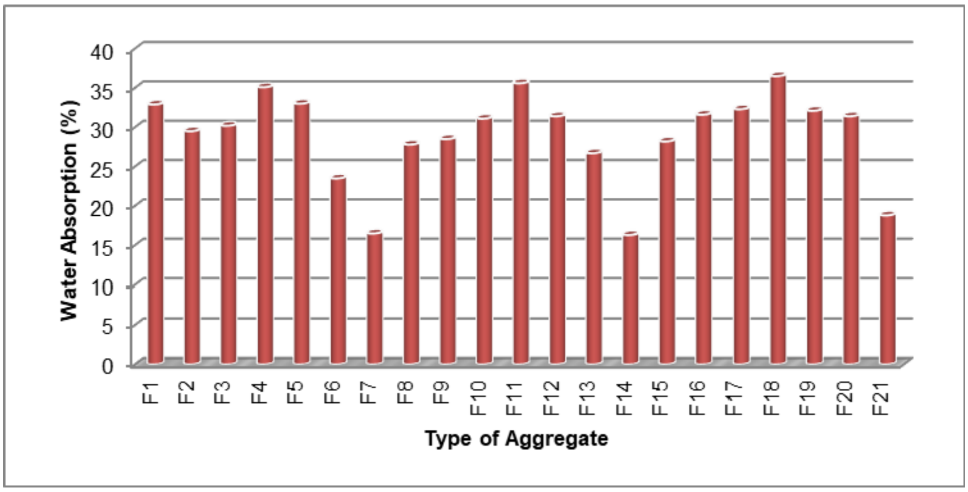

Fig. 9 Water absorption values of different artificial aggregates

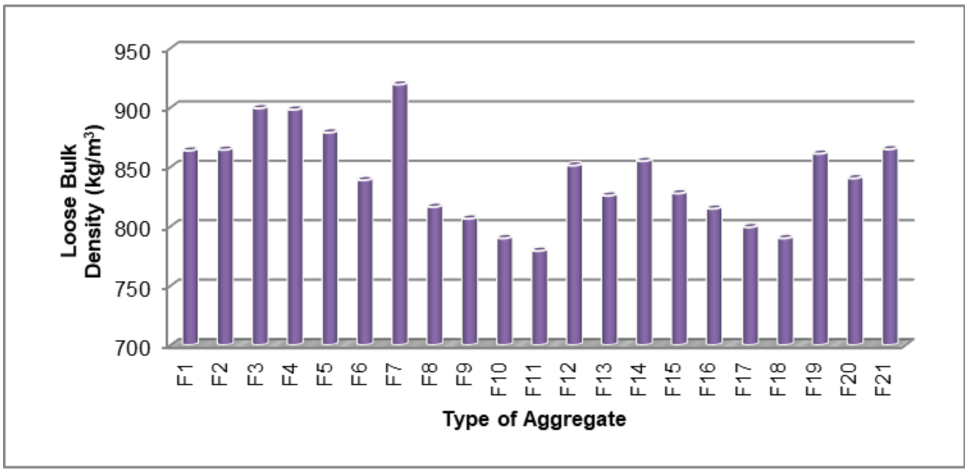

Fig. 10 Loose Bulk Density values of different artificial aggregates

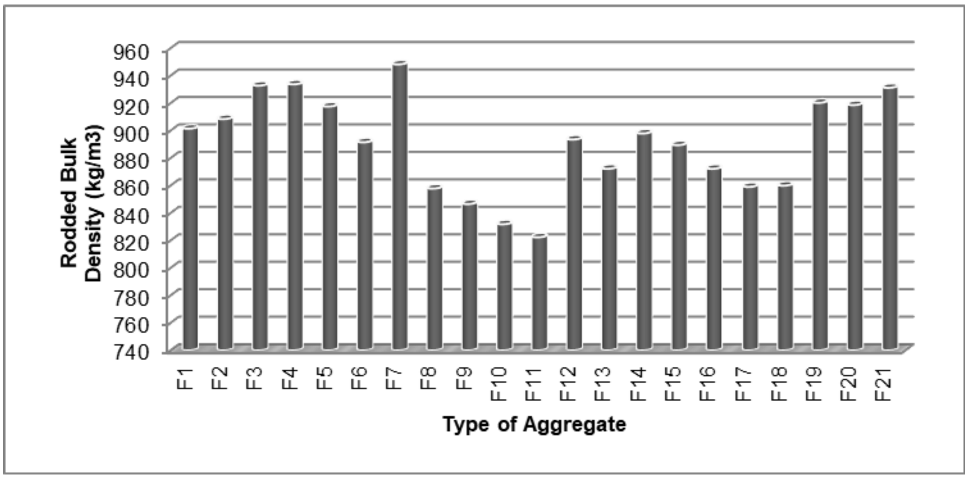

Fig. 11 Rodded Bulk Density values of different artificial aggregates

decrease in water absorption was noticed with the addition of glass fibers at 0.17% and again addition at 0.34% fibers the water absorption values increase. From the overall results, very much decrease in water absorption for cement (FC) binder alone around 15.5% for 0.17% fibers and a 14.3% decrease for 0.34% fibers. Therefore, FHG1 (F14) artificial aggregate combination shows a higher reduction in absorption values compared with aggregates manufactured with cement and fly ash binder combination in which 20.8% and 24% water absorption values obtained [28, 29 and 30].Higher water absorption values with high porosity related to the decreased in stiffness of artificial lightweight aggregates [29]. Water absorption values of all the artificial aggregates are very much higher when compared with natural gravel aggregate which is given in Table 4. The effect of utilizing pozzolanic binders with fibers was to give less porous lightweight aggregates, which involves the hydration reaction produces solid structure due to alarge amount of calcium silicate hydrate (C–S–H).

3.2.5. Bulk density of artificial lightweight aggregates

The loose bulk density (L.B.D) and rodded bulk density (R.B.D) of fiber-reinforced artificial lightweight aggregates manufactured with different binders are given in Figure. 10, 11. It is noted that the highest bulk density was observed for hydrated lime - GGBFS binder without fiber (F7) as 919.4kg/m^3 and lower bulk density for hydrated lime - sodium bentonite binder with 0.17% fibers (F11) as 779.4kg/m^3. All the **fiber-reinforced** lightweight aggregates manufactured will be satisfying the loose bulk density **(L.B.D)** values as perIS: 9142 (Part 2) – 2018 [22]. The bulk density of F7 artificial aggregate is 40% lesser than natural gravel aggregate which is given in Table 4. The highest bulk density occurred because of good pore structure while pelletization which results in lower water absorption [30]. Furthermore, the bulk density was found to decrease with the addition of fiber content compared to reference aggregate without fibers. The bulk density values are lower for the hydrated lime mix combinations than cement binder mix combination.

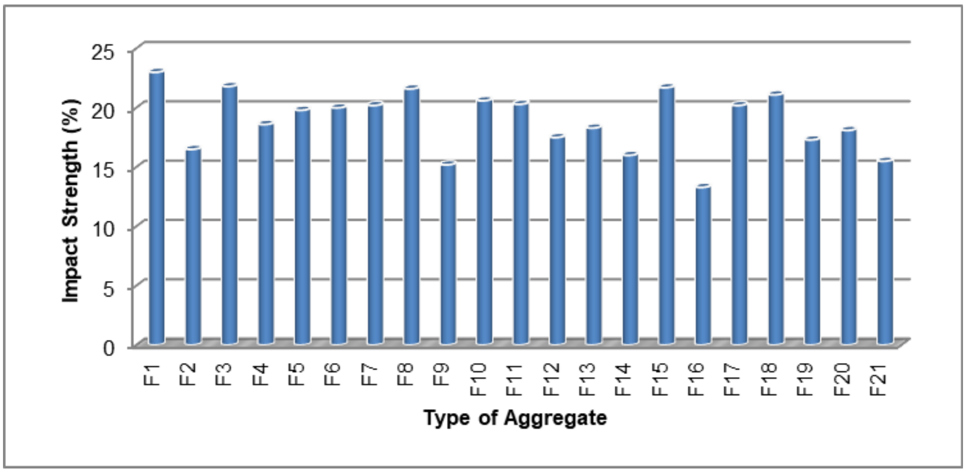

Fig. 12 - Impact Strength of different artificial aggregates

3.2.6. Aggregate impact strength values of artificial lightweight aggregates

Impact strength test results of fiber-reinforced artificial aggregates manufactured with various binders are given in Figure. 12. It is examined that the lowest impact strength for cement – hydrated lime binder with 0.34% fibers (F16) as 13.3% and highest impact strength for cement binder without fibers (F1) as 23%. From Table 4, results show that the natural gravel aggregate impact value is lesser than the F16 type artificial aggregate. All the mix combination of aggregates with various binders and glass fiber satisfies the structural demand as per IS: 2386 (part IV) – 1963 [25] and IS: 9142 (Part 2) – 2018 [22]. The artificial aggregates manufactured with fly ash, cement, lime mix binder combination have 25.4% impact strength [28] which is much higher than F16 type artificial aggregate.It is found from the test results that, the impact strength of various artificial aggregates manufactured depends on the type of binder and percentage addition of glass fiber. This enhanced the bonding properties with an increase of microstructure. All the mix combinations except hydrated lime and sodium bentonite (FHSB) binder as the percentage increase in glass fiber the impact values decreases. The highest percentage increase of 13.4 with reference aggregate for hydrated lime - sodium bentonite binder with 0.34% fibers (F18)

Table 6

Individual pellet compressive strength of artificial lightweight aggregates

Mix ID	Compressive strength of individual aggregate (MPa)					
	20mm	16mm	12mm	10mm	8mm	6mm
F1	19.6	23.7	24.1	25.2	30.6	45.8
F2	19.2	19.7	24.0	26.7	29.5	34.7
F3	22.8	23.3	25.5	28.5	33.4	46.5
F4	17.5	18.8	19.2	19.8	21.0	22.2
F5	17.3	18.8	19.2	21.4	22.4	24.7
F6	17.5	19.5	21.2	22.9	26.9	27.2
F7	35.9	36.6	36.7	44.6	45.9	47.0
F8	20.7	25.0	25.8	28.6	37.6	47.5
F9	21.1	22.7	27.2	33.1	44.8	45.5
F10	22.9	23.3	26.8	29.6	38.0	42.3
F11	14.0	18.5	19.0	24.4	26.2	29.5
F12	17.4	21.9	29.8	33.1	35.2	37.9
F13	18.3	22.0	25.4	29.1	33.3	37.8
F14	40.8	44.2	47.8	52.3	56.1	57.4
F15	20.6	25.0	25.2	29.0	39.0	44.5
F16	22.3	23.4	28.6	34.1	46.2	47.3
F17	22.9	23.6	25.5	29.2	34.8	39.4
F18	13.8	18.2	18.7	22.5	25.3	27.4
F19	17.6	22.3	30.5	34.0	34.4	39.8
F20	18.2	22.0	25.5	29.5	32.3	39.1
F21	41.0	43.3	48.1	50.7	56.7	58.4

and similarly the highest percentage decrease of 23.3 for hydrated lime - GGBFS binder with 0.34% fibers (F21). In general, all the lightweight aggregates manufactured with glass fibers exhibit higher impact values.

3.2.7. Individual Aggregate compressive strength of artificial lightweight aggregates

The experimental results on the individual aggregate compressive strength of fiber-reinforced artificial aggregates are given in Table 6. Strength investigations were considered based on the type of binder with the added percentage of glass fibers. Also, it is noticed that irrespective of various mix combinations for the small size aggregate (6mm) gives maximum strength compared to large size aggregate (8, 10, 12, 16 and 20mm) respectively. It is noticed that as the percentage increase in glass fiber the compressive strength increases for all the types of aggregates. A highest individual 12mm aggregate compressive strength was observed for hydrated lime - GGBFS binder with 0.34% fiber (F21) as 48.1MPa and the lowest compressive strength for hydrated lime - sodium bentonite binder with 0.34% fiber (F18) as 18.7MPa. Moreover, the fineness of materials had offered the major amount of adjacent packing of particles caused due to greater efficiency in the form of strength through water stiffness.

In the present study, cold-bonded artificial aggregates produced were found to be acceptable in terms of strength due to their strong binding efficiency because of intergranular particles bonding. It is additionally necessary that the specific surface area (SSA) increases when the binding material particles are finer and can produce quicker filling of intergranular particles [9, 29-32]. Artificial aggregates manufactured with fly ash, bentonite binder combination have 23.1MPa compressive strength for 10mm aggregate which is much lesser when compared with F21 type aggregate [33]. Also, the aggregates manufactured with and without fibers from pozzolanic binder exhibits higher strengths than clay form binders. The highest percentage increase in compressive strength of 61.1 for hydrated lime and calcium bentonite binder at 0.34% fibre (F19) for 6mm pellet with reference aggregate and the highest percentage decrease in compressive strength of 0.4 for hydrated lime and silica fume binder for 20mm pellet at 0.17% and 0.34% fibre (F10 and F17) with reference aggregate. In general, it is concluded that the different fiber-reinforced lightweight aggregates manufactured in this study give a reasonable strength gaining meeting the performance demands of artificial lightweight aggregates.

4. Conclusions

Based on the investigational results, the following conclusions are drawn.

1. The addition of alkali-resistant glass fibers with different binders during pelletization provided an extra stable production of aggregates with improved physical and mechanical characteristics.
2. The artificial aggregates manufactured with ternary mix combination exhibited greater efficiency with higher strength than with binary mix combination (F1, F8, and F15).
3. Specific gravity values were observed to be higher as 2.48 for F14 aggregate and the least specific gravity as 1.0 was noticed for F18 aggregate. The specific gravity of natural aggregate is 8.4% higher than the F14 artificial aggregate.
4. The lowest water absorption was observed for F14 aggregate as 16.3% and the highest water absorption for F18 aggregate as 36.5%. The natural gravel aggregate water absorption value is very much lesser compared with all the types of artificial aggregates. Also, a decrease in water absorption was noticed with the addition of glass fiber at 0.17% and again addition at 0.34% fibers the water absorption values increases.
5. The lowest bulk density of 779.4kg/m^3 was observed for F11 aggregate and the highest bulk density of 919.4kg/m^3 for F7 aggregate. The bulk density of F7 artificial aggregate is 40% lesser than natural gravel aggregate.
6. The highest impact strength was noticed for F1 aggregate as 23% and the lowest impact strength for F16 aggregate as 13.3%. The natural aggregate impact value is lesser than the F16 type of artificial aggregate.
7. A highest individual 12mm aggregate compressive strength of 48.1MPa was noticed for F21 aggregate and the lowest compressive strength of 18.7MPa for F18 aggregate. Irrespective of fiber content and a binder material, as the size of aggregate decreases pellet crushing strength increases, due to its decrease in specific surface area.
8. However, due to the fineness of binder materials packing of particles leading to greater efficiency in the form of lower impact strength, lower water absorption, higher specific gravity and higher compressive strength of individual pellets manufactured with 0.17% fibers which are comparable with natural gravel aggregate.
9. It is summarized that for artificial lightweight aggregates with the addition of glass fibersat 0.17% is optimum. Hence, the aggregates manufactured with fly ash-hydrated lime-GGBFS with 0.17% glass fibers (F14) exhibited adequate results.

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