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SHORT COMMUNICATION

Development of greener lightweight aggregates from industrial waste products for use in construction composites

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Abstract
Lightweight aggregates for construction applications are beneficial in terms of reducing the deadweight of structures coupled with an enhancement in properties such as thermal and acoustic properties. In this study, greener lightweight aggregates are developed from industrial wastes, and the corresponding properties are evaluated. Blast furnace flue dust which is a by-product of steel production was used to replace up to 60% fly ash which is a by-product of coal production in the production of the greener lightweight aggregates. The findings from this study showed that it is possible to produce greener lightweight aggregates with a density as low as 650 kg/m^3. However, the optimum content of blast furnace flue dust to replace fly ash as the precursor was found to be 40% as there was a decrease in compressive strength and increase in water absorption at higher contents. The compressive strength and water absorption of greener lightweight aggregate composed of 52% fly ash, 40% blast furnace flue dust and 8% semi-plastic clay is 8.3 MPa and 17%, respectively. Microstructural investigation of the aggregates indicated that the porous nature of the developed aggregates is responsible for their corresponding higher water absorption.

Keywords Lightweight aggregates · Industrial wastes · Fly ash · Blast furnace flue dust · Sustainable construction

Introduction

The construction industry is one of the fast-growing sectors all over the world, and it is a critical backbone of infrastructure development [1]. Currently, the construction industry depends on the use of natural resources to fulfil the demand for the majority of construction materials. Of such are naturally occurring stone aggregates which are very critical components of various construction materials such as cement-based and asphalt-based materials [2]. However, the increasing demand and utilization of these natural aggregates for various construction applications due to increasing urbanization have resulted in over-exploitation of the natural sources of these aggregates [3]. In addition, the sourcing of these aggregates results in the defamation of the environment and a corresponding high carbon dioxide emission as a result of their mining/production and transportation. Hence, in order to ensure sustainable construction; it is essential to develop/source alternative sustainable aggregates that can be used as a construction material.

The increased sustainability awareness in the construction industry in the last decade has yielded the use of various recycled/waste materials as aggregates as construction materials [4]. Some of the common recycled/waste materials that have been used in construction are recycled glass, recycled asphalt, crumb rubber, plastics [5–7]. The use of these sustainable alternatives has resulted in improving the sustainability of construction materials and supplementing the natural deposits of aggregates [8]. The lower density of some of these recycled/waste materials has also been found to make them suitable in the production of lightweight construction composites. Several other studies have shown that these lightweight recycled/waste materials can improve

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properties, such as thermal and acoustic properties of composites [9].

On the other hand, there also exist various industrials wastes generated in large quantities that can be sintered together to produce lightweight aggregates for various construction applications. Of such wastes are fly ash (FA) and blast furnace flue dust (BFD) which are generated as by-products during power generation from coal plants and steel production, respectively. The improper disposal or management of these industrial wastes could result in a huge threat to the sustainability of the environment resulting in various menaces such as contamination of groundwater or pollution of the air. Though several studies have utilized these industrial wastes as a binder component in various cementitious composites [10, 11], there is an imminent need to find other alternative uses for these industrial wastes.

In contrast to existing studies, the FA and BFD were used as the composition of the aggregates rather than as a binder [12, 13]. In addition, there is limited use of BFD for construction applications. In order to improve the sustainability of construction materials, innovative greener lightweight aggregates from these industrial wastes were developed in this study. FA and BFD were utilized as precursors and bentonite which is a semi-plastic clay (SPC) was used as the binder. The SPC was used at a fixed dosage of 8% and BFD was used as a replacement of the FA up to 60% starting at 20% at an increment of 10%. The resulting performance of the developed aggregates was assessed in terms of the bulk dry density, compressive strength and water absorption. The precursors were also characterized in terms of particle size distribution and chemical properties. It is anticipated that the results presented in this paper would gear more research and development of sustainable construction materials.

Experimental program

Materials and mixture composition

Fly ash (FA) and blast furnace flue dust (BFD) was used alongside semi-plastic clay (SPC) to produce lightweight aggregates. The specific gravity of the FA is 2.8 while that of BFD is 1.9. The BFD was used as a replacement of the FA up to 60% at an increment of 10%. The detailed composition of the samples evaluated is presented in Table 1. The sample ID used in Table 1 represents the content of BFD in the sample. For example, BFD20 and BFD50 indicate aggregates produced with 20% and 50% BFD, respectively.

Table 1 Composition of aggregate mixtures (%)

Sample ID	FA	BFD	SPC
BFD20	72	20	8
BFD30	62	30	8
BFD40	52	40	8
BFD50	42	50	8
BFD60	32	60	8

Sample preparation and evaluation

The aggregates were produced using the agglomeration method by using a suction grate sinter machine with a cross-sectional area of 300 mm × 300 mm and a height of 500 mm as shown in Fig. 1. For the preparation of each sample, the FA, BFD and SPC were mixed thoroughly and then pelletized in the presence of 12–16% water by a disc-granulator to make ball-shaped particles with sizes less than 20 mm sizes for sintering operation. The suction grate sintering takes place by downward air draft and movement of heat zone from top to bottom of the bed. The temperature and speed of sintering in this system are related to the bed permeability and bed height, the solid carbon content in the material and air suction pressure below the grate bar.

The sintering experiment was carried out by maintaining a bed height of 400 mm for the granulated particles on a 50 mm thick hearth layer with suction pressure 400 mm WG below the grate to complete the pre-heating, sintering and cooling in 25–30 min. Sintering and cooling are a continuous process and it takes place within the hearth itself [14, 15]. The sintering proceeds through granulated layers where the residence time of the maximum heat zone in the layers is two to three minutes. Therefore, uniform sintering of particles by suction method mostly depends on the granulated size of the aggregate pellet and residence time of the heat zone in the layer.

After the sintering and cooling of the aggregates have been completed, the properties of the developed aggregates were evaluated in accordance with IS 383 [16] in order to determine the suitability of using the aggregates for construction applications. Figure 2 shows the developed aggregates. The properties evaluated are bulk dry density,

Fig. 1 Suction grate sinter machine

Fig. 2 Photograph of developed aggregates

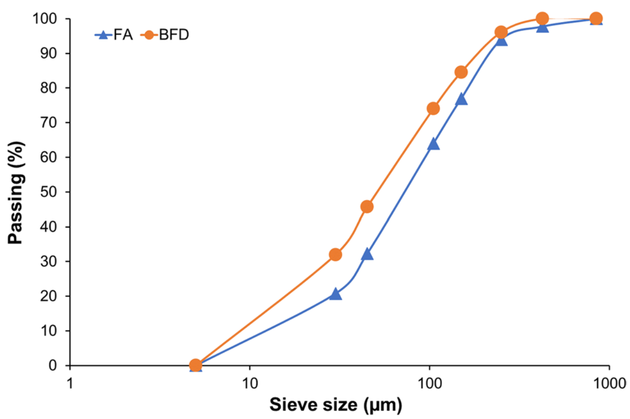

Fig. 3 Particle size distribution of precursors

compressive strength and water absorption. For the evaluation of these properties, three samples were made for each mixture and the corresponding average results were presented. Microstructural observation of the aggregate with the optimum BFD content was also carried out.

Results and discussion

Characterization of precursors

The particle size distribution of FA and BFD is presented in Fig. 3. It can be observed from Fig. 3 that BFD is finer than FA. The maximum particle size of FA and BFD is 42.5 μm and 25 μm, respectively. X-ray powder diffraction (XRD) was used to identify the phases in the precursors (i.e., FA and BFD), the resulting spectrum is presented in Fig. 4 while the corresponding chemical composition is presented in Table 2.

Figure 4 showed that Quartz, mullite, magnetite and minor amounts of vitreous silicates are the mineral phases present in the FA whereas the BFD contains phases like magnetite, hematite, ferrosilicate ($FeSiO_3$), Fe-metal, quartz, mullite and glassy silicates. The chemical composition of the precursors indicated that FA is primarily composed of SiO_2 and Al_2O_3 which results in 83.5% of the chemical composition of the precursor. On the other hand, BFD is composed of 10.7% and 38.8% SiO_2 and Fe_2O_3, respectively. Similar phases and chemical composition has been reported for FA and BFD [17–19]. The higher LOI of BFD compared to that of FA indicates it contains higher organic minerals and moisture.

Fig. 4 XRD spectrum of precursors

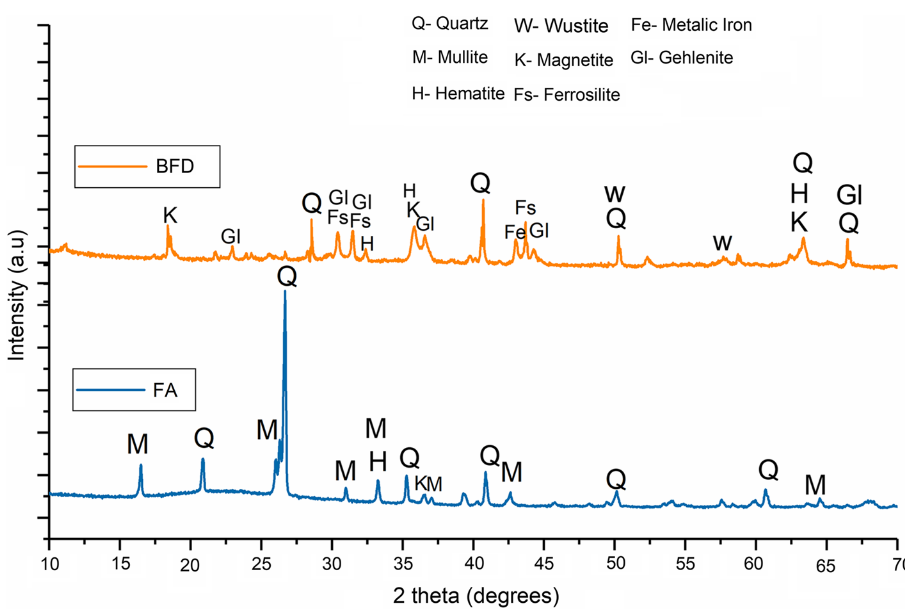

Table 2 Chemical composition of FA and BFD (%)

Compound	FA	BFD
SiO_2	56	10.70
Al_2O_3	27.50	6.45
Fe_2O_3	2.15	38.75
TiO_2	0.80	0.12
Mn_2O_3	0.18	2.30
MgO	1.20	2.85
CaO	1.45	8.20
Na_2O+K_2O	0.55	1.18
P_2O_5	0.25	0.35
SO_3	0.80	0.10
LOI	8.00	28.60

Dry bulk density

The effect of BFD content used as the replacement of FA on the bulk dry density of the aggregates is presented in Fig. 5. It can be observed that the bulk density of the aggregates reduced with the higher content of the BFD. The density of aggregates composed of 20%, 30%, 40%, 50% and 60% BFD are approximately 950 kg/m^3, 850 kg/m^3, 830 kg/m^3, 740 kg/m^3 and 650 kg/m^3, respectively. The reduction in the density of the aggregates with increasing BFD content can be associated with the lower specific gravity of BFD (1.9) compared to that of FA (2.8). The lower density of the aggregates indicates these aggregates can be incorporated into various cement-based and asphalt-based composites to produce lightweight composites. Lightweight composites are known to be beneficial in terms of reduction in deadweight, reduction in construction cost and time, and improvement in insulation properties. Several studies have also shown that the use of lightweight aggregate in the production of construction composites would result in an enhancement in the thermal and acoustic properties [20–23]. Hence, in addition to the developed aggregates offering a sustainable alternative to the conventional aggregates and effectively managing industrial wastes; they can be utilized to enhance certain performances of construction composites.

Compressive strength

Figure 6 shows the compressive strength of the developed aggregates in terms of the content of BFD. It is evident from Fig. 6 that the optimum content of BFD is 40% as there was a decrease in the compressive strength at higher contents (i.e., 50% and 60%). The increase in the compressive strength of the aggregates with an increase in the content of BFD as a replacement of up to 40% FA could be a result of the good distribution of various particle sizes. However, the reduction in compressive strength when 50% and 60% of BFD are used could be associated with the more uniform distribution of particles rather than a good/non-uniform distribution which would result in more refinement of the matrix. Nonetheless, the compressive strength of aggregates made with 50% and 60% is 85.7% and 34.3% higher than those made with 20% BFD. Hence, BFD can still be utilized at higher dosages past the optimum content (i.e., 40%) to produce aggregates.

Water absorption

The influence of BFD content on the water absorption of the aggregates is presented in Fig. 7. It can be observed that similar to the compressive strength trend, increasing the BFD content up to 40% is beneficial to the properties of the aggregate. However, the use of BFD as 50% and 60% replacement of the FA resulted in an increase in the water absorption compared to when 40% BFD was used. The water absorption of BFD50 and BFD60 is 22.7% and 50.1% higher than that of BFD40. The higher water absorption of BFD50 and BFD60 can be associated with the presence of more uniform particle distribution within the matrix which results in the formation of voids within the particles and a corresponding higher water absorption.

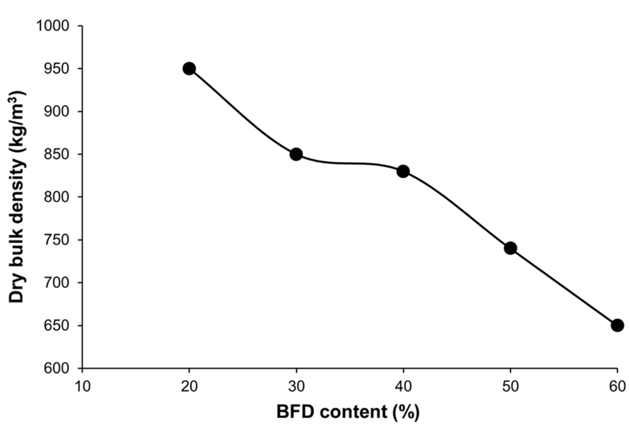

Fig. 5 Bulk dry density of aggregates

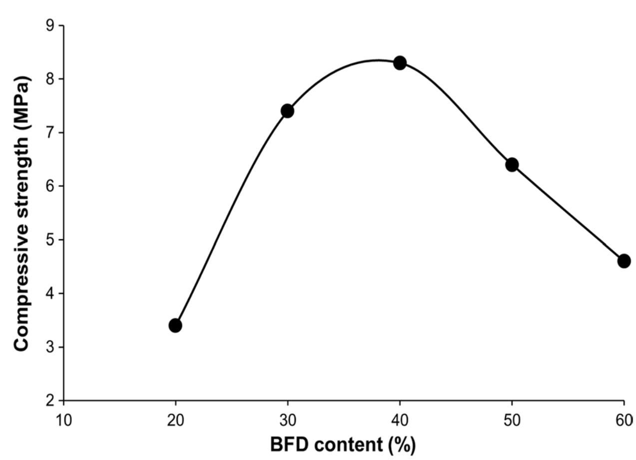

Fig. 6 Compressive strength of aggregates

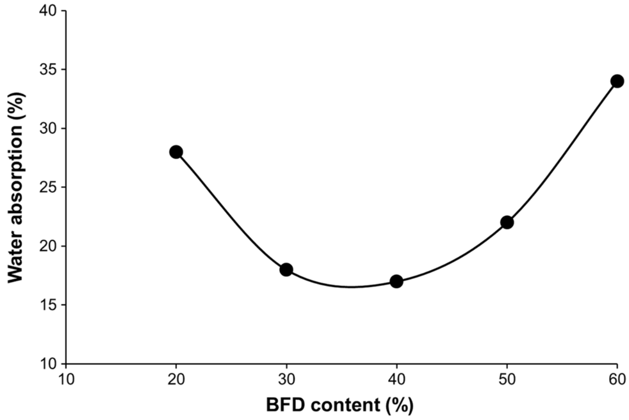

Fig. 7 Water absorption of aggregates

Nonetheless, regardless of the BFD content, the water absorption of the aggregates is relatively high (i.e., 17% to 33%). Hence, it is recommended that various methods to reduce the water absorption of composites should be utilized when these aggregates are used.

Microstructural property

A scanning electron microscope (SEM) was used to observe the microstructural morphology of the aggregate made with the optimum content of BFD (i.e., BFD40). The SEM images of BFD40 are presented in Fig. 8. In accordance with IS 383, the morphology of the developed aggregates can be classified as irregular or partly rounded. It is evident from Fig. 8 that these aggregates have a porous nature which can be associated with their lightweight. The porous nature of the aggregates is also responsible for their high-water absorption. For example, despite BFD40 being the optimum; it exhibited an absorption of 17%. Hence, it is recommended that when these aggregates are utilized in construction materials such as cement-based ones, supplementary cementitious materials (SCMs) should be incorporated to reduce the porosity of the composites. Several studies have shown that the use of SCMs, such as fly ash, silica fume can be used alongside lightweight aggregate in cement-based materials in order to reduce/eliminate the detrimental effect of the porous aggregates on the resulting performance of the composites [24, 25]. The use of these SCMs would result in the refinement and reduction in the pores present in the matrixes of the aggregates.

Conclusion

Greener lightweight aggregates for construction applications are developed from fly ash and blast furnace flue dust. Results from this study showed that it is viable to utilize these industrial wastes (i.e., fly ash and blast furnace flue dust) to produce aggregates by sintering methods. Increasing the content of the blast furnace flue dust reduces the bulk density of the aggregates. The density of the aggregates developed in this study in the range of 650–950 kg/m^3 showed that they can be classified as lightweight aggregates and utilized in the production of lightweight construction composites. The lightweight nature of these aggregates also makes them suitable in the production of composites with enhanced thermal and acoustic properties. Microstructural investigation of some of the aggregates indicates they possess a porous nature which corresponds to their lower density and higher water absorption. To improve the performance of construction composites made with these aggregates, it is recommended that additives such as supplementary cementitious materials be incorporated alongside these greener aggregates to enhance the microstructure of the composites' matrix.

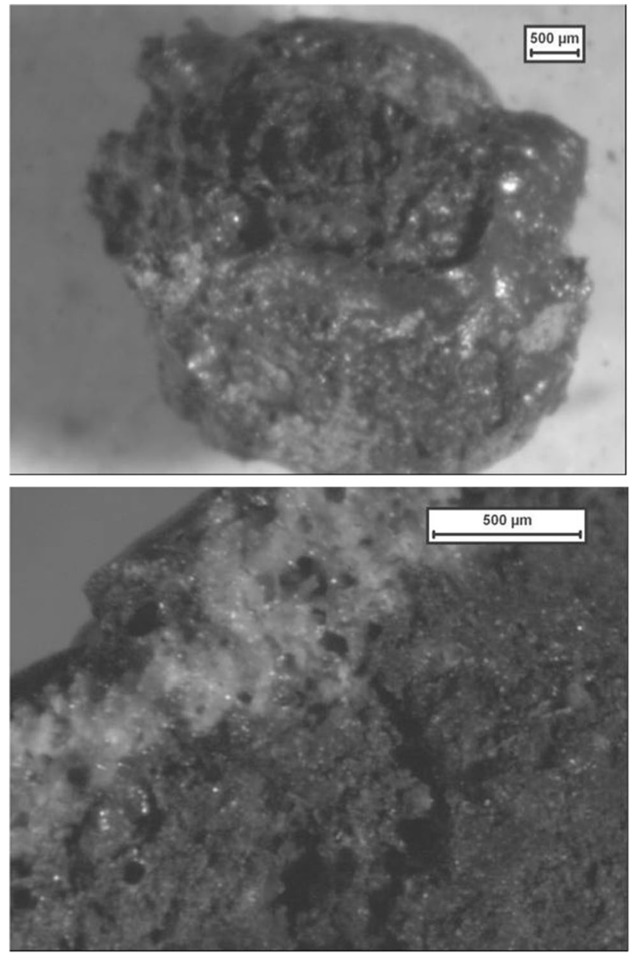

Fig. 8 SEM image of BFD40

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Authors contributions SMM- Conceptualization, Methodology, Visualization, Validation, Formal analysis, Supervision, Writing—original draft. SKD- Conceptualization, Visualization, Methodology, Formal analysis, Data curation, Validation, Investigation, Writing—review & editing. TSahu- Validation, Writing—review & editing, AA- Validation, Visualization, Writing—original draft, Writing—review & editing.

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Data availability The datasets during and/or analyzed during the current study available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

References

1. Hossain MU, Ng ST, Antwi-Afari P, Amor B (2020) Circular economy and the construction industry: existing trends, challenges and prospective framework for sustainable construction. Renew Sustain Energy Rev. https://doi.org/10.1016/j.rser.2020.109948
2. Huang BT, Yu J, Wu JQ, Dai JG, Leung CK (2020) Seawater sea-sand engineered cementitious composites (SS-ECC) for marine and coastal applications. Compos Commun. https://doi.org/10.1016/j.coco.2020.04.019
3. Meyer C (2009) The greening of the concrete industry. Cem Concr Compos 31:601–605. https://doi.org/10.1016/j.cemconcomp.2008.12.010
4. Das SK, Mustakim SM, Adesina A, Mishra S, Mishra J (2021) Solid wastes: alternative materials for cementitious composites production. In: Hussain CM, Velasco-Muñoz SRM (eds) Sustainable Resource Management. Elsevier, pp 199–220
5. Omoding N, Cunningham LS, Lane-Serff GF (2021) Effect of using recycled waste glass coarse aggregates on the hydrodynamic abrasion resistance of concrete. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2020.121177
6. Toghroli A, Mehrabi P, Shariati M, Trung NT, Jahandari S, Rasekh H (2020) Evaluating the use of recycled concrete aggregate and pozzolanic additives in fiber-reinforced pervious concrete with industrial and recycled fibers. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2020.118997
7. Li-Ping G, Miao W, Cong D, Li-Juan C (2020) Effect of incorporating reclaimed asphalt pavement on macroscopic and microstructural properties of high ductility cementitious composites. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2020.119956
8. Adesina A, Das S (2020) Mechanical performance of engineered cementitious composite incorporating glass as aggregates. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.121113
9. Gheni AA, ElGawady MA, Myers JJ (2017) Thermal characterization of cleaner and eco-efficient masonry units using sustainable aggregates. J Clean Prod. https://doi.org/10.1016/j.jclepro.2017.07.189
10. Das SK, Mustakim SM, Adesina A, Mishra J, Alomayri TS, Assaedi HS, Kaze CR (2020) Fresh, strength and microstructure properties of geopolymer concrete incorporating lime and silica fume as replacement of fly ash. J Build Eng. https://doi.org/10.1016/j.jobe.2020.101780
11. Kan L, Shi R, Zhao Y, Duan X, Wu M (2020) Feasibility study on using incineration fly ash from municipal solid waste to develop high ductile alkali-activated composites. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.120168
12. Das SK, Mishra J, Mustakim SM, Adesina A, Kaze CR, Das D (2021) Sustainable utilization of ultrafine rice husk ash in alkali activated concrete: Characterization and performance evaluation. J Sustain Cem Mater 11(2):1–19
13. Krishna RS, Mishra J, Meher S, Das SK, Mustakim SM, Singh SK (2020) Industrial solid waste management through sustainable green technology: Case study insights from steel and mining industry in Keonjhar, India. Mater Today Proc. https://doi.org/10.1016/j.matpr.2020.02.949
14. Wang G, Zhang C, Wang W, Wu S, Li J, Wang X, Wu C (2021) Preparation and physico-chemical performance optimization of sintering-free lightweight aggregates with high proportions of red mud. Materials (Basel). https://doi.org/10.3390/ma14010218
15. Lee KH, Lee KG, Lee YS, Wie YM (2021) Manufacturing and application of artificial lightweight aggregate from water treatment sludge. J Clean Prod. https://doi.org/10.1016/j.jclepro.2021.127260
16. IS383, Coarse and fine aggregate for concrete, Indian Stand. Code. Third edit (2016) 1–17
17. Das SK, Mishra J, Singh SK, Mustakim SM, Patel A, Das SK, Behera U (2020) Characterization and utilization of rice husk ash (RHA) in fly ash – blast furnace slag based geopolymer concrete for sustainable future. Mater Today Proc. https://doi.org/10.1016/j.matpr.2020.02.870
18. Mustakim SM, Das SK, Mishra J, Aftab A, Alomayri TS, Assaedi HS, Kaze CR (2020) Improvement in fresh, mechanical and microstructural properties of fly ash- blast furnace slag based geopolymer concrete by addition of nano and micro silica. SILICON. https://doi.org/10.1007/s12633-020-00593-0
19. Das SK, Singh SK, Mishra J, Mustakim SM (2020) Effect of rice husk ash and silica fume as strength-enhancing materials on properties of modern concrete—a comprehensive review. Lect Notes Civ Eng. https://doi.org/10.1007/978-981-15-1404-3_21
20. Adesina A (2020) Sustainable application of cenospheres in cementitious materials – overview of performance. Dev Built Environ 4:100029. https://doi.org/10.1016/j.dibe.2020.100029
21. Sargam Y, Wang K, Alleman JE (2020) Effects of modern concrete materials on thermal conductivity. J Mater Civ Eng 32:04020058. https://doi.org/10.1061/(asce)mt.1943-5533.0003026
22. Tiwari V, Shukla A, Bose A (2004) Acoustic properties of cenosphere reinforced cement and asphalt concrete. Appl Acoust 65:263–275. https://doi.org/10.1016/j.apacoust.2003.09.002
23. Sair S, Mandili B, Taqi M, El Bouari A (2019) Development of a new eco-friendly composite material based on gypsum reinforced with a mixture of cork fibre and cardboard waste for building thermal insulation. Compos Commun 16:20–24. https://doi.org/10.1016/j.coco.2019.08.010
24. Shaban WM, Yang J, Su H, Liu QF, Tsang DCW, Wang L, Xie J, Li L (2019) Properties of recycled concrete aggregates strengthened by different types of pozzolan slurry. Constr Build Mater. 216:632–647. https://doi.org/10.1016/j.conbuildmat.2019.04.231
25. Dimitriou G, Savva P, Petrou MF (2018) Enhancing mechanical and durability properties of recycled aggregate concrete. Constr Build Mater 158:228–235. https://doi.org/10.1016/j.conbuildmat.2017.09.137