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Article

Mechanical Properties of Concrete Produced by Light Cement-Based Aggregates

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Abstract: There is great growing concern regarding the environmental impact of the building and construction industry. Aggregate, one of the most crucial ingredients of concrete, is among the concerns in this regard. There will be a steady increase in demand for aggregates in the near future, but limited natural reserves will not be able to respond to this demand due to the risk of depletion. This current situation is forcing researchers to conduct new and artificial material production techniques that keep the resources within the allowed boundaries. Artificial aggregate production is one of the new methods for sustainable, environmentally friendly material production. The mechanical and environmental properties of lightweight concrete produced via artificial aggregates in different ratios were investigated in this study. Fly ash (FA), ground granulated blast-furnace slag (GGBFS), and quartz powder (QP) were utilized in the production of artificial lightweight aggregate (LWA) by using a special technique known as cold-bonding pelletization. The prepared concrete samples with the artificial aggregates were subjected to compressive, tensile, flexural, and bonding tests. The test results demonstrated that the bonding, tensile, and compressive strength values of lightweight concrete with a 20% GGBFS coarse aggregate replacement ratio of lightweight aggregates increased by 11%, 12%, and 30%, respectively. Moreover, it has been observed that a 41% increase in compressive strength is possible with a 40% QP coarse aggregate replacement ratio of lightweight aggregates. Finally, in addition to significantly impacting the mechanical properties of the lightweight concrete produced via artificial lightweight aggregates, we demonstrated that it is possible to control and reduce the harmful environmental effects of waste materials, such as FA, GGBFS, and QP in the present study.

Keywords: artificial aggregate; lightweight concrete; fly ash; ground granulated blast furnace slag; quartz powder

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1. Introduction

It is crucial to keep industrial waste under control and to reduce its impact on the environment as much as possible. Due to rapid urbanization and a large increase in the world's population [1], a large amount of solid waste has been generated and this is increasing rapidly in Turkey. According to the Turkish Statistical Institute, up to 16 million tons of FA are being created yearly, but only two or three percent can be used efficiently in the cement and concrete industry. FA, GGBFS as a waste material of steel factories, and QP with high reserve areas in Turkey are capable of having alkali-activated binder properties in terms of concrete production technology. Therefore, the goal of this research is to determine the optimal amount of waste materials to use in the production of lightweight aggregate for concrete mixes. Some other discussions have been had in the literature regarding the recycling of waste materials into new building materials, such as municipal solid waste incineration bottom ash (MSWIBA), silica fume (SF), and rice husk ash (RHA) for use as cement replacement materials. It was found that the use of FA as partial replacement for cement in concrete resulted in enhanced durability of the produced concrete in addition to reducing CO_2 emissions [2]. The influence of FA in the cement hydration process and its pozzolanic reaction inside concrete has been investigated by the authors in [3–5]. However, several researchers have investigated using FA and GGBFS in producing artificial LWA [6–13] such as: recycling bottom ash in artificial LWA to be used directly in concrete [14] and minimizing cumulative quantities and preserving the environment. The aggregate in concrete provides a large percentage of (often between 65 and 75 percent) and contributes significantly to the material's heavy weight; therefore, it makes sense to investigate the possibility of turning waste materials into lightweight artificial concrete. The different chemical and physical properties of waste materials directly affect the mechanical and durability of the produced concrete [15]. It was observed in some studies that the replacement of 30 percent of recycled aggregate with the natural aggregate had no significant impact on the performance of concrete when compared to natural concrete [16–18]. Therefore, the goal of this research was to determine the optimal amount of waste materials for use in the production of lightweight aggregate for concrete mixes.

Different materials and procedures may be used to produce artificial aggregate, such as cold-bonding and sintering techniques [7,19]. According to BS EN 13055, aggregates are considered lightweight aggregates if their particle densities do not exceed 2000 kg/m^3. Lightweight artificial aggregate was produced via the sintering method using alkaline palm oil fuel ash (POFA) combined with silt [20]. Although sintering consumes more energy than cold bonding, the benefits of achieving the sintered aggregate properties in less time outweigh waiting 28 days for cold-bonded aggregate to cure [21].

Lightweight aggregate manufacture via cold bonding was developed in the early 2000s, and FA was used as the dry powder. In this process, a million tons of waste materials was employed to generate aggregate, and this was found to be an appropriate material for producing lightweight aggregates [22–25]. The cold-bonding process has been widely used to utilize various types of waste materials and protect the environment by controlling the leaching of pollutants [26]. The technique can thus be considered a proper treatment channel for recycling waste materials [27]. Moreover, the technique is more economical than the sintering method, but the crushing strength of aggregates usually gives lower results [10,28,29]. In addition, the technique has more advantages in terms of cost, energy consumption, and gas emissions [30].

Concrete with different compressive characteristics can be made from a wide variety of structural components around the world, simplifying construction while increasing durability and versatility. Depending on the intended function, concrete may be poured in almost any form, shape, or color. Concrete may now be found in many locations, thanks to the tremendous expansion in the building industry. However, concrete has some drawbacks including its low tensile strength and heavy weight. Many research studies have looked at ways to amplify these unfavorable traits. High-strength concrete may be enhanced with recycled cement kiln dust and fibers made from recycled polyethene [31]. Artificial aggregates are also employed to reduce the concrete's weight. For industrial purposes, a variety of light aggregates have been employed successfully. For example, bottom FA, concrete waste powder, and pulverized granulated blast-furnace slag [32] may all be used when using a cold-bonding technique. Various studies examined the mechanical behaviors of concrete produced with cold-bonded lightweight FA aggregates [10,13]. Sintered and cold-bonded artificial aggregate produced by utilizing washed sludge ash (WAS) and GGBFS was used to produce concrete with mechanical properties comparable to ordinary concrete with a lower oven-dry density [33]. This form of artificial aggregate may be utilized in various concretes with varying mechanical properties. Depending on the aggregate content, the compressive strength may be readily achieved at concrete manufacture between 20 and 80 MPa. The use of 10% FA with recycled aggregate resulted in a slight increase in the axial compressive strength of the concrete [34]. Furthermore, the addition of FA to the concrete with recycled aggregate improved the workability—due to the spherical and flat shape of pellets—in addition to the mechanical and durability properties of concrete [2].

Although lightweight concrete has a lower strength than normal-weight concrete, it has some advantages such as having a reduced dead load, being eco-friendly, being low cost, and having higher seismic and fire resistant properties [35–37]. From an environmental protection point of view, using FA artificial aggregate as a fine aggregate in concrete could reduce CO_2 emissions by up to 60% compared to conventional concrete [38]. Furthermore, replacing 50% of the cement with FA as a binder could reduce greenhouse emissions by 54% [39]. In addition to the environmental impact of using an FA artificial aggregate, the cost of producing concrete can be reduced by 13–15% compared to conventional concrete [40]. Sintered artificial aggregate is widely preferred in concrete production in order to provide a higher strength. Using sintered FA aggregate in lightweight concrete production has resulted in good mechanical and durability properties [41]. Similarly, the fly ash cenosphere (FAC) features include being hollow spherical, lightweight, and air-filled [42]. It is favored in different industries due to its high workability, low conductivity and bulk density, and its thermal resistance [40]. FAC is also a fine aggregate in sustainable lightweight concrete production [43]. A combination of 50% FAC and 75% SFA is suitable for producing sustainable lightweight concrete [43]. However, a high volume of FAC and SFA (up to 75%) leads to a significant reduction in lightweight concrete strength; the strength could be enhanced by adding silica fume [44,45]. Based on these previous studies, it is observed that a high volume of FAC and SFA could be utilized in lightweight concrete production with the aid of silica fume.

There is a lack of research on the use of QP in manufacturing aggregate and its influence on the mechanical performance of the bond strength effects of lightweight aggregates between concrete and reinforcing bars in particular. Hence, this study was focused on the influence of an artificial aggregate made from FA, GGBFS, and QP powder on the properties of concrete. Additionally, the effect of lightweight aggregate on the adhesion of concrete to steel was examined. The experimental findings were compared with the outcomes of conventional concrete made using typical aggregate. Due to prior research, the optimal value of the aggregates was determined based on the water absorption, bulk density, and crushing strength. These aggregates were substituted for conventional coarse aggregate with varying ratios to assess the concrete's compressive strength, modulus of elasticity, and tensile strength, and the strength of the bond between the aggregates and the cement paste.

2. Materials and Methods

During this experimental study, concrete was cast using three different types of artificial LWAs to examine their influence on concrete's mechanical and fracture properties. Different replacement ratios (20%, 40%, and 60%) were applied with natural coarse aggregate by weight.

2.1. Materials

This experiment used the same cement for producing artificial aggregate and testing concrete containing artificial aggregate. The specific gravity of CEM I 42.5 R Portland cement is 3.14, and the Blaine fineness is 326 m^2/kg. Table 1 shows the chemical qualities that were employed in this experiment.

Two types of coarse aggregate utilized in manufacturing lightweight aggregate concrete are cold-bonded artificial aggregates and normal aggregates. Materials utilized in artificial aggregate synthesis include FA, GGBFS, and Q powder (see Table 1). The decision was made to use a blend of river sand and crushed limestone sand as the final fine aggregate obtained from a local supplier.

Slag from iron and steelmaking is known as GGBFS. FA from a thermal power plant in Turkey was utilized in this investigation with a specific gravity of 2.25 m^2/kg and a fineness of 287 m^2/kg. The GGBFS and QP qualities utilized in this experiment are shown in Table 1. Concrete mixes were made more manageable using a water-reducing additive with a specific gravity of 1.19. A superplasticizer (SP) was added to the mix.

Table 1. Physical and chemical properties of cement, FA, GGBFS, and QP.

Chemical Composition (%)	Portland Cement	FA	QQBFS	QP
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)	326.00	287.00	418.00	–

2.2. Production of Artificial LWAs

The FA, GGBFS, and QP LWAs were made using the cold-bonding technique in a titled pan at ambient temperature with varied ratios of Portland cement (20%, 30%, and 50% by weight of cement). For the first 10 min, Figure 1 depicts the process whereby the dry materials were fed onto the disc and rotated at a constant speed to ensure uniformity. During the rotation, the dry mixture was sprayed with water to act as a coagulant and form pellets [9,12]. The process was repeated for 10–12 min in order to produce pellets with a diameter ranging between 6 mm and 12 mm. The aggregates were kept in plastic bags at 70% relative humidity for 28 days. The specific gravity, bulk density, water absorption, and crushing strength of the aggregates were determined following the curing period. This method was carried out for all the aggregate types manufactured.

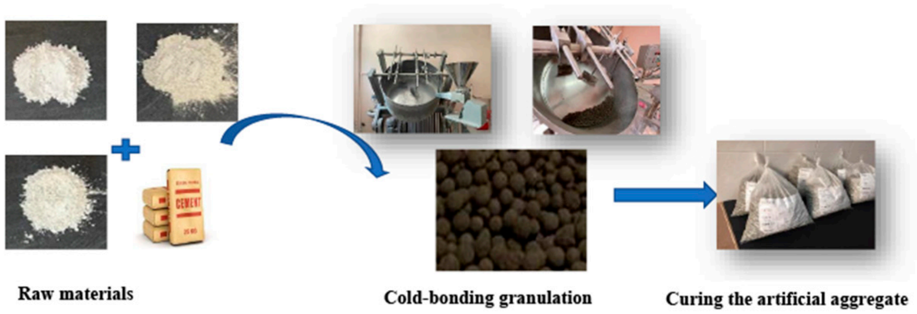


Figure 1. The process of cold-bonding manufacturing the LWA [22].

2.3. Concrete Mix Proportions

The artificial aggregate types were produced to develop the concrete mixes in the experimental investigation. FA and GGBFS were combined with crushed QP powder in the LWA production process. The materials used to make the artificial aggregate and the replacement ratio with coarse aggregate are listed in Table 2. A complete list of the concrete mix proportions used in the investigation is provided in Table 3. FAAC, GGBFSAC, and QPAC refer to the FA, GGBFS, and QP aggregate concrete mixtures in Table 3. This also shows how much superplasticizer (SP) was needed to achieve appropriate workability.

Table 2. The design for concrete mixtures.

Mix ID	Replacement Rate (%)	Cement (kg/m^3)	Water (kg/m^3)	River Sand (kg/m^3)	Natural Aggregate (kg/m^3)	Manufactured Aggregate (kg/m^3)	SP (kg/m^3)
	20	360	158	733.3	589.4	80	4.45
FAAC	40	360	158	733.3	442	157.7	4.45
	60	360	158	733.3	294.7	236.7	4.45
	20	360	158	733.3	589.3	93.7	4.45
GGBFSAC	40	360	158	733.3	442	187.7	4.45
	60	360	158	733.3	294.7	281.3	4.45
QPAC	20	360	158	733.3	589.4	82.5	4.45
	40	360	158	733.3	442.1	165	4.45
	60	360	158	733.3	294.7	247.5	4.45

Table 3. Physical and mechanical properties of artificial LWA.

Mix ID	Maximum Aggregate Size (mm)	Fineness Modulus	Specific Gravity	Apparent Specific Gravity	Density (kg/m^3)	Water Absorption (%)	Crushing Strength (N)
FAA	16	1.78	1.43	2.43	937.59	28.52	722.96
GGBFSA	12.5	2.67	1.74	2.43	1114.42	16.27	1038.98
QA	12.5	1.53	1.61	2.70	928.00	18.00	675.51

2.4. Concrete Casting and Specimen Preparation

Three series of concrete mixes were cast in this investigation according to the three types of artificial aggregates. The coarse aggregate was used in each case to make up 20%, 40%, and 60% of the original volume. In total, ten different concrete combinations and a control concrete mixture were prepared. According to ASTM C192-18, the control mixture was poured, whereas the artificial aggregate-containing mixture required further operations to be completed. To achieve a saturated surface dry state, it was essential to soak the lightweight aggregate pellets used in the concrete mixes overnight in water, and then dry them with a towel to remove the excess water. The concrete mixtures were prepared and created using a rotating pan mixer with a 40-litre capacity.

In accordance with TS EN 12350-2, a slump cone was used to test the workability of each combination once the mixing step was completed. The hardened characteristics of the concrete mixes were investigated once the workability was established. A total of six specimens were used in the investigation of hardened properties. These included three specimens of 100 mm cubes for compression strength testing, three specimens of 100 * 200 mm cylinders for splitting tensile and three-point load testing, three specimens of 75 * 75 * 280 mm for modulus of elasticity testing, and three specimens of 150mm cubes for the water permeability test. Water curing was performed for 28 days on all the concrete sample seeds that had been removed from the molds after 24 h of drying.

2.5. Test Methods

2.5.1. Aggregate Tests

The particle size distribution of artificial LWA was determined. The tests for the physical properties of the artificial LWA were conducted in terms of specific gravity, bulk density, and water absorption in accordance with ASTM 127. The crushing strength test was performed in accordance with BS 812 part 110 by placing the pellet between two parallel plates and applying a direct load until failure, an average of 10 pellets was taken as the crushing strength. Furthermore, mineralogy and microstructural analyses were performed on the manufactured pellets by using scanning electron microscopy (SEM).

2.5.2. Concrete Tests

Compressive strength was determined using cubic samples according to the ASTM C39-18. The splitting tensile strength was calculated using ASTM C496-17 and Equation (1):

$$f_s = \frac{2P}{\text{л}DL} \tag{1}$$

where f_s = splitting tensile strength (MPa), P = maximum load (N), D = specimen diameter (mm), and L = specimen length (mm).

The fracture energy was established in accordance with RILEM 50-FMC Technical Committee [46]. Figure 2 shows a beam with notches during the test. The notch-to-depth ratio was 0.4. An LVT transducer measured midspan deflection (LVDT). The area under the load–displacement curve was used to compute the fracture energy by using Equation (2):

$$G_F = \frac{W_0 + mg\frac{S}{U}\delta_s}{B(W-a)} \tag{2}$$

where G_F is the fracture energy (N/mm), W_0 is the area under load–displacement curve (N.mm), m is the specimen mass (kg), g is acceleration of gravity (m/s^2), S is the distance between support (mm), U is the specimen length (mm), δ_s is the specimen deflection (mm), B is the specimen width (mm), W is the specimen depth (mm), and a is the notch depth (mm).

Figure 2. A notch beam under fracture energy test.

Also, the notched beams were used to determine the net flexural strength in accordance with ASTM C1609, 2005 by using Equation (3) [47]:

$$f_{flex} = \frac{3P_{max}S}{2B(W-a)^2} \quad (3)$$

where f_{flex} is the failure load (MPa) and P_{max} is the maximum load (N).

Furthermore, to measure the characteristic length to indicate the brittleness of each specimen, Equation (4) was used: [48]

$$l_{ch} = \frac{EG_F}{f_s{}^2} \quad (4)$$

where $\boldsymbol{l_{ch}}$ is the characteristic length (mm) and E is the static modulus of elasticity (GPa).

RILEM RC6 requires 150 × 150 × 150 mm cube specimens with embedded reinforcement bars with a 16 mm diameter at the center of the sample to determine the bond strength between the steel and the lightweight aggregate [49]; Equation (5) is used to measure the bond strength:

$$\tau = \frac{\boldsymbol{P}}{\pi \boldsymbol{d_b L_b}} \quad (5)$$

where τ is bond strength (MPa), $\boldsymbol{d_b}$ is the diameter of the embedded steel bar (16 mm), and $\boldsymbol{L_b}$ is the embedded length of the steel bar (150 mm).

3. Results and Discussion

3.1. Results of Aggregate Tests

The particle size distribution of artificial LWA is shown in Figure 3. The physical and mechanical properties are displayed in Table 3. It is noted that the GGBFSA recorded the highest crush strength value and minimum water absorption rate. The microstructure for each type of artificial LWA aggregate is shown in Figure 4. The minor differences between the artificial LWAs are that the QPA has sharp corners and the presence of voids in FAA is less than in GGBFSA and QPA. The FAA particles exhibited a denser surface structure when compared to the other types of aggregate. The core of the aggregate particles showed a porous structure that gives the lighter weight and the high water absorption, leading to a reduction in the strength and stiffness of artificial aggregate particles.

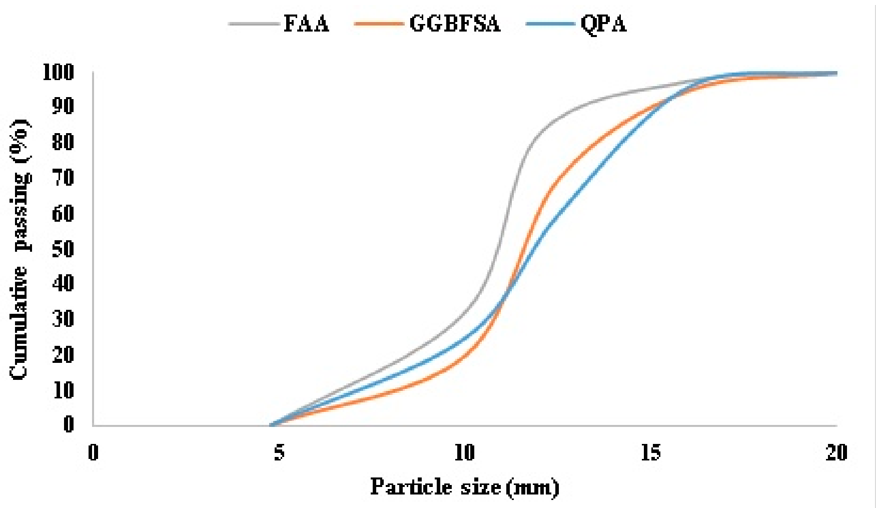
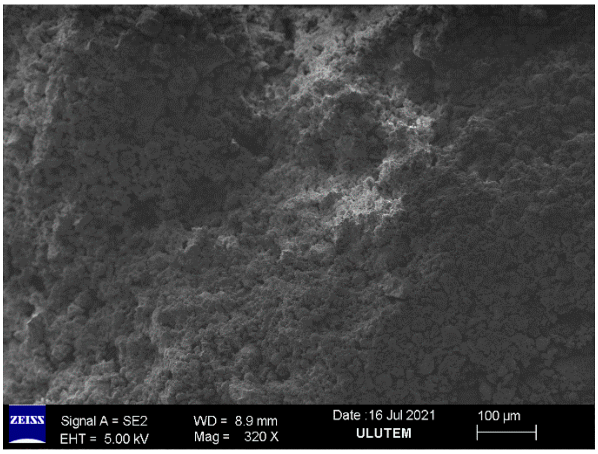


Figure 3. Particle size distribution of artificial LWAs.



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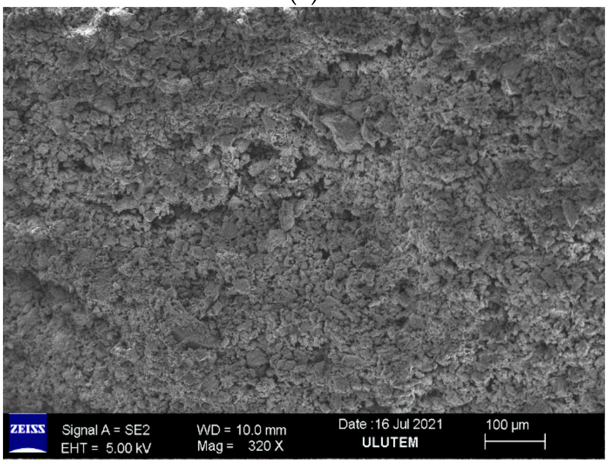

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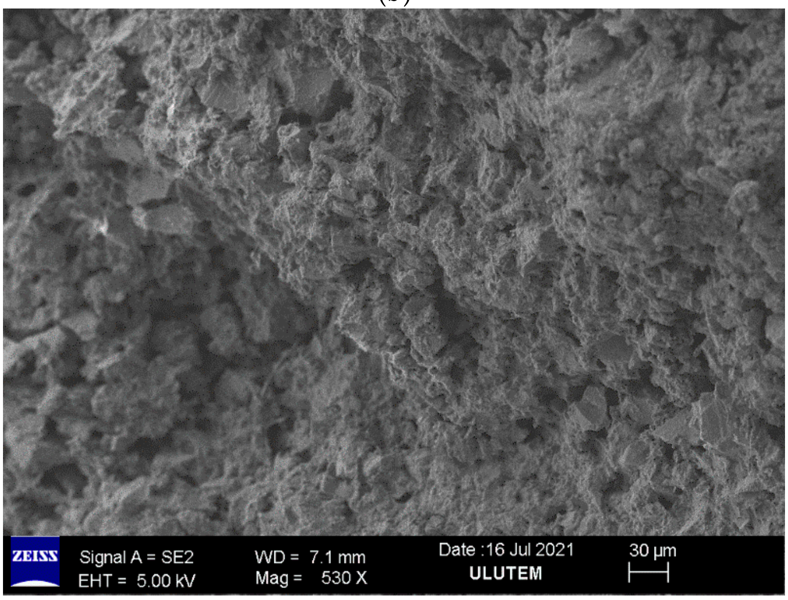


(**c**)

Figure 4. The microstructure of artificial LWAs (**a**) FAA, (**b**) GGBFSA, and (**c**) QPA.

3.2. Results of Concrete Tests

The results of compression, splitting tensile, flexure, bonding, and modulus of elasticity tests are discussed in detail below. Furthermore, the photographic views and graphical illustrations were added for a clear and detailed discussion and evaluation.

3.2.1. Compressive Strength

The average compressive strength results of the cube samples which were treated for 28 days are illustrated in Figure 5.

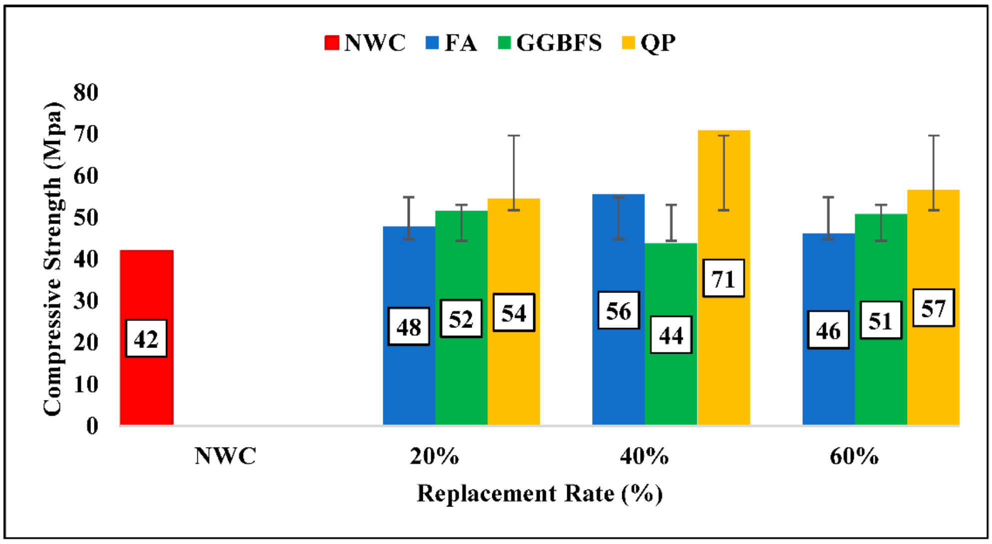


Figure 5. The compressive strength of LWA concretes.

All of the mixtures generated similar results when the pressures ranged between 40 MPa and 55 MPa, compared with the natural normal-weight concrete (NWC). According to these results, the artificial aggregate used up to 60% of the traditional coarse aggregate and may still offer appropriate compressive strength. The experimental results indicate that artificial LWA concrete requires a lower water-to-cement ratio than regular aggregate concrete. A higher cement percentage is needed to compensate for the artificial aggregate's increased porosity and softness and decreased hardness [50].

The maximum compressive strength was attained at a 40% volume replacement ratio for the mixture comprising quartz artificial aggregate in this experiment. Although the lowest value was obtained by replacing 60% of the natural aggregate with GGBFS artificial aggregate, it was still 1% higher than for the regular aggregate. However, when the artificial aggregate ratios were increased, compressive strength was slightly reduced. There is a reasonable amount of strength in the concrete formed using artificial aggregates, although it is not as strong as traditional concrete. According to the previous research, adding sintered FA LWA decreases the compressive strength by 10% to 13%. The results of this experiment confirm those of Nadesan [45].

3.2.2. Splitting Tensile Strength

A splitting tensile test assesses the concrete's tensile strength. It is a method through which a fracture occurs due to applied stress attempting to locate weaker paths. The average tensile strength was calculated using three 100 * 200 mm cylindrical samples. In this study, the tensile strength of the concrete with artificial LWA is equivalent to that of sound concrete, as shown in Table 2 and Figure 6. It is estimated that the performance of lightweight concrete created using artificial aggregate is comparable to that of control concrete prepared with ordinary coarse aggregates. Artificial aggregate has a reduced strength, round shape, and poor anchoring potential with cured cement paste, which are the causes of limited improvement for the splitting tensile strength. For these reasons and because of artificial aggregates' moderate tensile strength, artificial LWA could not enhance the tensile strengths to levels higher than for ordinary concrete. Tensile strength is dependent on the shear of the interfaces zone between the cement paste and aggregate particles and this can be improved by the curing time and condition, for example, steam curing can improve the tensile strength more than water curing. Concrete is used for several purposes; however, the splitting tenacity results of concrete, including artificial aggregate, were satisfactory.

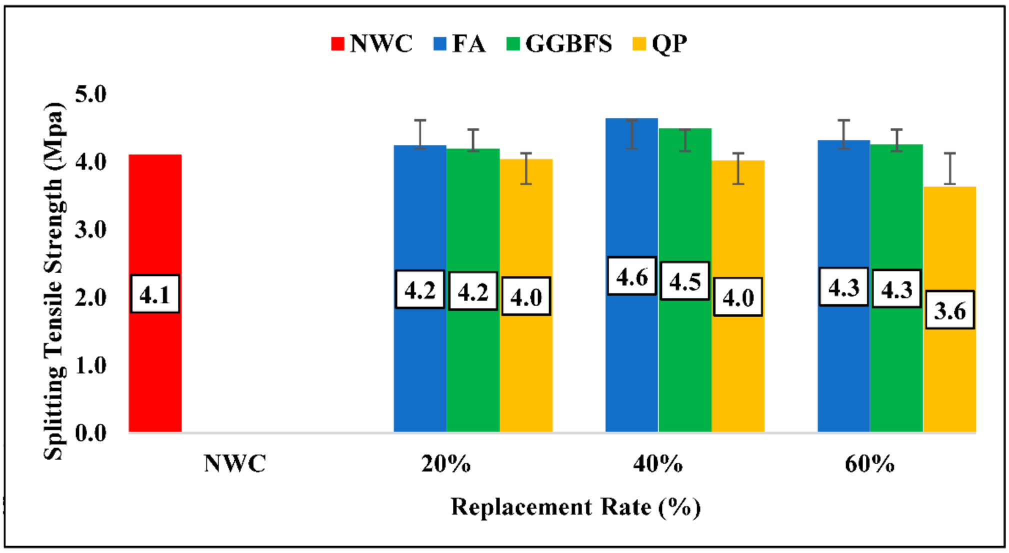


Figure 6. The splitting tensile strength of lightweight aggregate concretes.

3.2.3. Net Flexural Strength

A different type of tensile strength test, known as the net flexural strength, is shown in Figure 7. According to the results, concrete's net flexural strength was more significant than its splitting tensile strength. Concrete mixtures constructed with FA artificial LWA had values ranging from 5.41 MPa to 6.62 MPa, while GGBFS and QP artificial aggregates had values ranging from 4.48 MPa to 5.45 MPa and 5.56 MPa to 6.09 MPa, respectively. Particles with a higher crushing strength showed better flexural strength values. While the net flexural strength of artificial LWA concretes was lower than that of normal-weight concrete, the compressive, splitting, and net flexural strengths were all comparable to normal-weight aggregate concrete and it could be improved by improving the cement paste quality and reducing the water-cement ratio. Although the flexural strength of artificial LWA concretes was lower than that of natural normal-weight aggregate concrete, there was a consistency between the compressive strength, tensile strength, and net flexural strength for the artificial LWA concrete.

3.2.4. Load–Displacement Curves

Figure 6 shows typical load–displacement curves for concrete mixtures. Concretes with a lower compressive strength as demonstrated in Figure 8 have more significant displacements based on the load–displacement curve. Concretes constructed with lightweight artificial particles display ductile behavior because their maximum displacement values are more crucial. Adding artificial LWA to a concrete mix improves the concrete's ductility.

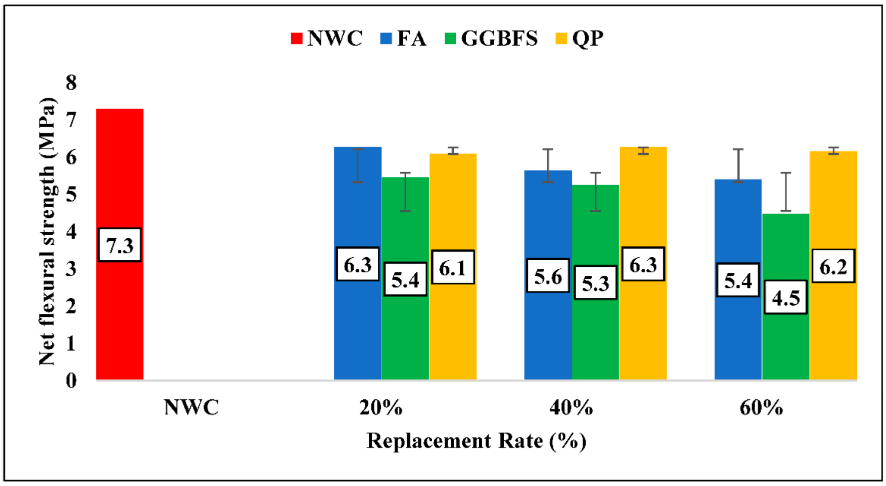
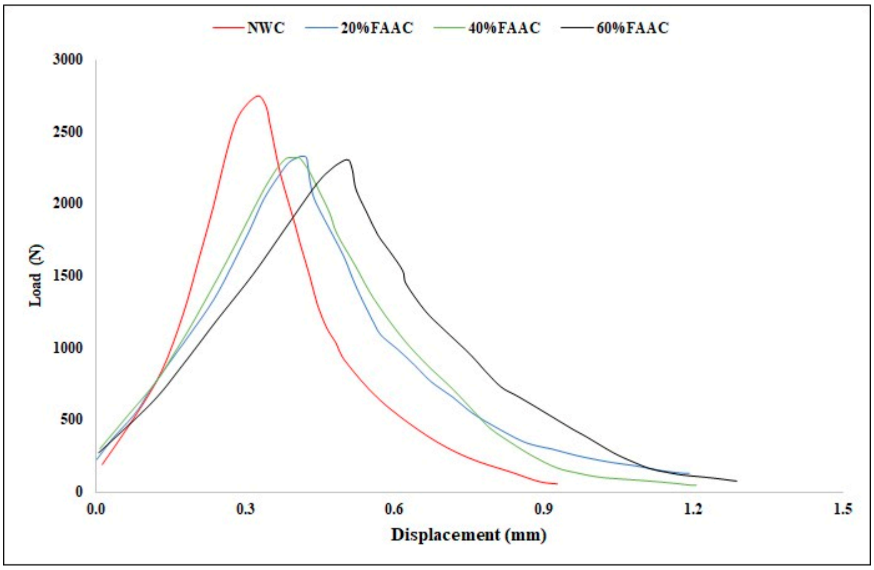


Figure 7. The net flexural strength of artificial aggregate concrete.



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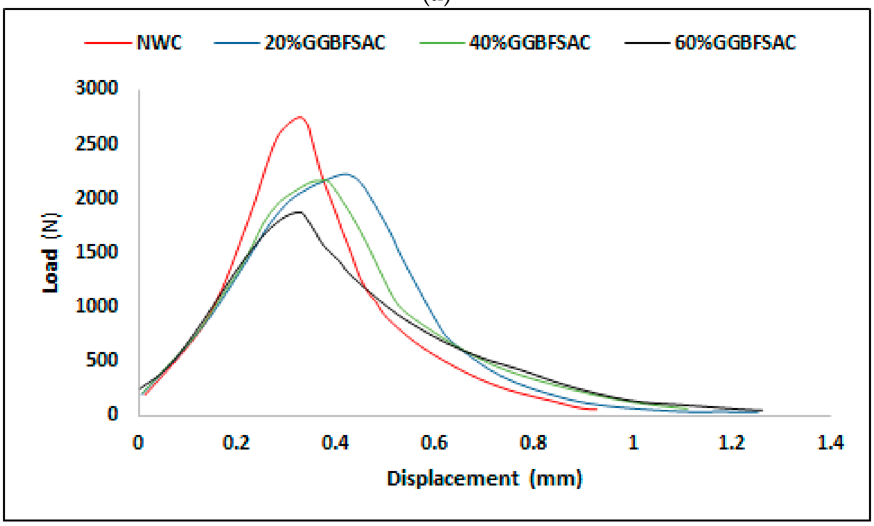

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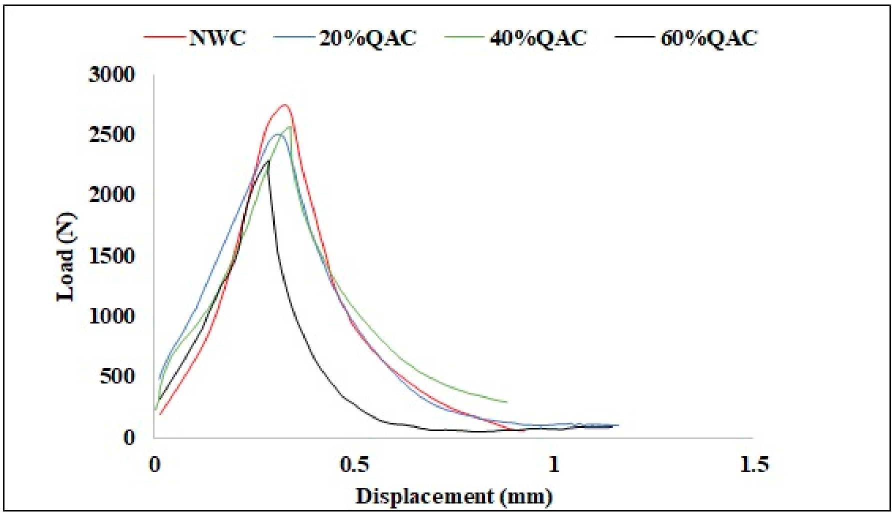
Figure 8. *Cont.*



(**c**)

Figure 8. Load–displacement curves for (**a**) FAAC, (**b**) GGBFSAC, and (**c**) QAC.

3.2.5. Fracture Energy

A three-point bending machine was used to test a notched beam, and the results are shown in Figure 9. Artificial aggregate concretes constructed from FA, QP, and GGBFS fiber-reinforced materials had fracture energies of 391 MPa, 328 MPa, and 310 MPa, respectively. The strength of artificial LWA concrete was reduced when compared to natural normal-weight aggregate concrete. The fracture energy is the sum of the actuator's energy and weight. The decreased fracture energy of artificial LWA concretes may be attributed to the results of this calculation. Because of the lower weight of the concrete, the amount of energy given by weight is reduced. The area under the load–displacement curves for concrete created using artificial LWA was less than for concrete manufactured with natural normal-weight aggregate. Since natural normal-weight aggregate has a lower density than artificial aggregate, the fracture energy provided by the actuator in the concrete will be more substantial.

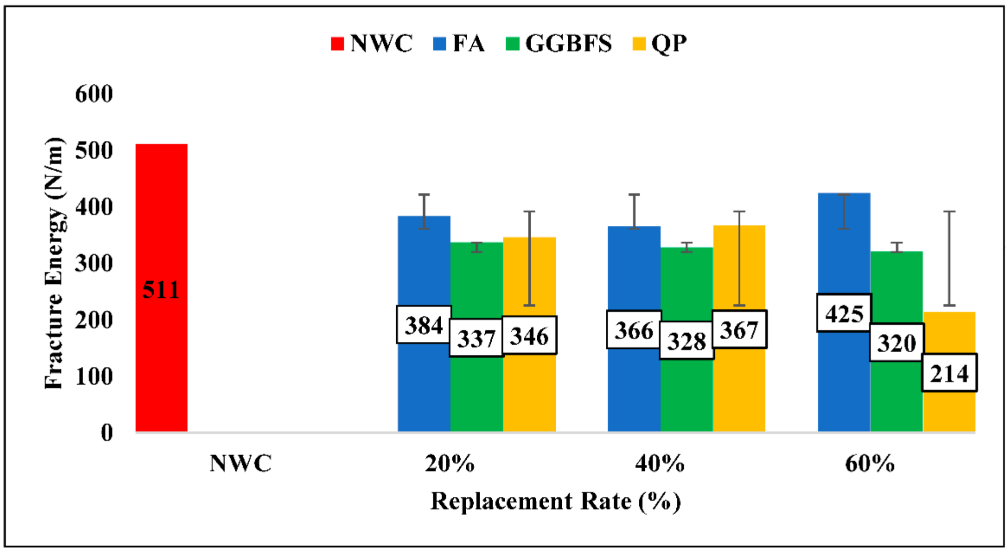


Figure 9. Fracture energy of artificial aggregate concretes.

3.2.6. Characteristic Length

Figure 10 depicts the characteristic length values, which are a brittleness measurement. The concrete mixes made using artificial lightweight particles had the most significant characteristic length values. With its distinctive length as a consequence, it is clear that artificial LWA makes concrete more ductile. Because of its higher compressive strength, the stronger concrete also had shorter characteristic length values. This provides further evidence that the ductility of concrete increases with its compressive strength.

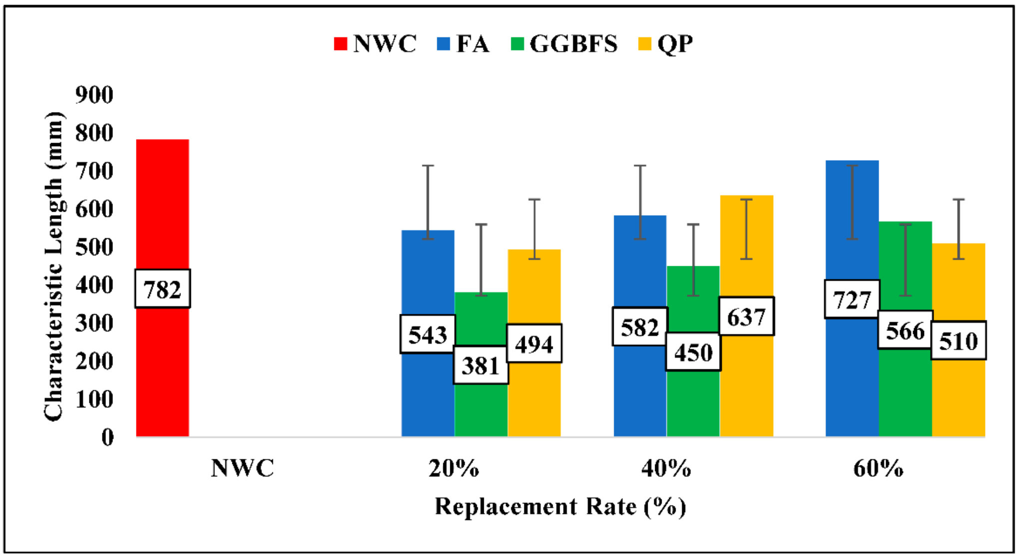


Figure 10. Characteristic length of artificial aggregate concretes.

3.2.7. Bond Strength

We could determine the concrete's binding strengths using the findings of this experiment. Increasing the FA artificial lightweight replacement boosts the concrete mix's binding strength. The results are shown in Figure 11. GGBFS artificial LWAs increased bond strength at a 20 percent replacement ratio by approximately 42 percent, while increasing the GGBFSA content to 60 percent reduced bond strength by 18 percent. Almost all bond strength tests for quartz artificial aggregate concrete were passed. When compared to natural normal-weight aggregate, manufactured LWA was weaker. This, however, directly affects the steel bar–concrete relationship; pulling out the steel bar easily breaks or crushes the weaker aggregate of the implanted steel bar.

The findings of the other studies demonstrated that artificial LWA works well, if not exceptionally. As a result, concretes constructed using artificial LWA have lower bond strength than concretes made with normal-weight natural aggregate. Thus, bond strength was determined to be the least effective measure when assessing the entire performance of artificial LWA.

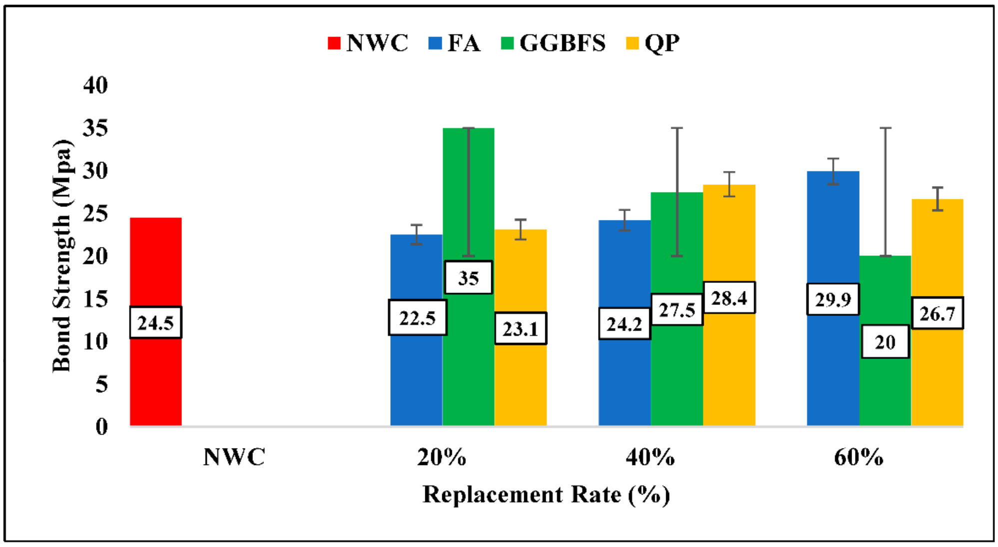


Figure 11. Bond strength of artificial aggregate concretes.

4. Conclusions

Based on the results gained from this experimental study, the following conclusions can be attained:

1. Artificial LWA was used to build concrete with compressive strengths of 40 MPa and 60 MPa. The maximum compressive strength was achieved for QPLWAC, which recorded 71 MPa at a 40 percent replacement ratio. The artificial LWA may be employed for any desired concrete strength class.
2. When used in concrete mixtures, artificial lightweight and ordinary weight particles produced splitting tensile strengths almost identically. Only slightly different changes were discovered. The lower splitting tensile strength values in concrete, including artificial LWA, are related to the lower crushing strength of artificial aggregates and the curing condition of the constructed concrete.
3. Artificial LWA concretes resulted in lower net flexural strength results when compared to normal concrete. However, the outcomes were satisfactory for all the concrete mixtures when the correlation between compressive strength and splitting tensile strength was taken into consideration. Regarding the concrete mixes, it was found that the higher ultimate loads occurred in the concrete, including natural, normal-weight aggregate. In contrast, more significant maximum displacement occurred in concrete containing artificial LWA. As a result, it can be concluded that concrete's tensile strength is reduced by using artificial LWA.
4. Because artificial LWA has a lower self-weight, the fracture energy of concrete is lower than that of concrete made with natural, heavier particles. Furthermore, this study's findings were consistent with previous research on the fracture energy of concrete mixes using artificial LWA. As a result, this shows that lightweight artificial aggregate may be used to make high-fracture-energy concretes.
5. Concrete ductility was enhanced as a consequence of using artificial LWA in concrete manufacturing, according to the findings regarding the characteristic length, which is a practical approach to quantify brittleness.
6. Artificial LWA used in concrete manufacturing considerably impacts the strength of the connection between the concrete and the reinforcing bar. There is a strong correlation between the reinforcing bar and the artificial LWA. Natural aggregate particles are more rigid than artificial LWA particles. As a result, the lower and comparable concrete resistance to normal concrete is generated after removing the reinforcing bar.

7. In conclusion, utilizing artificial LWA in concrete production has a significant impact, not only in terms of preserving the environment, but in the production of concrete with mechanical properties that are comparable with normal concrete and which can be applied in several construction fields.

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References

1. Kodur, V.K.R.; Naser, M.Z.; Bhatt, P.P. *Energy Engineering*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 113–122.
2. Lima, C.; Caggiano, A.; Faella, C.; Martinelli, E.; Pepe, M.; Realfonzo, R. Physical Properties and Mechanical Behaviour of Concrete Made with Recycled Aggregates and Fly Ash. *Constr. Build. Mater.* **2013**, *47*, 547–559. [CrossRef]
3. Paya, J.; Borrachero, M.V.; Monzo, J.; Peris-Mora, E.; Bonilla, M. Long Term Mechanical Strength Behaviour in Fly Ash/Portland Cement Mortars Prepared Using Processed Ashes. *J. Chem. Technol. Biotechnol. Int. Res. Process Environ. Clean Technol.* **2002**, *77*, 336–344.
4. Sakai, E.; Miyahara, S.; Ohsawa, S.; Lee, S.-H.; Daimon, M. Hydration of Fly Ash Cement. *Cem. Concr. Res.* **2005**, *35*, 1135–1140. [CrossRef]
5. Moon, G.D.; Oh, S.; Choi, Y.C. Effects of the Physicochemical Properties of Fly Ash on the Compressive Strength of High-Volume Fly Ash Mortar. *Constr. Build. Mater.* **2016**, *124*, 1072–1080. [CrossRef]
6. Cheeseman, C.R.; Virdi, G.S. Properties and Microstructure of Lightweight Aggregate Produced from Sintered Sewage Sludge Ash. *Resour. Conserv. Recycl.* **2005**, *45*, 18–30. [CrossRef]
7. Joseph, G.; Ramamurthy, K. Influence of Fly Ash on Strength and Sorption Characteristics of Cold-Bonded Fly Ash Aggregate Concrete. *Constr. Build. Mater.* **2009**, *23*, 1862–1870. [CrossRef]
8. Kayali, O. Fly Ash Lightweight Aggregates in High Performance Concrete. *Constr. Build. Mater.* **2008**, *22*, 2393–2399. [CrossRef]
9. Arslan, H.; Baykal, G. Utilization of Fly Ash as Engineering Pellet Aggregates. *Environ. Geol.* **2006**, *50*, 761–770. [CrossRef]
10. Kockal, N.U.; Ozturan, T. Durability of Lightweight Concretes with Lightweight Fly Ash Aggregates. *Constr. Build. Mater.* **2011**, *25*, 1430–1438. [CrossRef]
11. Li, D.; Xu, Z.; Luo, Z.; Pan, Z.; Cheng, L. The Activation and Hydration of Glassy Cementitious Materials. *Cem. Concr. Res.* **2002**, *32*, 1145–1152. [CrossRef]
12. Baykal, G.; Döven, A.G. Utilization of Fly Ash by Pelletization Process; Theory, Application Areas and Research Results. *Resour. Conserv. Recycl.* **2000**, *30*, 59–77. [CrossRef]
13. Kockal, N.U.; Ozturan, T. Effects of Lightweight Fly Ash Aggregate Properties on the Behavior of Lightweight Concretes. *J. Hazard. Mater.* **2010**, *179*, 954–965. [CrossRef]
14. Keulen, A.; Van Zomeren, A.; Harpe, P.; Aarnink, W.; Simons, H.A.E.; Brouwers, H.J.H. High Performance of Treated and Washed MSWI Bottom Ash Granulates as Natural Aggregate Replacement within Earth-Moist Concrete. *Waste Manag.* **2016**, *49*, 83–95. [CrossRef] [PubMed]
15. Bravo, M.; De Brito, J.; Pontes, J.; Evangelista, L. Durability Performance of Concrete with Recycled Aggregates from Construction and Demolition Waste Plants. *Constr. Build. Mater.* **2015**, *77*, 357–369. [CrossRef]
16. Limbachiya, M.; Meddah, M.S.; Ouchagour, Y. Use of Recycled Concrete Aggregate in Fly-Ash Concrete. *Constr. Build. Mater.* **2012**, *27*, 439–449. [CrossRef]
17. Lotfy, A.; Al-Fayez, M. Performance Evaluation of Structural Concrete Using Controlled Quality Coarse and Fine Recycled Concrete Aggregate. *Cem. Concr. Compos.* **2015**, *61*, 36–43. [CrossRef]
18. Poon, C.S.; Kou, S.C.; Lam, L. Influence of Recycled Aggregate on Slump and Bleeding of Fresh Concrete. *Mater. Struct.* **2007**, *40*, 981–988. [CrossRef]
19. Liu, J.; Li, Z.; Zhang, W.; Jin, H.; Xing, F.; Tang, L. The Impact of Cold-Bonded Artificial Lightweight Aggregates Produced by Municipal Solid Waste Incineration Bottom Ash (MSWIBA) Replace Natural Aggregates on the Mechanical, Microscopic and Environmental Properties, Durability of Sustainable Concrete. *J. Clean. Prod.* **2022**, *337*, 130479. [CrossRef]

20. Kwek, S.Y.; Awang, H. Utilisation of Recycled Silt from Water Treatment and Palm Oil Fuel Ash as Geopolymer Artificial Lightweight Aggregate. *Sustainability* **2021**, *13*, 6091. [CrossRef]
21. Ibrahim, M.A.; Atmaca, N. Cold Bonded and Low Temperature Sintered Artificial Aggregate Production by Using Waste Materials. *Period. Polytech. Civ. Eng.* **2022**, 1–11. [CrossRef]
22. Wei, Y.L.; Cheng, S.H.; Chen, W.J.; Lu, Y.H.; Chen, K.; Wu, P.C. Influence of Various Sodium Salt Species on Formation Mechanism of Lightweight Aggregates Made from Coal Fly Ash-Based Material. *Constr. Build. Mater.* **2020**, *239*, 117890. [CrossRef]
23. Sahoo, S.; Selvaraju, A.K.; Suriya Prakash, S. Mechanical Characterization of Structural Lightweight Aggregate Concrete Made with Sintered Fly Ash Aggregates and Synthetic Fibres. *Cem. Concr. Compos.* **2020**, *113*, 103712. [CrossRef]
24. Nadesan, M.S.; Dinakar, P. Structural Concrete Using Sintered Flyash Lightweight Aggregate: A Review. *Constr. Build. Mater.* **2017**, *154*, 928–944. [CrossRef]
25. Balapour, M. *Conversion of Waste Coal Combustion Ash to Value-Added Construction Lightweight Aggregates Through a Holistic Thermodynamics-Guided Manufacturing Framework*; Drexel University: Philadelphia, PA, USA, 2021.
26. Senneca, O.; Cortese, L.; Di Martino, R.; Fabbricino, M.; Ferraro, A.; Race, M.; Scopino, A. Mechanisms Affecting the Delayed Efficiency of Cement Based Stabilization/Solidification Processes. *J. Clean. Prod.* **2020**, *261*, 121230. [CrossRef]
27. Ferraro, A.; Colangelo, F.; Farina, I.; Race, M.; Cioffi, R.; Cheeseman, C.; Fabbricino, M. Cold-Bonding Process for Treatment and Reuse of Waste Materials: Technical Designs and Applications of Pelletized Products. *Crit. Rev. Environ. Sci. Technol.* **2021**, *51*, 2197–2231. [CrossRef]
28. Gomathi, P.; Sivakumar, A. Accelerated Curing Effects on the Mechanical Performance of Cold Bonded and Sintered Fly Ash Aggregate Concrete. *Constr. Build. Mater.* **2015**, *77*, 276–287. [CrossRef]
29. Colangelo, F.; Messina, F.; Di Palma, L.; Cioffi, R. Recycling of Non-Metallic Automotive Shredder Residues and Coal Fly-Ash in Cold-Bonded Aggregates for Sustainable Concrete. *Compos. Part B Eng.* **2017**, *116*, 46–52. [CrossRef]
30. Tajra, F.; Elrahman, M.A.; Stephan, D. The Production and Properties of Cold-Bonded Aggregate and Its Applications in Concrete: A Review. *Constr. Build. Mater.* **2019**, *225*, 29–43. [CrossRef]
31. Kang, M.C.; Yoo, D.Y.; Gupta, R. Machine Learning-Based Prediction for Compressive and Flexural Strengths of Steel Fiber-Reinforced Concrete. *Constr. Build. Mater.* **2021**, *266*, 121117. [CrossRef]
32. Colangelo, F.; Cioffi, R. Use of Cement Kiln Dust, Blast Furnace Slag and Marble Sludge in the Manufacture of Sustainable Artificial Aggregates by Means of Cold Bonding Pelletization. *Materials* **2013**, *6*, 3139–3159. [CrossRef] [PubMed]
33. Özkan, H.; Kabay, N.; Miyan, N. Properties of Cold-Bonded and Sintered Aggregate Using Washing Aggregate Sludge and Their Incorporation in Concrete: A Promising Material. *Sustainability* **2022**, *14*, 4205. [CrossRef]
34. Dabhade, A.N.; Chaudari, S.R.; Gajbhaye, A.R. Effect of Fly Ash on Recycle Coarse Aggregate Concrete. *Int. J. Civ. Eng. Res.* **2014**, *2278*, 3652.
35. Faraj, R.H.; Sherwani, A.F.H.; Jafer, L.H.; Ibrahim, D.F. Rheological Behavior and Fresh Properties of Self-Compacting High Strength Concrete Containing Recycled PP Particles with Fly Ash and Silica Fume Blended. *J. Build. Eng.* **2021**, *34*, 101667. [CrossRef]
36. Faraj, R.H.; Hama Ali, H.F.; Sherwani, A.F.H.; Hassan, B.R.; Karim, H. Use of Recycled Plastic in Self-Compacting Concrete: A Comprehensive Review on Fresh and Mechanical Properties. *J. Build. Eng.* **2020**, *30*, 101283. [CrossRef]
37. Faraj, R.H.; Sherwani, A.F.H.; Daraei, A. Mechanical, Fracture and Durability Properties of Self-Compacting High Strength Concrete Containing Recycled Polypropylene Plastic Particles. *J. Build. Eng.* **2019**, *25*, 100808. [CrossRef]
38. Glavind, M.; Munch-Petersen, C. 'Green' Concrete in Denmark. *Struct. Concr.* **2000**, *1*, 19–25. [CrossRef]
39. Li, Z.; Ding, Z.; Zhang, Y. *Proceedings of the International Workshop on Sustainable Development and Concrete Technology*; Center for Transportation Research and Education Iowa State University: Beijing, China, 2004; pp. 55–76.
40. Danish, A.; Mosaberpanah, M.A. Formation Mechanism and Applications of Cenospheres: A Review. *J. Mater. Sci.* **2020**, *55*, 4539–4557. [CrossRef]
41. Cui, H.Z.; Lo, T.Y.; Memon, S.A.; Xu, W. Effect of Lightweight Aggregates on the Mechanical Properties and Brittleness of Lightweight Aggregate Concrete. *Constr. Build. Mater.* **2012**, *35*, 149–158. [CrossRef]
42. Ranjbar, N.; Kuenzel, C. Cenospheres: A Review. *Fuel* **2017**, *207*, 1–12. [CrossRef]
43. Patel, S.K.; Satpathy, H.P.; Nayak, A.N.; Mohanty, C.R. Utilization of Fly Ash Cenosphere for Production of Sustainable Lightweight Concrete. *J. Inst. Eng. Ser. A* **2020**, *101*, 179–194. [CrossRef]
44. McBride, S.P.; Shukla, A.; Bose, A. Processing and Characterization of a Lightweight Concrete Using Cenospheres. *J. Mater. Sci.* **2002**, *37*, 4217–4225. [CrossRef]
45. Nadesan, M.S.; Dinakar, P. Influence of Type of Binder on High-Performance Sintered Fly Ash Lightweight Aggregate Concrete. *Constr. Build. Mater.* **2018**, *176*, 665–675. [CrossRef]
46. RILEM, D.R. Draft Recommendation: "Determination of the Fracture Energy of Mortar and Concrete by Means of Three-Point Bend Tests on Notched Beams". *Mater. Struct.* **1985**, *18*, 484.
47. Balendran, R.V.; Zhou, F.P.; Nadeem, A.; Leung, A.Y.T. Influence of Steel Fibres on Strength and Ductility of Normal and Lightweight High Strength Concrete. *Build. Environ.* **2002**, *37*, 1361–1367. [CrossRef]
48. Hillerborg, A. The Theoretical Basis of a Method to Determine the Fracture EnergyG F of Concrete. *Mater. Struct.* **1985**, *18*, 291–296. [CrossRef]

49. RILEM, R.C. Recommendations for the Testing and Use of Constructions Materials Bond Test for Reinforcement Steel. *Pull-Out Test* **1996**, *3*. [CrossRef]
50. İpek, S.; Ayodele, O.A.; Mermerdaş, K. Influence of Artificial Aggregate on Mechanical Properties, Fracture Parameters and Bond Strength of Concretes. *Constr. Build. Mater.* **2020**, *238*, 117756. [CrossRef]