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IMPACT OF NANO SIO2 ON THE PROPERTIES OF COLD-BONDED ARTIFICIAL AGGREGATES WITH VARIOUS BINDERS

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ABSTRACT

The impact of nano SiO_2 particles on the physical and mechanical properties of cold-bonded artificial lightweight aggregates by the pelletization process is investigated in this study. Twelve (12) varying cold-bonded artificial lightweight aggregates were manufactured from fly ash, cement, hydrated lime, metakaolin and steel slag (GGBFS) binder, with the addition of 0%, 0.5%, 1% and 1.5% nano SiO_2, at a standard 17 min pelletization time, with 28% water content on a weight basis. The aggregates were air-dried for 24 hrs, followed by hardening of the pellets by cold-bonding (water curing) for 28 days and then testing. The study found the highest individual aggregate compressive strength of 49.3 Mpa for 12mm aggregate and lowest water absorption of 12.5% with a 0.5 FHG combination. Moreover, the lowest impact strength of 13.6% for the 0.5 FCH aggregate combination was observed. The results, obtained from different binders and the influence of nano SiO_2 particles, could be very useful in the enhancement of both the physical and mechanical properties of artificial lightweight aggregates.

Keywords: Cold-bonded artificial lightweight aggregates; Nano SiO_2; Pelletization process; Physical and mechanical properties; Scanning electron microscope

1. INTRODUCTION

Artificial lightweight aggregates (LWA) are produced from either conventional materials or industrial by-products (Cheeseman & Virdi, 2005; Turu'allo, 2015; Han et al., 2016). The manufacture of LWA from industrial by-products is by means of the pelletization process, which involves cohesive as well as tumbling forces, which bond the moisture particles. The fresh pellets are removed from the pelletizer and air-dried for 24hrs to attain strength for handling, but not to the level of utilization in concrete. Therefore, hardening techniques need to be subsequently used to produce stronger pellets (aggregates) and some of the materials used to enhance the properties of artificial light weight aggregates which are utilized in concrete (Ramadhansyah et al., 2011; Vali & Abdul, 2016). The hardening of artificial aggregates involves different methods, such as sintering, cold-bonding and auto claving. Among these, sintering has high power demand but leads to high strength aggregates (Wainwright & Cresswell, 2001; Cheeseman & Virdi, 2005; Ramamurthy & Harikrishnan, 2006; Tsai et al., 2006; Vali & Murugan, 2017).

Cold-bonding is an alternative and more economical method of sintering (Bijen, 1986). Cold-bonded artificial lightweight aggregates have been manufactured both with Class-C and Class-Ffly ash (Chi et al., 2003; Gesoglu et al., 2004; Manikandan & Ramamurthy, 2007), the addition of binder for Class-F fly ash which has a calcium hydroxide origin in order to enhance theproperties of the aggregates, such as production efficiency, density, specific gravity, water

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absorption and strength (Yang & Huang, 1998; Baykal & Doven, 2000; Gesoglu et al., 2004;Vali & Murugan, 2019).In general, cold-bonded artificial light weight aggregates are heavier than sintered artificial aggregates. C-S-H gel forms during the reaction, which results in the strengthening of the aggregate (Bijen., 1986). LWA properties and their related effect on concrete depend on their microstructure. For the manufacture of artificial light weight aggregates, the binder type hardening method has an impact on their microstructure.

The use of nano technology in the manufacture of cement mortar and concrete is an area of vital interest at present. The majority of nanoscale structure materials have been shown to offer an effective approach to the development of advanced sources of cement-based materials due to their superior properties (Sanchez & Soboley, 2010; Park et al., 2016). Different types of nanoparticles, such as nano-SiO_2, nano-Al_2O_3, nano-TiO_2, nano-ZnO_2, nano-$CaCO_3$, carbon nanotubes and carbon nanofibers, are utilized in concrete to modify its properties. Among these, nano-SiO_2 has attracted interest and has been observed to be efficient because of its pozzolanic reaction with cement-based materials, in addition to the dense microstructure of aggregatedue to its fine particle size (Sanchez & Soboley, 2010). Therefore, this studyaims to determine the physical and mechanical properties of artificial lightweight aggregates without nano SiO_2in order to examine the influence of the addition of different percentages of nano SiO_2 with binder materials and to make a comparison with natural gravel aggregate properties.

2. METHODOLOGY

2.1. Materials Used

The fly ash chosen was classified as F-Type,which is low calcium fly ash as per ASTM C618-19, (2019); it has major advantages (French & Mitham et al., 2007; Malhotra., 2008) and is used for the manufacture of artificial lightweight aggregates.

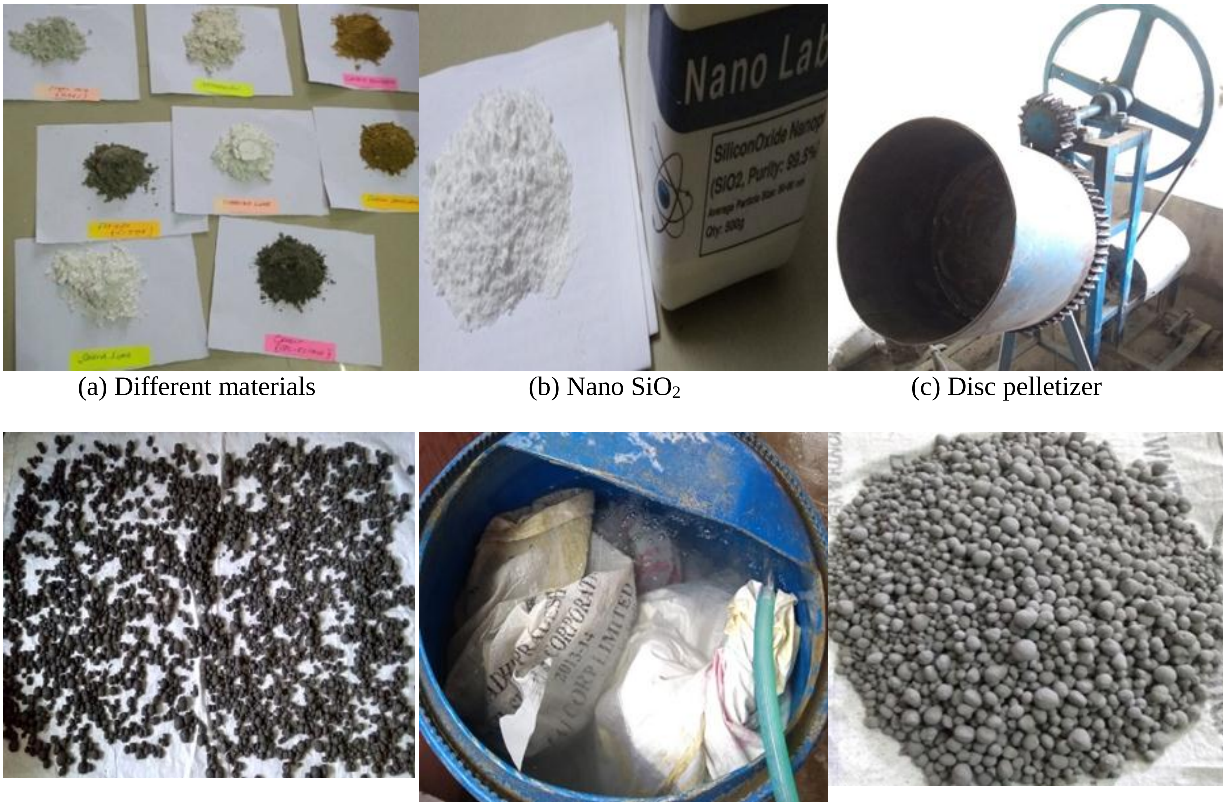
Table 1 Chemical and physical properties of the different binder materials

Observation	Fly ash (F)	Hydrated lime	Cement	Metakaolin	Steel slag	Nano SiO_2
SiO_2	39.4	0.3	22.3	51.35	35	>99.5
Fe_2O_3	18.54	0.23	3	1.21	0.95	<0.05
Al_2O_3	17.9	0.42	6.93	40.31	17.7	<0.02
CaO	17.45	69	63.5	0.32	41	<0.08
MgO	2.88	0.5	2.54	0.11	11.3	<0.1
TiO_2	0.95	-	-	2.13	-	-
Na_2O	0.28	-	-	0.06	0.2	-
K_2O	1.78	-	-	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	-
Specific gravity	2.12	2.24	3.12	2.6	2.85	2.1
Appearance (powder)	Gray	White	Gray	Off-white	Off-white	Pure white
Specific surface area (m^2/kg)	407	-	290	805	409	-
pH Value	-	12.4	6.3	5.1	-	-
Loss on ignition	1.76	-	0.84	2.02	0.26	-
Moisture (%)	0.5	-	-	0.7	0.10	-

The fly ash aggregate bonding was attained through binding materials like cement (OPC-53 grade), hydrated lime, metakaolin, and steel slag. Nano SiO_2 powder of 99.5% purity was added at different percentages by total weight of the material. Water was sprayed onto the materials at the time of pelletization. Details of the chemical and physical characteristics of the different materials are given in Table 1.

2.2. Preparation of Artificial Lightweight Aggregates

For the manufacture of the artificial light weight aggregates, a disc pelletizer was employed, as shown in Figure1. The pelletizer disc was fabricated with a diameter of 500mm with 250mm depth; the inclination angle could be modified between 35° and 50°, and the rotating speed between 40 and 55rpm (Bijen, 1986; Harikrishnan & Ramamurthy, 2006). Following the preliminary investigations conducted on the pelletization method, the inclination angle was fixed at 36º, with a rotation speed of 55 rpm and standard pelletization time of 17 minutes in order to attain maximum efficiency. A total of 12 types of lightweight aggregate were manufactured, with and without the addition of nano SiO_2, as specified in Table 2.



(a) Different materials (b) Nano SiO_2 (c) Disc pelletizer

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

Figure 1 Manufacturing process of the artificial lightweight aggregates

Table 2 Mix combinations of various aggregates manufactured with and without nano SiO_2

Combination	Binder content (%)					Nano SiO_2 (%)
	Fly ash	Hydrated lime	Cement	Metakaolin	Steel slag	
0FHC	80	10	10	-	-	0.0
0FHM	80	10	-	10	-	0.0
0FHG	80	10	-	-	10	0.0
0.5FHC	80	10	10	-	-	0.5
0.5FHM	80	10	-	10	-	0.5
0.5FHG	80	10	-	-	10	0.5
1FHC	80	10	10	-	-	1.0
1FHM	80	10	-	10	-	1.0
1FHG	80	10	-	-	10	1.0
1.5FHC	80	10	10	-	-	1.5
1.5FHM	80	10	-	10	-	1.5
1.5FHG	80	10	-	-	10	1.5

2.3. Tests Conducted on the Different Artificial Lightweight Aggregates

After the curing period, the aggregates were sieved into size fractions varying from 40mm to 0.15mm, as per IS: 2386-(Part I)-1963. The efficiency of the aggregates produced was noted, and their various properties were then tested for specific gravity, water absorption, bulk density, impact strength and the crushing strength of individual pellets. The specific gravity and water absorption tests were conducted as per IS: 2386-(Part III)-1963; the bulk density test was conducted as per IS: 2386-(Part III)-1963, and the impact strength test was performed as per IS: 2386-(Part IV)-1963, as shown in Figure 2. The crushing strength of individual artificial aggregates (pellet) was tested by means of the California bearing ratio (CBR) testing apparatus, as shown in Figure 3.The individual crushing strength 'σ' was calculated by means of the strength index formula, shown as Equation 1 (Kockal & Ozturan, 2010):

$$\text{Individual crushing strength } `\sigma\text{'} = \frac{2.8 \times P}{\pi \times X^2} \quad (1)$$

Where P is the failure load and X is the distance between two plates or diameter of the pellet.

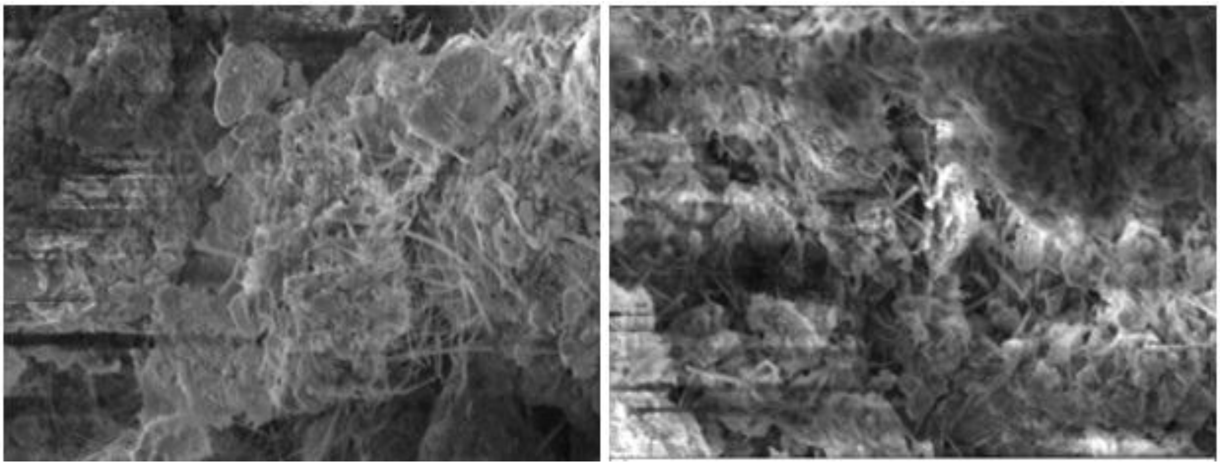
Figure 2Aggregate impact test apparatus

Figure 3Crushing strength test apparatus

2.4. Scanning Electron Microscope (SEM) Studies of the Artificial Lightweight Aggregates

A 1cm size piece of aggregate was placed in an oven for 24 hrs at 105±5ºC to remove the evaporable water content and was mounted on alloy stubs and sputter covered before being subjected to an electron beam from a ZEISS EVO/18. SEM studies were conducted on different artificial lightweight aggregates.The structure of the aggregates with different binder materials shows different pore patterns; in general, these are uneven, round and disconnected, whereas others are stretched out and interconnected. As a result, the artificial lightweightaggregate was investigated through SEM observations at different magnifications.

Microstructure studies suggest that development in the strength of artificial lightweight aggregates with a combination of hydrated lime and steel slag binder is possibly due to a reaction taking place between the minerals and calcium hydroxide (portlandite), resulting in a solid structure. At the time of hydration, the $Ca(OH)_2$ reacts with the steel slag ingredients, developing calcium silicate hydrate (C-S-H), which helps to fill the empty spaces (Jo et al., 2007; Shiho et al., 2013). Crystals of calcium hydroxide (portlandite), which are long with slender needles of ettringite and crystals of C-S-H, can be seen in the 0.5FHG and 1.5FHG aggregates, as shown in Figure 4.



(a) 0.5FHG Aggregate (b) 1.5FHG Aggregate

Figure 4 SEM observations

3. RESULTS AND DISCUSSION

3.1. Properties of Natural Gravel Aggregate

Table 3 present the characteristics of natural aggregate as per Indian Standards. The different artificial lightweight aggregates were manufactured and compared with natural aggregate values.

Table 3 Natural aggregate characteristic values

Characteristics ofnatural 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

3.2. Properties of Artificial Lightweight Aggregates

3.2.1. Grading of artificial lightweight aggregates

Grading of artificial lightweight aggregate size and shape is an important phase within the manufacturing process of lightweight concrete. The cold-bonded aggregates manufactured with the addition of nano SiO_2 and different binder combination satisfy the requirements specified in IS: 9142 (Part 2) - 2018 and calculated as per IS: 2386 (Part I) – 1963. The fineness modulus values were calculated as per the percentage of lightweight aggregates produced at the time of manufacturing, as shown in Table 4. It was noted that initially at the time of pelletizationpellet size was small, but with the increase in pelletization time, the dimensions of the pellets increased. Various trials were conducted to fix the pelletization time with the desired water content.

3.2.2. Grading of artificial lightweight aggregates

The efficiency of lightweight aggregate combinations largely depends on the performance of the agglomeration method, the binder content and the addition of nano SiO_2 at the time of pelletization. From the investigations, excellent pelletization efficiency was achieved when the angle was positioned at 36°, with 55rpm pelletizer speed. The efficiencies of the different artificial lightweight aggregates manufactured are given in Table 4.

The efficiency of the aggregates was calculated for the various levels: at the time of manufacturing of aggregates (fresh pellets); after they had been air-dried for 24hrs (before cold-bonding); and before testing (after cold-bonding). Excellent bonding efficiency within the stable production of pellets was detected with the addition of a binder and nano $SiO_2$to the fly ash. In the case of the fresh pellets and those air-dried for 24hrs, the very best efficiency was found in those with 0.5FHM, and the lowest in the fresh pellets with 0FHG. For the pellets before testing, the best efficiency was found with 0.5FHG and the lowest with 1FHM. It was found that the addition of nano SiO_2 with a binder resulted in good efficiency in the production, with a uniform LWA size.

Table 4 Fineness modulus values and production efficiency of artificial lightweight aggregates

Combination	Fineness Modulus	Efficiency of aggregate production (%)		
		Fresh pellets	After 24hrs	Before testing
0FHC	6.94	95.5	84.4	88.5
0FHM	6.96	96.2	86.6	86.9
0FHG	7.30	90.1	86.8	92.6
0.5FHC	6.90	97.3	88.6	89.5
0.5FHM	6.92	97.8	89.0	88.6
0.5FHG	6.90	95.3	89.8	94.7
1FHC	6.93	96.3	85.5	86.7
1FHM	6.93	94.4	81.3	84.1
1FHG	6.90	93.8	87.4	90.2
1.5FHC	6.88	96.8	81.5	84.8
1.5FHM	6.93	97.3	81.8	84.4
1.5FHG	6.90	96.3	85.6	88.3

3.2.3. Specific gravity values of artificial lightweight aggregates

Based on the results, the specific gravity values of the different artificial lightweight aggregates manufactured with and without the addition of nano SiO_2. From Table5, it can be seen that increases and decreases in the specific gravity values were observed; the specific gravity of 2.64 was noted to be the highest for 0.5 FHG aggregate. In addition, the lowest specific gravity for the 1.5 FHM aggregate, at 1.49. The specific gravity of the natural aggregate, as shown in Table 3, is 1.9% higher than the 0.5 FHG type artificial aggregate which is a minor difference. The higher specific gravity values clearly show that the influence of nano SiO_2 dosage with binder.

As the dosage of nano SiO_2 increases beyond 0.5% the specific gravity values decreases. Hence, the dosage of 0.5% Nano SiO_2 was found to be optimum.

The lower specific gravity values are correlated with the decreased stiffness of the artificial aggregates (Mehmet et al., 2004). The corresponding values of the artificial lightweight aggregates with the addition of 0.5% nano SiO_2 were noted to be higher because the particles experience a packing impact from the packing up of the voids among the particles. Artificial lightweight aggregates manufactured with fly ash, cement, and lime binder have a specific gravity value of 2.12, which is lower than the 0.5 FHG aggregate (Priyadharshini et al., 2011).

3.2.4. Water absorption values of artificial lightweight aggregates

The water absorption values over 24 hrs of the various artificial lightweight aggregates manufactured with and without the addition of nano SiO_2 are given in Table 5. The lowest water absorption was observed for the 0.5 FHG aggregate, at 12.5%, which satisfies the demands of IS: 9142 (Part 2) – 2018, with the highest water absorption of 30.1% for the 1.5 FHC aggregate. It was noticed that the water absorption values of the aggregates followed the porosity and the test showed that the lightweight aggregate porosity decreased with the addition of nano SiO_2 with a binder. High water absorption values with high porosity are associated with the decreased stiffness of the artificial aggregates, resulting in high shrinkage in light weight aggregate concrete (Mehmet et al., 2004).

The results are shown for 0.5FHG aggregate that decreases in water absorption values of around 24.2% to reference aggregate without nano SiO_2. The 0.5 FHG aggregate water absorption is 12.5% which is very much less when compared with the artificial aggregates manufactured with a fly ash and cement binder combination, for which 20.8% and 24% water absorption were obtained (Mehmet et al., 2004; Priyadharshini et al., 2011; Mehmet et al., 2015). Therefore, this can result in the efficient packing of particles and produce a better micro-structure, during which the hydration reaction generates extra C–S–H.

3.2.5. Bulk density of artificial lightweight aggregates

The loose bulk density (LBD) and rodded bulk density (RBD) of the different artificial lightweight aggregates manufactured with and without the addition of nano SiO_2 are given in Table 5. The highest bulk density was observed for 0.5 FHG, at 928 $kg/m^{3,}$ which is lower than the aggregates manufactured with fly ash, cement, and lime, with a corresponding figure of 1247 kg/m^3 (Priyadharshini et al., 2011), with the lowest bulk density for the 1.5 FHM aggregateat 814.8 kg/m^3. All the LBD values of the manufactured artificiallight weight aggregates satisfy the structural demands of IS: 9142 (Part 2) - 2018. The LBD of the 0.5 FHG artificial lightweight aggregate is 37% lower than that of the natural gravel aggregate, as given in Table 3. In addition, the bulk density was found to increase with the addition of 0.5% nano SiO_2 and again the addition of Nano SiO_2 dosage the bulk density values were found to decrease. Nano SiO_2 has a packing effect, which leads to the highest bulk density because of the improved pore structure, while pelletization results in hardened cementitious structure (Chi et al., 2003).

Table 5 Specific gravity, water absorption and bulk density values of artificial lightweight aggregates

Combination	Specific gravity	Water absorption (%)	Bulk density of aggregates (kg/m^3)	
			L.B.D	R.B.D
0FHC	1.82	29.5	864.5	908.5
0FHM	2.18	23.5	838.9	891.6
0FHG	2.42	16.5	919.4	948.3
0.5FHC	2.00	22.9	870.9	922.3
0.5FHM	2.33	20.7	844.5	899.2
0.5FHG	2.64	12.5	928.0	957.6
1FHC	1.88	25.8	855.0	905.0
1FHM	2.22	22.0	831.3	882.0
1FHG	2.40	15.0	913.3	940.5
1.5FHC	1.49	30.1	836.8	891.7
1.5FHM	1.91	28.2	814.8	860.2
1.5FHG	1.62	23.8	896.4	919.4

3.2.6. Impact strength values of artificial lightweight aggregates

The impact strength values for the different artificial aggregates manufactured with and without the addition of nano SiO_2 arespecified in Table 6. The highest impact value was observed for the 0 FHG aggregate at 20.2%, and the lowest value for the 0.5 FHC aggregate at 13.6%. The results in Table 3 show that the natural aggregate impact value is lower than that of all types of artificial lightweight aggregate. All the mix combinations of the artificial aggregates satisfy the structural demands of IS: 2386 (part IV) – 1963 and IS: 9142 (Part 2) – 2018. The test results show that the impact strength of the different artificial light weight aggregates depends on the type of binder and percentage of nano SiO_2. In all the mix combinations, with a percentage increase in nano SiO_2, the impact values decrease. The highest percentage decrease in impact value was 24.7% for the 0.5 FHC aggregate combination with reference aggregates. Artificial lightweight aggregates manufactured with the fly ash, cement and lime combination have 25.4% impact strength, which is higher than 0.5 FHC aggregate (Priyadharshini et al., 2011), in which nano SiO_2 enhances the bonding characteristics, with an additionalincrease in microstructure. In general, all the artificial lightweight aggregates manufactured with nano SiO_2 exhibit good impact strength values.

3.2.7.Individual aggregate crushing strength values of artificial lightweight aggregates

The experimental results on the individual pellet crushing strength of the different artificial lightweightaggregates produced with diameters varying from 6mm to 20mm are given in Table 6. They show that the strength values depend on the binder, with the additional dosage of nano SiO_2 at the time of pelletization. Moreover, the fineness of the materials offered adjacent packing of particles, which led to greater efficiency in the form of strength. In this study, the cold-bonded artificial lightweightaggregates produced were found to be acceptable in terms of strength, due to their strong bonding efficiency which helps intergranular particle bonding. It is also necessary that the specific surface area (SSA) will increase when the binding particles are finer, which causes effective packing of the intergranular particles (Chi et al., 2003; Mehmet et al., 2004; Bui et al., 2012).

With the percentage increase in nano SiO_2, the crushing strength increases for all types of aggregate, apart from hydrated lime-steel slag binder strength increases till 0.5% Nano SiO_2 again increasing in the dosage the strength values got decreased. The highest crushing strength was observed for the 0.5 FHG aggregate compared to the other type of aggregates, while the lowest was for the 0FHM aggregate. Artificial aggregates manufactured with a flyash-bentonite combination have a 23.1 Mpa crushing strength for 10 mm aggregate, which is lower than the 0.5 FHG aggregate (Kockal & Ozturan, 2011).Irrespective of nano SiO_2 dosage and binder type, as aggregate size decreases from 20 mm to 6 mm, the crushing strength increases due to thesmaller specific surface area of the smaller aggregate. The highest percentage increase with reference aggregate in crushing strength of 57.6% for 0.5 FHG combination of 6mm aggregate. Similarly, the highest percentage decrease with reference aggregate in crushing strength of 18.7% for 1.5 FHG combination of 20 mm aggregate. In general, the different aggregates manufactured for the study had a reasonable strength gain, meeting the performance demands of artificial lightweight aggregate.

Table 6 Impact and individual aggregate crushing strength of the different lightweight aggregates

Combination	Impact Strength (%)	Crushing strength of individual aggregate (Mpa)					
		20mm	16mm	12mm	10mm	8mm	6mm
0FHC	16.5	19.2	19.7	24.0	26.7	29.5	34.7
0FHM	20.0	17.5	19.5	21.2	22.9	26.9	27.2
0FHG	20.2	35.9	36.6	36.7	44.6	45.9	47.0
0.5FHC	13.6	22.6	25.5	29.1	35.4	45.7	54.7
0.5FHM	16.7	19.8	23.3	27.0	30.5	33.6	42.8
0.5FHG	15.2	41.5	44.9	49.3	52.5	56.0	58.9
1FHC	16.1	21.0	22.6	27.3	33.3	44.5	53.7
1FHM	16.8	19.4	23.0	26.5	30.1	33.1	40.3
1FHG	16.3	30.3	32.4	35.8	41.7	42.2	50.0
1.5FHC	15.6	20.8	22.4	26.6	32.1	41.9	50.2
1.5FHM	17.1	19.2	22.8	25.4	27.9	31.6	39.6
1.5FHG	15.9	29.2	31.4	36.0	39.5	40.4	49.5

4. CONCLUSION

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

1. The addition of nano SiO_2 with different binders during pelletization provides a more stable production and excellent bonding efficiency of the artificial lightweight aggregates, with improved properties.
2. In the case of the fresh pellets and those air-dried for 24 hrs, the highest efficiency was for the 0.5 FHM aggregate and the lowest for the 0 FHG aggregate.
3. The highest specific gravity value of 2.64 was observed for 0.5 FHG artificial aggregate which is 1.9% lower than the natural gravel aggregate value. The lowest specific gravity of 1.49 for the 1.5 FHC artificial aggregate.
4. It was found that the lowest water absorption value as 12.5% for the 0.5 FHG aggregate, and similarly the highest absorption value of 30.1% for the1.5 FHC aggregate.
5. Highest Bulk density was found to be 928 kg/m^3 for the 0.5 FHG aggregate and lowest to be 814.8 kg/m^3 for the 1.5 FHM aggregate. The bulk density of the 0.5 FHG artificial aggregate was 37% lower than the natural gravel aggregate.
6. The highest impact value of 20.2% was observed for the 0FHG aggregate and the lowest of 13.6% for the 0.5 FHC aggregate. The natural aggregate impact value was lower than the 0.5FHG type artificial lightweight aggregate but is still comparable.
7. The highest individual 12 mm aggregate crushing strength of 49.3 Mpa was noted for the 0.5 FHG aggregate and the lowest value of 21.2 Mpa for the 0FHM aggregate. Irrespective of nano SiO_2 dosage and binder type, as the size of the aggregate decreases, pellet crushing strength increases because of its smaller specific surface area for the smaller aggregate.
8. However, due to the fineness of the binder and the addition of nano SiO_2, the packing of the particles helps to decrease porosity which lead to greater efficiency in the form of lower impact

strength, lower water absorption, higher specific gravity and higher compressive strength of the pellets at 0.5% nano SiO_2, which are comparable values to the natural gravel aggregate.
9. In summary, for artificial lightweight aggregates with different binders, the addition of nano SiO_2 at 0.5% is the optimum level. From the different investigations conducted, the 0.5 FHG aggregate combination exhibited the most satisfactory results.

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