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Cold Bonded and Low Temperature Sintered Artificial Aggregate Production by Using Waste Materials

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Abstract

The paper presented the possibility of manufacturing aggregates from industrial waste materials and their ecological benefits. The cold bonding process to create aggregates uses substantially less energy than the sintering technique. This study deals with the outcomes of an experimental assessment of the physical and strength properties of environment-friendly cold-bonded and sintered fly ash (FA), ground granulated blast furnace slag (GGBFS), and quartz (Q) lightweight aggregates. The waste materials were mixed with Portland cement at 20–50 percent by weight to make artificial lightweight aggregates. To investigate the impacts of temperature on the physical properties, such as crushing strength, density, and water absorption, the pellets were sintered at 300, 600, and 900 °C for an hour. The results show that all the produced aggregates might be categorized as lightweight aggregates due to the combinations' average densities being less than 2,000 kg/m^3. The fly ash lightweight aggregates had higher density and crushing strength, as well as decreased water absorption. The density and crushing strength improved somewhat by raising the temperature, while the water absorption decreased with increased temperature. In this research, the most efficient mineral admixture concentration has been evaluated as 50 percent for both fly ash and ground granulated blast furnace slag and 30 percent for quartz for cold-bonded pellets. Furthermore, superior physical qualities have been reported at the 900 °C sintering temperature.

Keywords

fly ash, ground granulated blast furnace slag, quartz, lightweight artificial aggregate, recycling, waste materials, crushing strength

1 Introduction

The concept of recycling cement-based industrial waste materials in concrete production has been widely used, with various research providing results. However, studies and investigations are ongoing to obtain more accurate and practical results [1].

Since concrete is typically used in harsh environments and its strength against larger loads is its most significant attribute, improving its mechanical properties and endurance is crucial. It is essential to make high-strength, low-unit-weight concrete with good mechanical and durability properties and is environmentally friendly [2].

Concrete has many benefits and good mechanical properties but is weak in tensile and heavy. Many studies have been done to improve these features. Fibers, for example, are employed to manufacture concrete to improve tensile behavior, and lightweight artificial pellets are utilized to reduce the self-weight of concrete. The investigations associated with producing artificial lightweight aggregates and employing industrial wastes showed that the compressive and flexural strengths of the composite and its ductility could be improved. It was shown in Basa et al. [3] study that using sintered fly ash aggregate as a replacement for fine aggregates enhanced compressive strength, splitting tensile strength, and flexural strength. Cold bonded fly ash lightweight aggregate was employed to increase the permeability of self-compacting concrete [4].

Turkey's economy is growing and is now the 16th largest globally. This economic expansion has led to large amounts of industrial waste, including FA, GGBFS, and Q [5–7]. Around 15 billion tons of FA are produced annually in 11 Turkish coal-fired power plants, and 600,000 tons of GGBFS make recycling a priority due to increased disposal costs and an emphasis on sustainable development [8]. FA is accepted as a by-product. It is used as a primary

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material in the enhancement of concrete processes as well as the manufacturing of artificial aggregates [9]. The cold bonding technique is extensively used to recycle the different waste materials to produce lightweight aggregates used in concrete. Existing literature has investigated several aspects of different waste materials, such as municipal solid waste incinerator fly ash [10, 11], bottom ash [12, 13], granulated blast furnace slag [14], copper slag combined with fly ash [15], and quarry dust [16, 17]. Finer material fractions are utilized to improve pelletization efficiency and artificial aggregate strength. Also, the sintering process as a hardening technique and disc granulation at 35°–50° angle and 35–55 rpm disc speed for around 20 minutes are generally recommended [18].

FA aggregates might be formed by using pelletization to merge the tiny particles of cement and waste materials into pellets. The processing parameters and curing conditions considerably impact the quality of artificial aggregates. Pelletization might be accomplished using cold bonding or heat treatment [19]. Cold bonding is an energy-efficient approach that utilizes the pozzolanic capability of ash at room temperature. Green pellets are subjected to the curing phase to get the required strength for usage in concrete [12, 20]. When comparing the cold bonding and sintering methods, the sintered method has more advantages than the cold bonding method. The cold bonded aggregates require a long time (28 days) to gain strength, unlike the required duration in the sintered process [21].

Furthermore, sintered aggregates' physical and chemical properties were superior to cold bonded aggregates [22, 23]. The sintered aggregates up to 900 °C were lower in bulk density, specific gravity, and water absorption than the cold bonded aggregates [24]. Different types of artificial aggregates are utilized in the literature; Appendix A shows each type's properties in specific gravity, water absorption, and bulk density.

Thermal hardening, autoclaving, sintering, and steam curing strengthen ash pellets and reduce water absorption. The sintering process, which involves heating pellets to 1200 °C for 30 minutes to 2 hours, relies on atomic diffusion within the material [25, 26]. The impact of sintering temperature on the chemical and physical properties of sewage sludge and river sediment lightweight aggregates has been evaluated. Furthermore, the best sintering temperature for lightweight aggregates with high density, minimal water absorption, and high strength was determined to be 1100 °C [27]. Sintering the incinerator bottom ash lightweight aggregate at a temperature between 1000 °C and 1050 °C resulted in lightweight aggregates with potential use in construction products and geotechnical applications [28]. Sintered fly ash aggregates might produce high-strength concrete with high carbonation resistance [29]. Compressive strengths ranging from 20 to 80 MPa may be readily employed based on the lightweight mixture content used during casting concrete [30].

Because aggregates account for 65–75 percent of the total volume of concrete, utilizing waste in synthetic aggregates in its manufacture is a very sustainable recycling alternative that contributes to natural resource conservation [31]. Numerous studies have been conducted to improve the performance of artificial lightweight aggregates-based high-performance concretes with a reduced bulk density (1900 kg/m^3) than regular concrete yet a comparable outstanding strength range (30–80 MPa) [9, 10]. The mechanical performance of concrete, including fly ash-based lightweight cold bonding and sintering aggregates, was evaluated. The findings indicated that the sintered aggregates demonstrated the maximum compressive strength of concrete compared to the cold-bonded aggregates [24]. The compressive strength of concrete produced with sintered aggregates is higher than that of concrete made with granite aggregates [32]. A large number of voids in the cold-bonded fly ash aggregates reduced the mechanical properties of concrete in terms of compressive strength, flexural strength, shrinkage, porosity, and modulus of elasticity [33]. It is feasible to manufacture a 56 MPa-compressive strength lightweight concrete. Furthermore, it is found that the sintered fly ash aggregates positively affect the workability of lightweight concrete compared to the workability of concrete made with normal aggregates [34, 35].

In this research, a framework that examines the relevance of the utilization of waste components, FA, GGBFS, and Q, was offered, alongside a low-energy (cold bonding) and sintering technique to carry out the sustainability assessment of coarse aggregates. This study's findings are valuable for engineers, project managers, and academics in selecting sustainable alternative building materials for infrastructure projects.

2 Experimental methods

The present study focuses on the possibility of producing artificial, lightweight coarse aggregate by utilizing different types of industrial waste. The study aims to reveal the ideal dosage of FA, GGBFS, and Q to be mixed with ordinary Portland cement to achieve a coarse aggregate whose physical and mechanical properties are closer to those of natural aggregate. Tests of density, water absorption, and crushing strength are applied per ASTM standards to analyze the properties of the cold-bonded and sintered artificial aggregates.

2.1 Materials

2.1.1 Cement

This experiment utilized CEM I 42.5 N-type Portland cement (equivalent to ASTM Type I) with a Blaine fineness of 3430 cm^2/g and a specific gravity of 3.17. This kind of cement comprises a significantly greater quantity of main silicate compounds. It has an average fineness level, is ideal for desirable settings, and has safe hydration heat release. The chemical compositions of the Portland cement utilized in this investigation are provided in Table 1.

Table 1 Physical and chemical properties of cement, FA, GGBFS, and Q

Chemical composition (%)	Portland Cement	FA	GGBFS	Q
CaO	62.58	4.24	34.12	0.28
SiO_2	20.25	56.20	36.41	89.05
Al_2O_3	5.31	20.17	10.39	5.03
Fe_2O_3	4.04	6.69	0.69	3.62
MgO	2.82	1.92	10.26	–
SO_3	2.73	0.49	–	–
K_2O	0.92	1.89	0.97	0.28
Na_2O	0.22	0.58	0.35	–
Loss on ignition	3.02	1.78	1.64	
Specific gravity	3.15	2.25	2.79	2.65
Blaine fineness (m^2/kg)	326	287	418	–

2.1.2 Fly ash (FA)

The FA utilized in manufacturing artificial lightweight aggregates was class F, and its specific gravity was 2.25. The specific chemical compositions and physical properties of class F FA (conforming to ASTM C618-19 [36]) are presented in Table 1.

2.1.3 Ground granulated blast furnace slag (GGBFS)

This material is obtained by quenching molten iron GGBFS (a by-product of iron and steel-making) from a blast furnace in water or steam to provide a glassy, granular product that is then dried and ground right into a fine powder. Table 1 shows the chemical and physical properties of GGBFS.

2.1.4 Quartz (Q)

The chemical and physical properties of the used quartz are shown in Table 1.

2.2 Preparation of artificial lightweight aggregate via the cold-bonding technique

At the beginning of the experimental study, the cold-bonding palletization method was carried out to produce lightweight aggregates. As shown in Fig. 1, an electrical pelletizer pan with a diameter of 800 mm and a depth of 300 mm was used to manufacture the artificial lightweight aggregates. The pelletizer pan had a horizontal angle of 45 degrees and a rotational speed of 42 rev/min. As the dry powder material for the artificial lightweight aggregates, a combination of 20, 30, and 50% FA, GGBFS, and Q by weight of cement were used. Table 2 shows the exact mix proportions for all the artificial aggregates produced. This mixture of powder material was poured into the pelletization disc and allowed to be blended till a well-blended mixture was achieved. Water constituted 22 ± 2 percent of the powder material by weight and was sprayed onto the cement and mixtures at the primary level of the manufacturing method. Water in this system acted as the coagulant, and spherical pellets achieved the quilt for 10-min in the first

Fig. 1 Photographic view of pelletization disc

Table 2 Mix proportions of materials used in the artificial aggregate production

Mix ID	Cement (%)	FA (%)	GGBFS (%)	Q (%)
2F8C	80	20	0	0
3F7C	70	30	0	0
5F5C	50	50	0	0
2S8C	80	0	20	0
3S7C	70	0	30	0
5S5C	50	0	50	0
2Q8C	80	0	0	20
3Q7C	70	0	0	30
5Q5C	50	0	0	50

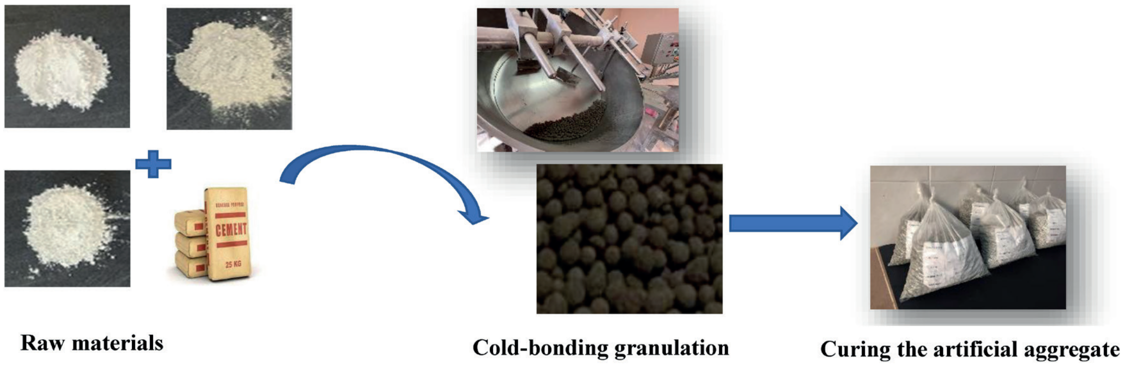


Fig. 2 Cold-bonding manufacturing process

stage. Next, the pelletization disc containing spherical pellets has been allowed to rotate for an extra 10 min. This is the second stage by which the stiff and compacted pellets have been manufactured. Fig. 2 indicates the method of manufacturing the aggregates. Also, the manufactured lightweight aggregates are proven in Fig. 3. These pellets were saved in plastic luggage with a relative humidity of 70% as soon as the manufacturing process was completed. Then, the plastic bags were preserved in the curing room, where the temperature was stored at 22 ± 2.

2.3 Preparation of the artificial lightweight aggregates via sintering technique

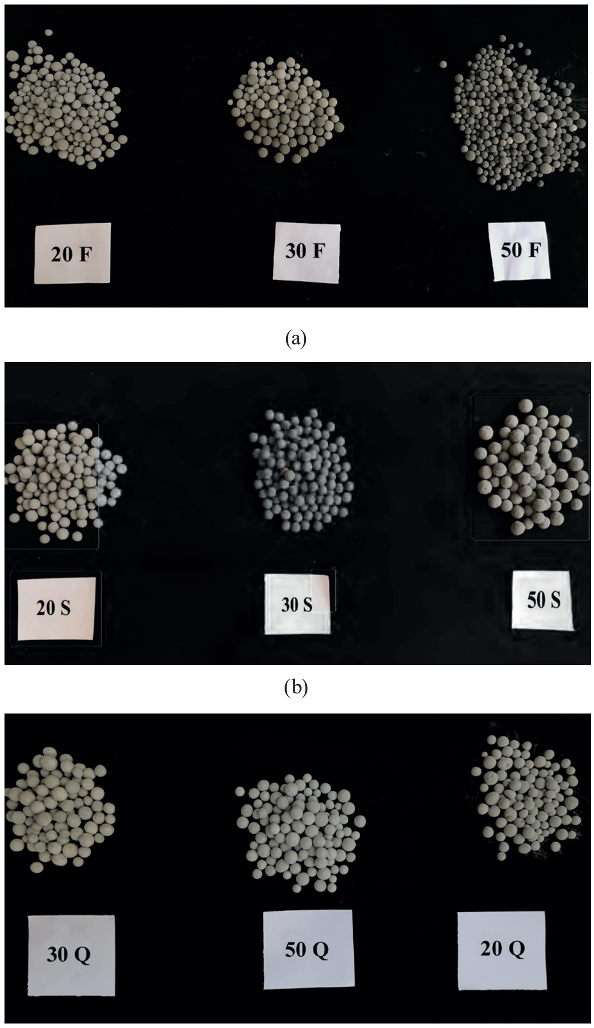
The impact of sintering on the attributes of the artificial lightweight aggregates was investigated by heating a series of aggregate samples at three different temperatures of 300, 600, and 900 °C. The temperature rise rate was set to 10 °C min^{-1} (Fig. 4). After sintering for 1 hour, the hot pellets were stored in the oven to be gently cooled to room temperature. After cooling, all the sintered pellets were examined in terms of particle density, water absorption capacity, specific gravity, and crushing strength. The colour and shape distortion for cold-bonded and sintered aggregates are exhibited in Fig. 5.

2.4 Applied test methods

2.4.1 Physical and mechanical properties investigations

The crumbled artificial lightweight aggregates were sieved by passing through the 4-mm sieve, and the passed aggregate particles were utilized in cementitious composite manufacturing. The sieve analyses of all aggregates are displayed in Fig. 6.

The dry density, bulk density, water absorption, and crushing strength tests were carried out to study the physical and mechanical parameters of the manufactured aggregate pellets. Density, specific gravity, and water absorption were performed according to ASTM 127 [37]. The



(c)

Fig. 3 Photographic view of cold-bonded (a) FA, (b) GGBFS, and (c) Q artificial lightweight aggregates

crushing strength test was performed on the individual pellets after 28 days of curing. It was completed by positioning the pellets between two parallel plates, applying the direct load, and constantly increasing force until the failure occurs, as per BS 812 part 110. The load was then recorded as the average of 10 pellets' readings as the final result.

Fig. 4 Sintering manufacturing process

Fig. 5 Effect of sintering on the color and shape of artificial aggregates, (left) is cold-bonded FA artificial aggregate, and (right) is sintered FA artificial aggregate at 900 °C

3 Results and discussion

3.1 Mineralogy and microstructural analysis

After covering the pellets with goal goat, the cold bonded and sintered pellets were analyzed using scanning electron microscopy (SEM). The microstructure of the cold-bonded and sintered FA, GGBFS, and Q aggregate pellets are shown in Fig. 7. The minor disappearance between the three cold bonded artificial aggregate types is the sharp-cornered GGBFS artificial aggregate and the presence of voids more than FA and Q aggregate. The effect of the elevated temperature resulted in more homogenous matrixes for all aggregate types, indicating that FA, GGBFS, and Q are active during heat exposure. However, the more compact and denser microstructure was found at 600 °C heating of Q artificial aggregate as the discontinuous cracks that clear at 300 °C started to disappear. The 300 to 900 °C heating of both FA and GGBFS aggregate resulted in significant changes in morphology and led to porosity enlargement.

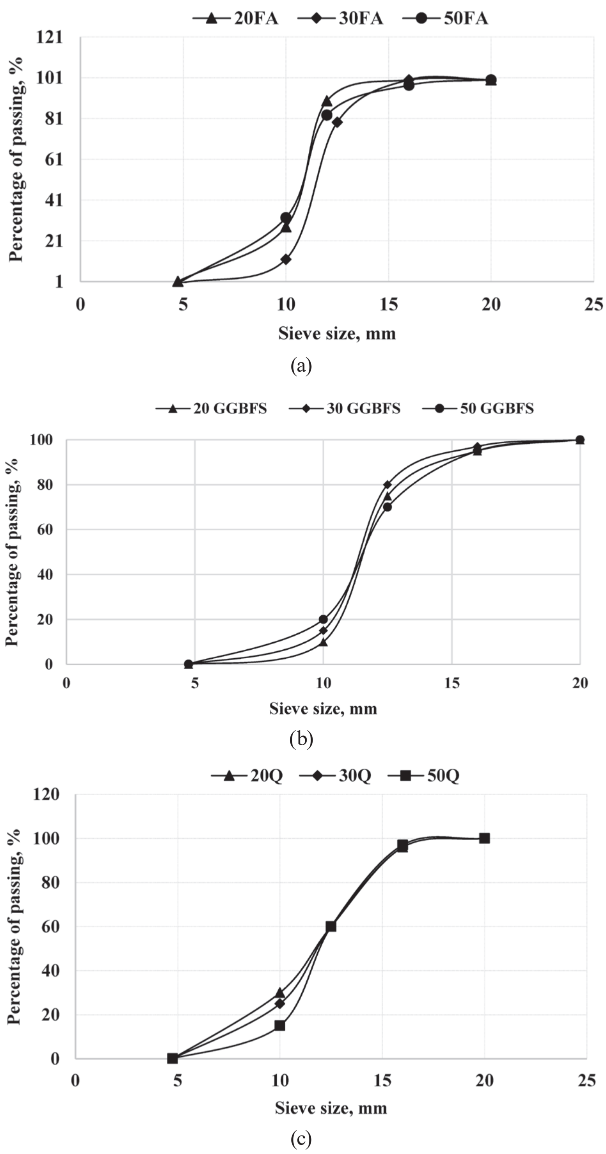
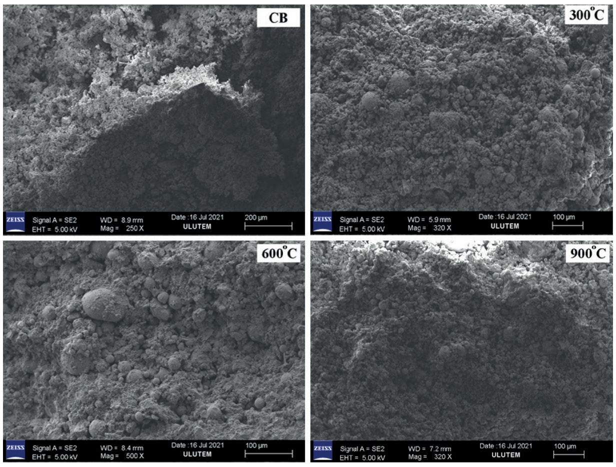
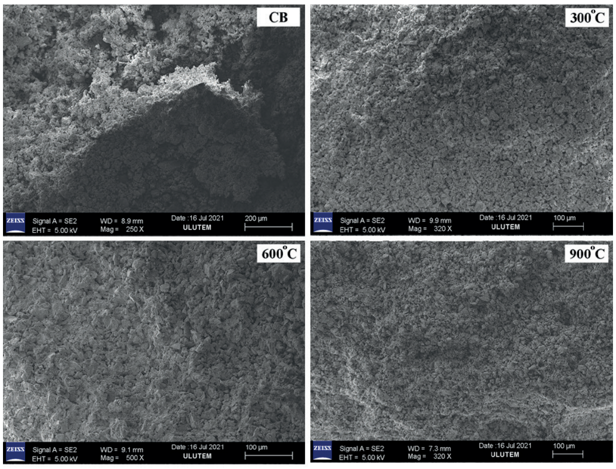


Fig. 6 Size distribution of the artificial of (a) FA, (b) GGBFS, and (c) Q aggregates



(a)



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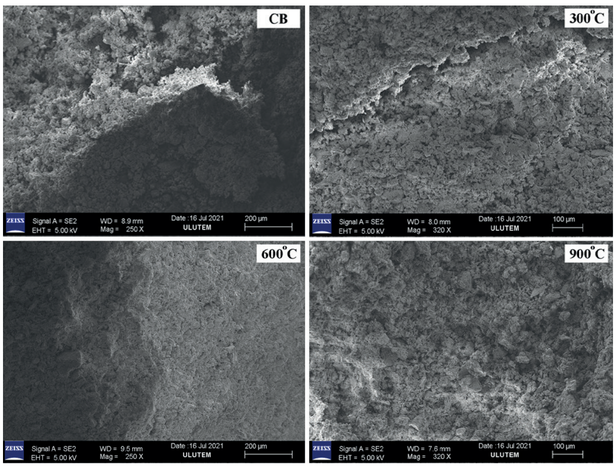

(c)

Fig. 7 Microstructure of cold-bonded and sintered (a) FA, (b) GGBFS, and (c) Q aggregates

3.2 Bulk density

The density results of cold-bonded artificial aggregates are shown in Table 3. The density results of all the artificial lightweight mixes were within the range of (652.18 and 1114.42 kg/m^3). The increase in density was caused by the SiO_2 content in the FA, GGBFS, and Q, which reacted with the $Ca(OH)_2$ from the cement's hydration response to provide a vital extension of calcium silicate hydrate gel (C-S-H), resulting in further reduction in porosity during hydration. Waste materials used in manufacturing artificial aggregates also improve the density of the aggregates due to their high specific gravity, as shown in Table 1. The outcomes agreed with the size distribution results of the manufactured aggregates (Fig. 6). The sizes of the mixes were close together, and thus the density effects of the mixes were as well. The bulk density of the sintered aggregates ranged between 881.5 and 1337 kg/m^3 at 900 °C for the fly ash and quartz aggregates, respectively. Also, microstructure analysis of the aggregates clearly shows the dense surface of the aggregates at higher temperatures (Fig. 7). The bulk density results of the cold-bonded and sintered aggregates are shown in Fig. 8. The abbreviations CB and S refer to the cold bonded and sintered artificial aggregates, respectively. The results agree with European Standards that aggregate density should not exceed 2000 kg/m^3. A comparison between the results of density and some previous studies is shown in Appendix A.

3.3 Water absorption

The water absorption of all synthetic aggregates is given in Table 3. The findings also indicated that the 5F5C FA mix had a maximum water absorption of 28.5 percent, which is related to defective adhesion (having a reduced density [937.59 kg/m^3]). The cement hydration and the pozzolanic reaction of FA developed a denser microstructure because of the larger quantities of the formed C-S-H. The outcome of the GGBFS mixes revealed a considerable increase in water absorption (16–18 percent). The Q mixes showed

Table 3 Physical properties and strength of cold-bonded artificial aggregates

Mix ID	Specific gravity	Apparent specific gravity	Density (kg/m^3)	Water absorption (%)	Crushing strength (N)
2F8C	1.64	2.62	912.24	22.56	271.11
3F7C	1.66	2.62	920	25	582.14
5F5C	1.43	2.43	937.59	28.52	722.96
2S8C	1.84	2.77	652.18	18.05	453.29
3S7C	1.80	2.60	750	17.20	541.78
5S5C	1.74	2.43	1114.42	16.27	1038.98
2Q8C	1.63	2.55	915.4	19.61	418.89
3Q7C	1.61	2.70	928	18	675.512
5Q5C	1.71	2.36	910.51	15.83	496.94

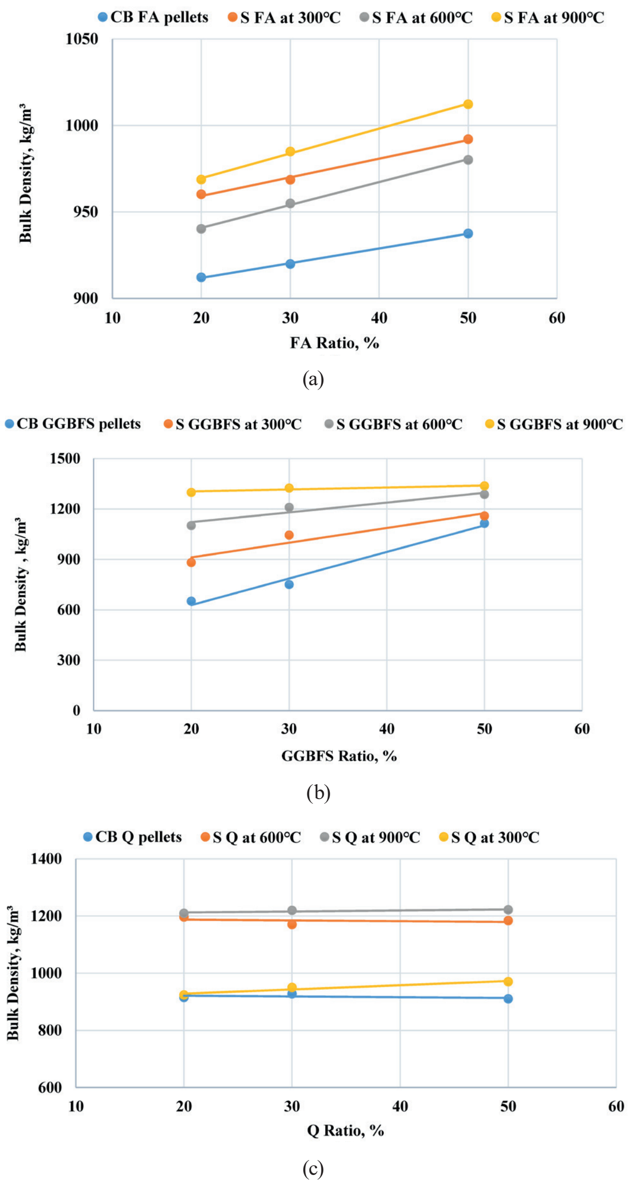

Fig. 8 Bulk density of (a) FA, (b) GGBFS, and (c) Q aggregates at the cold-bonded and sintering methods

a water absorption of 15 percent for the ratio of 50 percent Q. In contrast, the other ratios exhibited 19 percent and 18 percent water absorption for the 30 percent and 50 percent ratios, respectively. A greater porosity leads to a higher water absorption percentage. These water absorption findings are per the density results, in which water absorption rises with decreasing density.

On the other hand, the water absorption decreased with the rise of the sintering temperature (Table 4) owing to the fact creating a glassy texture on the surface of aggregates at the higher temperatures. Furthermore, as shown in Fig. 7, it is noted that at higher temperatures, the aggregates become smooth with a thick surface, which is related to the gas release and the melting of the basic materials that reduce water absorption. Fig. 9 illustrates the effects of heating on the rate of water absorption for all mixes.

3.4 Crushing strength

The crushing strength of all the artificial aggregates is presented in Table 3 and Fig. 10. The addition of FA to the Portland cement somewhat raises the crushing strength of the artificial aggregates. The combination containing 20 percent FA had the lowest crushing strength (271.11 N). Adding 50 percent of FA to the mixture of produced aggregates increased the crushing strength by 62% compared to the mixture containing 20 percent of FA. Adding 50percent of GGBFS to Portland cement significantly increased crushing strength to about 56 percent compared to the 20 percent of GGBFS mix. The artificial aggregates that mixed Q with cement showed optimum crushing strength at 30 percent of the Q value. Fig. 10 illustrates the effect of heating on the artificial aggregates. For the sintered aggregates, the crushing strength substantially increased with raising the temperature. At 900 °C, the fly ash aggregates

Table 4 Physical properties and strength of sintered artificial aggregates

Tests	Temperature (°C)	Mix ID								
		2F8C	3F7C	5F5C	2S7C	3S7C	5S5C	2Q8C	3Q7C	5Q5C
Bulk Density (kg/m^3)	300	960.2	968.6	992.1	881.5	1044.7	1159.2	923.85	950	970.5
	600	940.2	955	980.2	1101.3	1210	1286	1197	1171	1184
	900	968.8	985	1012.2	1299	1324	1337	1210	1220	1222
Water absorption (%)	300	21.99	23.5	25.3	19.55	18.32	15.28	16.98	15.9	14.2
	600	20.21	22	24.9	16.25	15	11.3	16.3	14.8	13.97
	900	20	20.3	22.8	15.85	14	11.15	14.2	12.65	12.17
Crushing strength (N)	300	112.3	298.3	687.3	420.3	584.5	782.2	520.8	565.5	670.5
	600	380.87	315.9	798	590.6	658.2	750.98	598.2	607.6	820.5
	900	412.5	590.8	945	690.8	858.5	1059.87	643.5	689.2	865.3

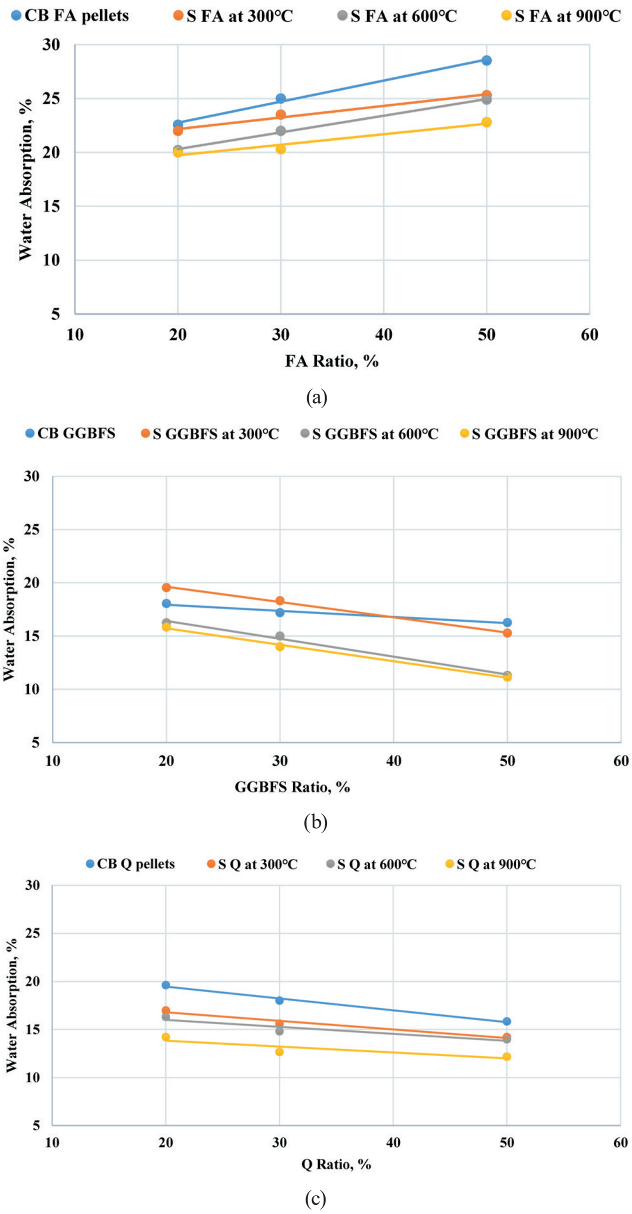

Fig. 9 Water absorption for (a) FA, (b) GGBFS, and (c) Q artificial aggregate at different temperatures

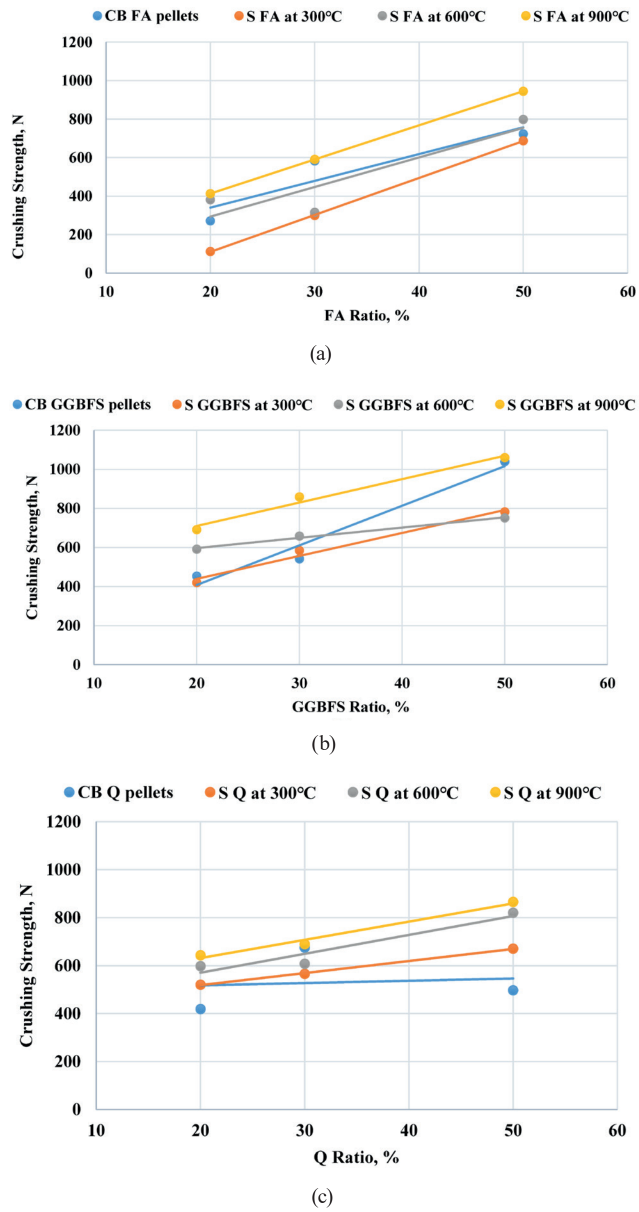

Fig. 10 Crushing strength for (a) FA, (b) GGBFS, and (c) Q artificial aggregate at different temperatures

with 50 percent fly ash exhibited 945 N strength, and the aggregates with 30 percent quartz exhibited 689.2 N strength (Table 4 shows the sintered aggregates results). The sintered slag containing aggregates did not exhibit much difference at different heating temperatures. The crushing strength findings conform with the density values. As indicated in Table 3, the maximum density of each combination is consistent with the highest crushing strength. The 5S5C mix had the greatest crushing strength and density values of 1038.98 N and 1114.42 kg/m^3, respectively.

The enhancement in strength occurred by adding FA, GGBFS, and Q, which is the result of the chemical composition of the materials. Their reaction with the interior silicate phase of FA allows the reaction and production of additional C-S-H. Moreover, the high quantity of CaO in the excessive calcium GGBFS reacted with the silicon oxide phase to generate hydration products that help increase aggregates' crushing strength [38].

4 Conclusions

Due to the urgent and continuous demand for natural aggregates to produce concrete and the negative effect of waste accumulation on the environment, by-products can be utilized as lightweight aggregates using the cold-bonding process, which uses little energy and is cost-effective. In this study, FA, GGBFS, and Q were chosen to be recycled and utilized in producing lightweight aggregates. Considering the collected findings, the following conclusions are drawn:

1. The density of the produced aggregates was in the range of 652.18-1114.42 kg/m^3. Therefore, according to BS EN 13055-1 [39], these materials may be employed to manufacture lightweight aggregates as the reported particle density was less than 2,000 kg/m^3. The highest density was reached in the mixture containing 50 percent GGBFS by weight with 50 percent Portland cement, while the mixture containing 20 percent GGBFS exhibited the minimum density.
2. The optimum crushing strength was 722.96 N, which belonged to the 5F5C mixture, and the 5S5C mixture exhibited a crushing strength of 1038.98 N. In addition, when considering the Q-containing mixtures, the maximum crushing strength was obtained by adding 30% Q by weight to the cement (675.51 N).
3. It was discovered that water absorption could be increased by increasing the quantity of Portland cement in the mixture. This is due to increasing quantities of hydrated products (C–S–H). It was observed that the 5F5C combination did not contain adequate water to agglomerate the binder for hydration or pozzolanic reaction. Nonetheless, it achieved the best crushing strength in the FA mixtures.
4. Due to the formation of the glassy texture at higher temperatures, sintered aggregates showed decreased water absorption with increasing the temperature for all the aggregate mixtures. The crushing strength increased with the temperature increase, demonstrating that the maximum strength was recorded at 900 °C. Furthermore, the recorded bulk density significantly increased by increasing the temperature. The optimum mixtures were selected at 900 for the minimum water absorption and the highest crushing strength, which are the most influential parameters in enhancing the strength of concrete.
5. Further experimental studies are scheduled to be carried out utilizing these artificial aggregates to replace the coarse aggregates in concrete mixes with varying ratios. These investigations might assist in analyzing the influence of artificial aggregates on the durability qualities of concrete.

References

[1] Turker, K., Birol, T., Yavas, A., Hasgul, U. "Effective steel fiber type investigation on ultra high performance fiber reinforced concrete beams", Afyon Kocatepe University Journal of Science and Engineering, 16, pp. 776–785, 2016.

[2] Mermerdaş, K., İpek, S., Algın, Z., Ekmen, Ş., Güneş, İ. "Combined effects of microsilica, steel fibre and artificial lightweight aggregate on the shrinkage and mechanical performance of high strength cementitious composite", Construction and Building Materials, 262, 120048, 2020. https://doi.org/10.1016/j.conbuildmat.2020.120048

[3] Basa, B., Pradhan, N., Priyadarshini Parhi, L. "Mechanical properties of concrete with sintered fly ash aggregate as substitute of natural fine aggregate", IOP Conference Series: Materials Science and Engineering, 970, 012013, 2020. https//doi.org/10.1088/1757-899X/970/1/012013

[4] Güneyisi, E., Gesoğlu, M., Booya, E., Mermerdaş, K. "Strength and permeability properties of self-compacting concrete with cold bonded fly ash lightweight aggregate", Construction and Building Materials, 74, pp. 17–24, 2015. https://doi.org/10.1016/j.conbuildmat.2014.10.032

[5] Uyanik, S., Topeli, M. "Development fly ash utilization in Turkey and contribution of ISKEN to the market", presented at Proceeding of EUROCOALASH 2012 Conference, Thessaloniki, Greece, Sep. 25–27, 2012.

[6] Arslan, H., Baykal, G. "Utilization of fly ash as engineering pellet aggregates", Environmental Geology, 50, pp. 761–770, 2006. https://doi.org/10.1007/s00254-006-0248-7

[7] Rehman, M. U., Rashid, K., Haq, E. U., Hussain, M., Shehzad, N. "Physico-mechanical performance and durability of artificial lightweight aggregates synthesized by cementing and geopolymerization", Construction and Building Materials, 232, 117290, 2020. https://doi.org/10.1016/j.conbuildmat.2019.117290

[8] Acar, I., Atalay, M. U. "Characterization of sintered class F fly ashes", Fuel, 106, pp. 195–203, 2013. https://doi.org/10.1016/j.fuel.2012.10.057

[9] Bentur, A., Igarashi, S., Kovler, K. "Prevention of autogenous shrinkage in high-strength concrete by internal curing using wet lightweight aggregates", Cement and Concrete Research, 31, pp. 1587–1591, 2001. https://doi.org/10.1016/S0008-8846(01)00608-1

[10] Colangelo, F., Messina, F., Cioffi, R. "Recycling of MSWI fly ash by means of cementitious double step cold bonding pelletization: Technological assessment for the production of lightweight artificial aggregates", Journal of Hazardous Materials, 299, pp. 181–191, 2015. https://doi.org/10.1016/j.jhazmat.2015.06.018

[11] Loginova, E., Schollbach, K., Proskurnin, M., Brouwers, H. J. H. "Municipal solid waste incineration bottom ash fines: Transformation into a minor additional constituent for cements", Resources, Conservation and Recycling, 166, 105354, 2021. https://doi.org/10.1016/j.resconrec.2020.105354

[12] Geetha, S., Ramamurthy, K. "Environmental friendly technology of cold-bonded bottom ash aggregate manufacture through chemical activation", Journal of Cleaner Production, 18, pp. 1563–1569, 2010. https://doi.org/10.1016/j.jclepro.2010.06.006

[13] Ibrahim, N. M., Ismail, K. N., Amat, R. C., Ghazali, M. I. M. "Properties of cold-bonded lightweight artificial aggregate containing bottom ash with different curing regime", E3S Web of Conferences, 34, 01038, 2018.
https://doi.org/10.1051/e3sconf/20183401038

[14] Gesoğlu, M., Güneyisi, E., Öz, H. Ö. "Properties of lightweight aggregates produced with cold-bonding pelletization of fly ash and ground granulated blast furnace slag", Materials and Structures, 45, pp. 1535–1546, 2012.
https://doi.org/10.1617/s11527-012-9855-9

[15] Thomas, J., Mohan, A., Dhannya, K. K. "Copper slag cold-bonded aggregate concrete exposed to elevated temperature", ACI Materials Journal, 117(6), pp. 215–230, 2020.
https://doi.org/10.14359/51727000

[16] Thomas, J., Harilal, B. "Properties of cold bonded quarry dust coarse aggregates and its use in concrete", Cement and Concrete Composites, 62, pp. 67–75, 2015.
https://doi.org/10.1016/j.cemconcomp.2015.05.005

[17] Thomas, J., Harilal, B. "Mechanical properties of cold bonded quarry dust aggregate concrete subjected to elevated temperature", Construction and Building Materials, 125, pp. 724–730, 2016.
https://doi.org/10.1016/j.conbuildmat.2016.08.093

[18] Ren, P., Ling, T.-C., Mo, K. H. "Recent advances in artificial aggregate production", Journal of Cleaner Production, 291, 125215, 2021.
https://doi.org/10.1016/j.jclepro.2020.125215

[19] Baykal, G., Döven, A. G. "Utilization of fly ash by pelletization process; theory, application areas and research results", Resources, Conservation and Recycling, 30, pp. 59–77, 2000.
https://doi.org/10.1016/S0921-3449(00)00042-2

[20] Manikandan, R., Ramamurthy, K. "Effect of curing method on characteristics of cold bonded fly ash aggregates", Cement and Concrete Composites, 30, pp. 848–853, 2008.
https://doi.org/10.1016/j.cemconcomp.2008.06.006

[21] Terzić, A., Pezo, L., Mitić, V., Radojević, Z. "Artificial fly ash based aggregates properties influence on lightweight concrete performances", Ceramics International, 41, pp. 2714–2726, 2015.
https://doi.org/10.1016/j.ceramint.2014.10.086

[22] Joseph, G., Ramamurthy, K. "Influence of fly ash on strength and sorption characteristics of cold-bonded fly ash aggregate concrete", Construction and Building Materials, 23, pp. 1862–1870, 2009.
https://doi.org/10.1016/j.conbuildmat.2008.09.018

[23] Nadesan, M. S., Dinakar, P. "Structural concrete using sintered fly-ash lightweight aggregate: A review", Construction and Building Materials, 154, pp. 928–944, 2017.
https://doi.org/10.1016/j.conbuildmat.2017.08.005

[24] Gomathi, P., Sivakumar, A. "Accelerated curing effects on the mechanical performance of cold bonded and sintered fly ash aggregate concrete", Construction and Building Materials, 77, pp. 276–287, 2015.
https://doi.org/10.1016/j.conbuildmat.2014.12.108

[25] Hwang, C.-L., Hung, M.-F. "Durability design and performance of self-consolidating lightweight concrete", Construction and Building Materials, 19, pp. 619–626, 2005.
https://doi.org/10.1016/j.conbuildmat.2005.01.003

[26] Risdanareni, P., Jaya Ekaputri, J., Maulidiyawati, I., Puspitasari, P. "Mechanical properties of concrete composed of sintered fly ash lightweight aggregate", MATEC Web of Conferences, 195, 01008, 2018.
https://doi.org/10.1051/matecconf/201819501008

[27] Kockal, N. U., Ozturan, T. "Characteristics of lightweight fly ash aggregates produced with different binders and heat treatments", Cement and Concrete Composites, 33, pp. 61–67, 2011.
https://doi.org/10.1016/j.cemconcomp.2010.09.007

[28] Harikrishnan, K. I., Ramamurthy, K. "Influence of pelletization process on the properties of fly ash aggregates", Waste Management, 26, pp. 846–852, 2006.
https://doi.org/10.1016/j.wasman.2005.10.012

[29] Liu, M., Wang, C., Bai, Y., Xu, G. "Effects of sintering temperature on the characteristics of lightweight aggregate made from sewage sludge and river sediment", Journal of Alloys and Compounds, 748, pp. 522–527, 2018.
https://doi.org/10.1016/j.jallcom.2018.03.216

[30] Cheeseman, C. R., Makinde, A., Bethanis, S. "Properties of lightweight aggregate produced by rapid sintering of incinerator bottom ash", Resources, Conservation and Recycling, 43, pp. 147–162, 2005.
https://doi.org/10.1016/j.resconrec.2004.05.004

[31] Nadesan, M. S., Dinakar, P. "Influence of type of binder on high-performance sintered fly ash lightweight aggregate concrete", Construction and Building Materials, 176, pp. 665–675, 2018.
https://doi.org/10.1016/j.conbuildmat.2018.05.057

[32] Haque, M. N., Al-Khaiat, H., Kayali, O. "Strength and durability of lightweight concrete", Cement and Concrete Composites, 26, pp. 307–314, 2004.
https://doi.org/10.1016/S0958-9465(02)00141-5

[33] Korat, L., Ducman, V., Legat, A., Mirtič, B. "Characterisation of the pore-forming process in lightweight aggregate based on silica sludge by means of X-ray micro-tomography (micro-CT) and mercury intrusion porosimetry (MIP)", Ceramics International, 39, pp. 6997–7005, 2013.
https://doi.org/10.1016/j.ceramint.2013.02.037

[34] Kayali, O. "Fly ash lightweight aggregates in high performance concrete", Construction and Building Materials, 22, pp. 2393–2399, 2008.
https://doi.org/10.1016/j.conbuildmat.2007.09.001

[35] Kockal, N. U., Ozturan, T. "Effects of lightweight fly ash aggregate properties on the behavior of lightweight concretes", Journal of Hazardous Materials, 179, pp. 954–965, 2010.
https://doi.org/10.1016/j.jhazmat.2010.03.098

[36] ASTM "ASTM C618-19 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete", ASTM International, West Conshohocken, PA, USA, 2019.
https://doi.org/10.1520/C0618-19

[37] ASTM "ASTM 127 Standard Test Method for Drop Melting Point of Petroleum Wax, Including Petrolatum", ASTM International, West Conshohocken, PA, USA, 2019.
https://doi.org/10.1520/D0127-19

[38] Wong, V., Jervis, W., Fishburn, B., Numata, T., Joe, W., Rawal, A., Sorrell, C. C., Koshy, P. "Long-term strength evolution in ambient-cured solid-activator geopolymer compositions", Minerals, 11(2), 143, 2021.
https://doi.org/10.3390/min11020143

[39] CEN "BS EN 13055-1 Lightweight aggregates - Part 1: Lightweight aggregates for concrete, mortar and grout", Committee for Standardization, Brussels, Belgium, 2002.

[40] Rahman, S. F., Chandrakala, S. K. "A Experimental study on partial replacement of cement with metakaolin and coarse aggregate with blast furnace slag", International Journal of Engineering Research and Technology, 8(12), pp. 341–347, 2019. https://doi.org/10.17577/ijertv8is120209

[41] Chinnu, S. N., Minnu, S. N., Bahurudeen, A., Senthilkumar, R. "Recycling of industrial and agricultural wastes as alternative coarse aggregates: A step towards cleaner production of concrete", Construction and Building Materials, 287, 123056, 2021. https://doi.org/10.1016/j.conbuildmat.2021.123056

[42] Sawant, A. B., Lavangare, V. H., Kolekar, S. M., Sawant, A. A. "Suitability of blast furnace slag in concrete", International Research Journal of Engineering and Technology (IRJET), 6(3), pp. 2927–2933, 2019.

[43] Nandagawali, S. D., Dhamge, D. N. R. "Study of blast furnace slag for improving mechanical property of concrete", International Journal of Innovative Research in Science, Engineering, and Technology, 3, pp. 473–477, 2014.

[44] Kumar, P. R, Pradeep Kumar, T. B. "Use of blast furnace slag as an alternative of natural sand in mortar and concrete", International Journal of Innovative Research in Science, Engineering, and Technology, 4(2), pp. 252–257, 2015. https://doi.org/10.15680/IJIRSET.2015.0402054

[45] Kumar, K. B., Vignesh, R., Srinithin, S., Selvakumar, G. "Experimental study on partial replacement of coarse aggregate by iron slag in cement concrete (M25)", International Journal of Civil Engineering and Technology, 8, pp. 1019–1027, 2017.

[46] Kayali, O. "Fly ash lightweight aggregates in high performance concrete", Construction and Building Materials, 22, pp. 2393–2399, 2008. https://doi.org/10.1016/j.conbuildmat.2007.09.001

[47] Kockal, N. U., Ozturan, T. "Optimization of properties of fly ash aggregates for high-strength lightweight concrete production", Materials and Design, 32, pp. 3586–3593, 2011. https://doi.org/10.1016/j.matdes.2011.02.028

[48] Chi, J. M., Huang, R., Yang, C. C., Chang, J. J. "Effect of aggregate properties on the strength and stiffness of lightweight concrete", Cement and Concrete Composites, 25, pp. 197–205, 2003. https://doi.org/10.1016/S0958-9465(02)00020-3

[49] Vaidhyanathan, S. N., Thenmozhi, R., Babu, B. R. "Experimental study on the mechanical properties of light weight fly ash aggregate concrete reinforced with steel fiber", International Journal of Civil Engineering, pp. 420–424, 2017.

[50] Priyadharshini, P., Mohan Ganesh, G., Santhi, A. S. "Experimental study on cold bonded fly ash aggregates", International Journal of Civil and Structural Engineering, 2(2), pp. 507–515, 2011. https://doi.org/10.6088/ijcser.00202010129

[51] Reddy, M. V. S., Nataraja, M. C., Sindhu, K., Harani, V., Madhuralalasa, K. "Performance of light weight concrete using fly ash pellets as coarse aggregate replacement", International Journal of Engineering Research and Technology, 9(2), pp. 95–104, 2016.

[52] Harilal, B., Thomas, J. "Concrete made using cold bonded artificial aggregate", In: National Conference on Recent Advances in Structural Engineering, RASE2013, Kerala, India, 2013, pp. 20–25. ISSN: 2320-0936

Appendix A

Table A1 Characteristics of various artificial coarse aggregates

References	Type of aggregate	Specific gravity	Crushing value (%)	Water absorption (%)	Bulk density (kg/m^3)
Rahman and Chandrakala [40]	Furnace slag	2.45	-	1	-
Chinnu et al. [41]		2.74	2.95	3	1800
Sawant et al. [42]		2.80	-	-	-
Nandagawali and Dhamge [43]		2.90	-	-	1300
Kumar and Pradeep Kumar [44]		2.52	-	2.59	1305
Kumar et al. [45]		2.02	18.36	14.20	750
Harikrishnan and Ramamurthy [28]	Sintered fly ash	1.75	-	21.31	-
Kayali [46],		1.69	28	36.1	-
Kockal and Osturan [47]		1.58	28	36.1	933
Chi et al. [48]		1.65	43.90	34.40	-
Vaidhyanathan et al. [49],		1.40	19.42	16.80	830
Kockal and Ozturan [35]	Cold bonded fly ash	1.89	35	25.50	789
Priyadharshini et al. [50],		2.12	22.70	13.23	-
Reddy et al. [51],		2.12	21.60	11.83	1247
Harilal and Thomas [52]		1.85	-	17.3	998
Joseph and Ramamurthy [22]		1.98	-	20.46	995