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FEASIBILITY OF TREATED SAND BRICK WASTE WITH SILICA FUME BASED GEOPOLYMER FOR COARSE AGGREGATE APPLICATION

Construction and demolition waste (CDW) management should focus on reducing CDW or properly recycling the materials since this waste is now a global problem. Sand brick waste, a component of a building's structure, is one type of CDW. To be used as recycled aggregate, these wastes are invariably categorised as low grade. Due of the improved qualities provided, geopolymer research has recently become more popular. The objective of this study is to investigate the physical and mechanical properties of recycled sand brick aggregate (RSB) treated with silica fume based geopolymer coating. Additionally, the effectiveness of the treated RSB will be applied in concrete as coarse aggregate. The sample was made using a solid-to-liquid ratio of 1.0, 1.2, 1.4, 1.6, and 1.8. At 2.5 and 10 M, alkaline activator is a constant variable. Testing of specific gravity, water absorption, and aggregate impact value were analysed. The treated RSB concrete will then be evaluated against normal concrete. In terms of density, water absorption, and compressive strength, natural concrete performs better than treated RSB concrete. In comparison to natural concrete, treated RSB concrete absorbs 5.8% more water. Treated RSB concrete has a density of 1815 kg/m^3, compared to natural concrete's 2080 kg/m^3. The compressive strength of concrete made using treated RSB aggregate is 18.1 MPa after 7 days, and 27.1 MPa at 28 days. The testing revealed that the treated RSB aggregate concrete met the specifications. As a result, treated RSB aggregate concrete offers an advantage over natural OPC concrete while saving the environment.

Keyword: geopolymer; construction and demolition waste; coarse aggregate; coating; concrete

1. Introduction

In recent years, the construction industry has faced a number of obstacles, including a dearth of natural resources and excessive energy consumption that contributes directly to environmental damage. This includes the consumption of energy and natural resources, the release of CO_2, and the increase of building and demolition trash [1-2]. Recycling demolition trash is the best method for mitigating the negative environmental effects of the construction industry. Through 2012, it is anticipated that the world will have to deal with the difficulties of disposing of 3 billion tonnes of crushed concrete waste annually [3]. In recent years, Zhang et al. [4] estimated that the global carbonation of concrete debris might yield around 3.0 billion tonnes of CO_2 from 2018 to 2035. Geopolymer has emerged as an alternate building material as a result of the most recent sustainable design development [5]. In recent years, construction and demolition waste (CDW) has accumulated as a result of population increase, continued industrial development, and infrastructural development, posing possible environmental degradation issues. Consequently, resource scarcity and environmental harm caused by unsustainable use of natural resources have become important worldwide issues [2]. In addition, some researchers have researched the effect of recycled concrete aggregates on the qualities of geopolymer concrete [6-12]. They discovered that the use of recycled aggregates improves the fresh properties of geopolymer concrete while increasing its water absorption. According to inferences drawn from a comparison of literature

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data, the role of parameters established by experimental studies using one set of parameters has been repeatedly questioned in other study employing various parameter combinations. Consequently, it is still challenging to fully appreciate how various parameters impact the qualities of geopolymer aggregate concrete [13].

Due to a shortage of natural aggregate, structural concrete is made from building and demolition waste. Recycled aggregate (RA) has a tendency to lose some of its properties due to the mortar that adheres to its exterior. Various techniques can be used to eliminate the mortar that adheres to recycled aggregate. In previous research, the treatment of materials with chemicals, mechanical grinding or ball milling, heat, calcium metasilicate slurry, carbonation and wrapping techniques, cement treatment, mineral admixtures, modified concrete mixers, and hydrated lime, warm mix asphalt, silica gel techniques, waste oil, asphalt emulsion, nanomaterials, and superplasticizers were discussed [14]. Coating treatment of recycled coarse aggregate (RCA) is the application of a thin protective layer to the RCA's surface in order to enhance its performance in concrete. The application of a coating to RCA can enhance its qualities, including as abrasion resistance, water absorption, and surface roughness [15-16]. It also increases the strength and durability of RCA, making it suitable for use in construction projects. Coating treatment of RCA can improve its performance in concrete. Thus, the coating process is also applicable to other types of RCA, including waste concrete, waste brick, and waste ceramics.

On the other hand, geopolymer has attracted a large number of researchers who are studying its benefits in a variety of applications, including construction materials, ceramics, supplemental materials, and coatings. The geopolymer produced from silica fume is suitable for applications requiring a greater compressive strength. Consequently, it may be able to create ultra-high-performance or high-strength concrete with minimal environmental impact utilising a geopolymer derived from silica fumes. The usage of silica fume decreases the disposal problem, hence enhancing sustainability [17].

The purpose of this investigation is to identify the physical and mechanical features of treated recycled sand brick (RSB) with coated silica fume based geopolymer. Good grade treated RSB can replace natural coarse aggregate and decrease the issues on CDW. A number of tests, including the specific gravity test, the water absorption test, and the aggregate impact value test, are conducted to determine the mechanical and physical properties of coarse aggregate. In addition, the performance of treated RSB with silica fume-based geopolymer as coarse aggregate in concrete will be investigated. It is crucial to study the performance of geopolymer to alter the water absorption of RSB in concrete. In this study, the qualities of concrete were determined by tests of slump, water absorption, density, and compressive strength on concrete.

2. Methodology

2.1. Materials

A recycled sand brick (RSB) is collected from the CDW at surrounding Perlis. The used sand bricks are then cleaned and crushed until they can pass through a sieve of 10 to 14 mm size. Additionally, the RSB need to be dried in the oven within a day before being proceed to another step.

Silica fume has been found to be the most efficient pozzolanic component to increase the strength of concrete. Some of the significant properties including were determined including chemical composition using X-Ray fluorescence (XRF), functional group using fourier transform infrared spectroscopy (FTIR), and phases using X-Ray Diffractometer (XRD). From the chemical composition analysis, it was found that the silica fume is highly potential to be used as precursor of geopolymer as it is mainly composed in term of weight over weight by 95.60% of silicon dioxide (SiO_2) which is significant as backbone of geopolymer. This silica fume is also composed of other chemical constituents in which can be summarized as in TABLE 1.

TABLE 1

Chemical composition of silica fume

Chemical Compound	Quantity (%)
Silicon dioxide (SiO_2)	95.60
Aluminum oxide (Al_2O_3)	1.12
Calcium oxide (CaO)	0.56
Iron oxide (Fe_2O_3)	0.77
Sulphur oxide (SO_3)	0.38
Magnesium oxide (MgO)	0.23
Titanium dioxide (TiO_2)	0.49
Potassium oxide (K_2O)	0.85

Meanwhile, as depicted by Fig. 1, the IR spectrum obtained also showed the availability of silanol group bonding (Si-O) in which were found at the wavenumber below 1100 cm^{-1} along with other chemical bonding including H-O-H stretching vibration at wavenumber 3361 cm^{-1} and H-O-H bending vibration

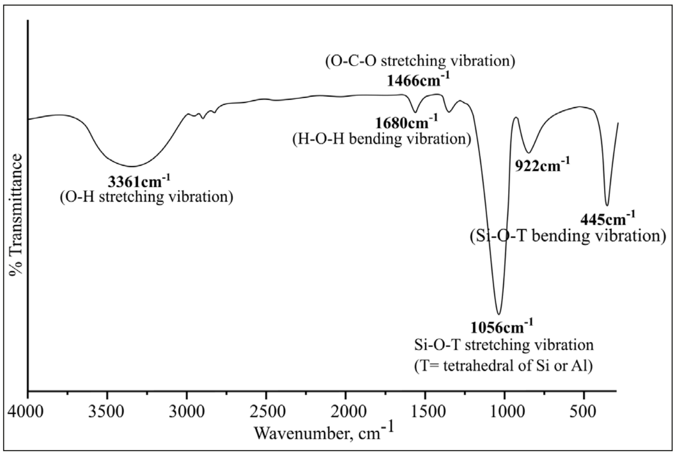

Fig. 1. IR Spectrum of silica fume

TABLE 2

Mix design of treated RSB with silica fume based geopolymer

Recycled Sand brick (RSB) (g)	Total Mixing (g)	Silica fume (g)	Solid to liquid ratio	Ratio of sodium silicate to sodium hydroxide	The concentration of NaOH	Sodium silicate (g)	Sodium hydroxide (g)
2500	500	250	1.0	2.5	10 M	178.57	71.43
2500	500	272.73	1.2	2.5	10 M	162.34	64.93
2500	500	291.67	1.4	2.5	10 M	148.81	59.52
2500	500	307.69	1.6	2.5	10 M	137.36	54.95
2500	500	321.43	1.8	2.5	10 M	127.55	51.02

1680 cm^{-1}. In term of phase analysis, as being illustrated in Fig. 2, the broad hump observed between 2theta 15-35° is attributed to the amorphous and glassy characteristics of the silica fume. In addition, quartz (PDF no: 01-073-0603) was found to be the dominant phases of the silica fume as being observed at several 2 theta including15.2° and 25-26° which is relevant to the major composition of Si in the silica fume.

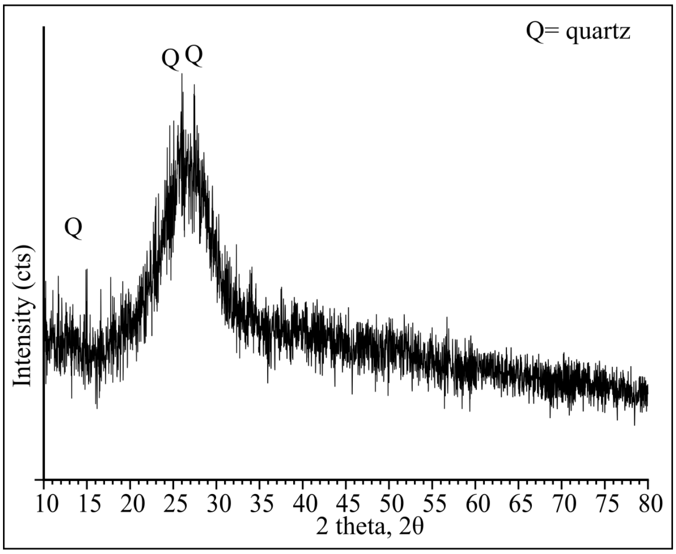

Fig. 2. XRD pattern of silica fume

In this study, a control variable of solid-to-liquid (S/L) ratio with values of 1.0, 1.2, 1.4, 1.6, and 1.8 is investigated. An alkaline activator is the mixture of sodium silicate (Na_2SiO_3) and flakes of 98% pure sodium hydroxide (NaOH). In this experiment, there is a fixed concentration of sodium hydroxide of 10 molars. Constant is set at 2.5 for Na_2SiO_3-to-NaOH. The materials proportion of mix design is shown in TABLE 2. Sodium hydroxide and sodium silicate are then combined to form an alkaline activator. After that, silica fume will be added to the alkaline activator mixture to create a geopolymer paste. The RSB will then be treated using the coating procedure with deeping the RSB in the geopolymer paste and left to air dry for a day.

The treated RSB then needs to be combined with cement, water, and fine aggregate to produce recycled concrete. In order to create concrete that has a 25 MPa strength, the usual water to cement ratio should be between 0.4 and 0.5. ASTM Type I Ordinary Portland Cement (OPC) is the type of cement employed in this study for concrete production. River sand is utilised as fine aggregate with 4.75 mm passing sieve.

The quality of concrete is further checked with a slump test. 100×100×100 mm are the measurements of the cube mould.The cube samples will be kept at room temperature for a day, then demolded, and the curing process will continue in a water tank until the testing days. The design of the concrete mix is shown in TABLE 3.

TABLE 3

Concrete mix design

Cement	Recycled sand brick (bucket)	Fine aggregate (bucket)	Water (bucket)
2	1	1	1

2.2. Testing

According to ASTM C127, the specific gravity and water absorption of sand brick waste that has been treated and left untreated were calculated. Test of aggregate impact value (AIV) is in accordance with BS 812:112 [18]. The wet and dry masses of a concrete cube will be weighed for the concrete water absorption test. It will be compared how much water natural and treated RSB can absorb.

The density test result is based on the ratio of concrete mass to concrete volume. The compressive strength of samples of recycled concrete and natural concrete was determined in accordance with BS EN 12390-3:2009.

3. Results and discussion

3.1. Physical and mechanical properties of RCA

Fig. 3 displays the specific gravity for various types of treated RSB coated with silica fume-based geopolymers. With the exception of the S/L ratio of 1.6, the specific gravity value for S/L ranged from 1.0 to 1.8 exhibited a rising trend. When S/L ratio exceeds 1.4, specific gravity exceeds 2.5. Untreated RCA has the lowest specific gravity value with a S/L ratio of 2.34 and the greatest specific gravity value is 1.4 with a specific gravity of 2.6. The treated RSB has a specific gravity that ranges from 2.3 to 2.6.

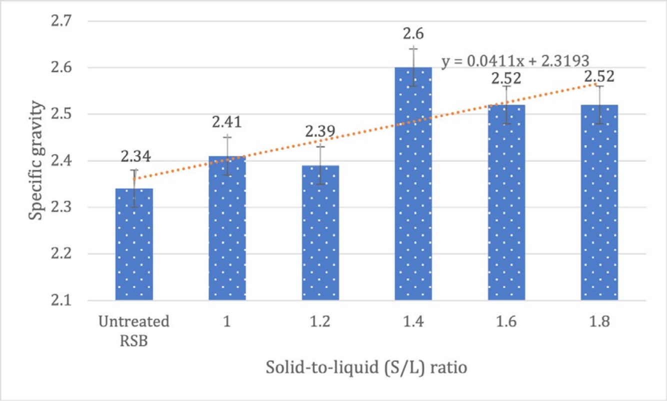

Fig. 3. Specific gravity of treated RSB coated with silica fume based geopolymer at various S/L ratio

Fig. 4 illustrates the difference of water absorption values between untreated RSB and treated RSB with coated silica fume based geopolymer. At 19.0% the untreated RSB had the highest water absorption. Overall, the RSB treated with a silica fume based geopolymer exhibited less water absorption than untreated RSB. The coating layer surrounding the RSB prevents absorption into the aggregate, hence minimising water absorption. The higher the S/L ratio, the less water treated RSB can absorb. This is due to the high viscosity of the mixed coating of silica fume-based geopolymer, which increases the aggregate's strength and decreases its water absorption. The treated RSB absorbs the least amount of water at 1.6 and 1.8 S/L ratios (8.0%).

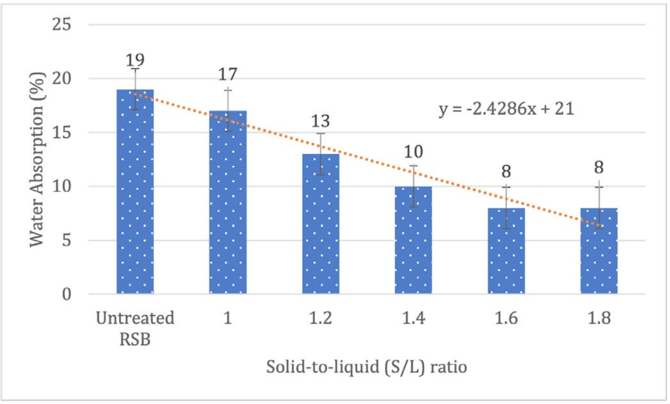

Fig. 4. Water absorption of treated RSB coated with silica fume based geopolymer at various S/L ratio

As demonstrated in Fig. 5, the aggregate impact value (AIV) of treated RSB is less than that of untreated RSB. All treated RSB at varied S/L ratios exhibited AIV values less than 30%.

The greater the AIV value, the weaker the aggregate strength. If the value of the AIV is less than 30%, the aggregate is called strong [19]. The untreated RSB has an AIV of 36.7%, which is considered to be of poor quality. This is due to the physical RSB aggregate's voids and cracks, which reduce the aggregate's strength. Meanwhile, the optimal treated RSB is determined to have a S/L ratio of 1.6. This is due to the fact that the water absorption of this ratio is lower than that of other RCA, as well as the AIV result, which exhibited the strongest aggregate at 19.24% of AIV. This can be explained by the high proportion of Si and Na ions that form geopolymer bonds and strengthen the geopolymer structure. At a high S/L ratio (1.8), the Si and Al ions are excessively elevated, resulting in an insufficiency of alkaline activator. At the optimal S/L ratio, the maximum formation rate of aluminosilicate gels with the available Na+ will generate NASH gels, hence enhancing aggregate strength.

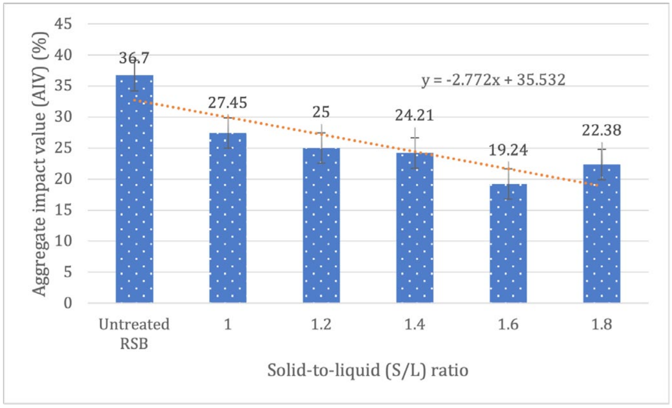

Fig. 5. Aggregate impact value (AIV) of treated RSB coated with silica fume based geopolymer at various S/L ratio

In contrast, the use of silica fume-based geopolymer as a coating for the RSB has demonstrated an exceptional aggregate strength. This indicates that silica fume increased the development of strength in RSB-coated silica fume-based geopolymer binder. The highly active silica (Si+) combines with $Ca(OH)_2$ in the RSB, which not only produces $Ca(OH)_2$ in the system but also generates CASH gel, which results in a compact structure surrounding the treated RSB [20-21]. The denser layer structure that forms around treated RSB will result in an increase in its strength. As shown in Figure 6, the fine particle of silica fume is diffused in the structure, particularly at the interfacial transition zone (ITZ) between RSB and coated silica fume based geopolymer. The geopolymer based on silica fume will fill the interior

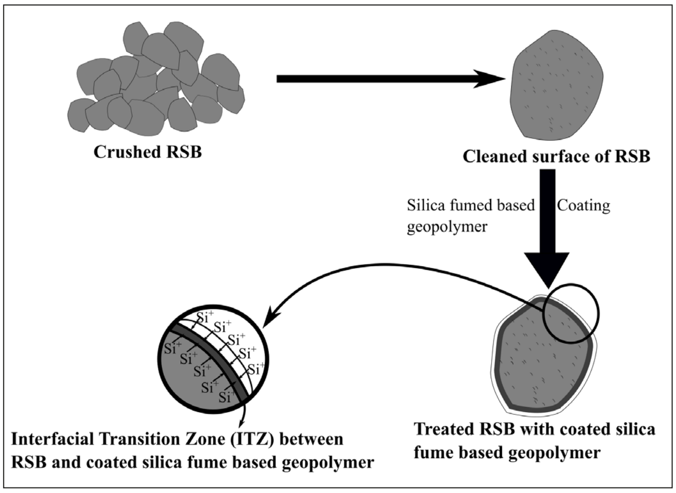

Fig. 6. Schematic diagram of bonding mechanism between RSB and coated silica fume based geopolymer

spaces, strengthening the ITZ and establishing a strong bridge between two surfaces [22-23].

Figs. 7 and 8 demonstrate that the mixture of silica fume-based geopolymer with a low S/L ratio of 1.0 S/L and a high S/L ratio of 1.8, which has too high viscosity at the 1.8 S/L ratio, would not necessarily provide the best aggregate strength. Too many solid particles will cause free Si, Al, and Ca ions to react with Na ions, reducing the aggregate's strength.

Fig. 7. The coating mixture of silica fume based geopolymer at 1.0 S/L ratio

Fig. 8. The coating mixture of silica fume based geopolymer at 1.8 S/L ratio

3.2. Physical and Mechanical Properties of RCA concrete

Natural concrete has a height of slump value of 45 mm, while recycled concrete has a value of 40 mm. These concretes have a low workability range between 25 and 50 mm, according to ASTM C 143. This rating indicates the consistency and workability of fresh concrete.

The density of treated RSB concrete is 1815 kg/m^3, compared to 2080 kg/m^3 for natural concrete, as shown in Fig. 9. According to ACI 213R-87 [24], the treated RSB concrete can be categorised as structural lightweight concrete (less than 1920 kg/m^3).

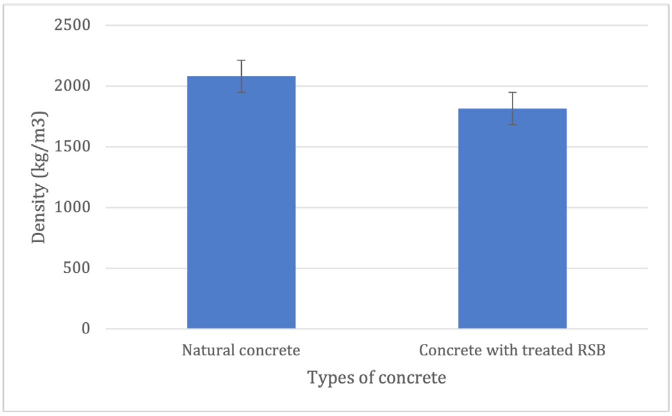

Fig. 9. Density of treated RSB concrete

Fig. 10 depicts an examination of the water absorption of both untreated and treated RSB concrete at 28 days. The concrete made with natural aggregate had a low water absorption rate of 4%, whereas the concrete made with treated RSB with coated silica fume-based geopolymer had a water absorption rate of 5.8%. It may be determined that the water absorption of treated RSB in concrete is comparable to that of natural aggregate. This indicates that the treated RSB has a great potential for usage as coarse aggregate in concrete.

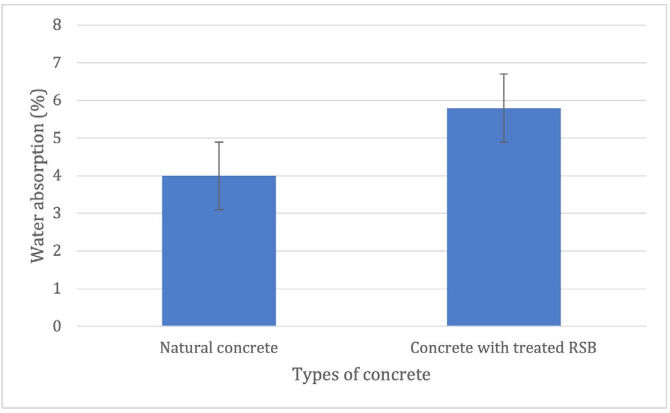

Fig. 10. Water absorption of treated RSB concrete

At 28 days of testing, the treated RSB concrete had a compressive strength of 26.1 MPa, whereas natural aggregate concrete had a compressive strength of 33 MPa. Fig. 11 depicts the concrete's compressive strength. Even though the strength of treated RSB concrete is lower than that of natural aggregate concrete, it nevertheless meets the minimum requirement of 17.2 MPa at 28 days based on ACI 213R-97 [24] and can be utilised for lightweight structural applications.

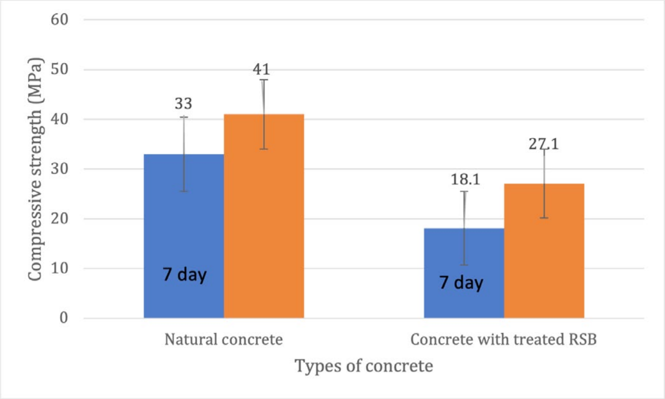

Fig. 11. Compressive strength of treated RSB concrete at 7 and 28 days

4. Conclusions

It was discovered that the optimal blend of treated RSB and coated silica fume-based geopolymer has a solid-to-liquid (S/L) ratio of 1.6, resulting in a specific gravity of 2.52, a water absorption of 8%, and the lowest aggregate impact value (AIV) of 19.24%. The denser layer structure that forms around treated RSB as a result of coating treatment will boost the particle aggregate strength.

After 28 days of curing, further measurement of the aggregate parameters of the concrete revealed that its density is 1815 kg/m^3, its compressive strength is 27.1 MPa, and its water absorption is 5.8%. According to ACI 213R-97 (2014), the lightweight aggregate concrete used in this research is designated as lightweight structural concrete.

REFERENCES

[1] S.D. Datta, M.J. Rana, M.N. Assafi, N.J. Mim, S. Ahmed, Investigation on the generation of construction wastes in Bangladesh. Inter. J. Constr. Manage. **23** (13), 2260-2269 (2022). DOI: https://doi.org/10.1080/15623599.2022.2050977

[2] J. Bao, S. Li, P. Zhang, X. Ding, S. Xue, Y. Cui, T. Zhao, Influence of the incorporation of recycled coarse aggregate on water absorption and chloride penetration into concrete. Constr. Build. Mater. **239**, 117845 (2020). DOI: https://doi.org/10.1016/j.conbuildmat.2019.117845

[3] D.H. Vo, C.L. Hwang, K.D. Tran Thi, M.D. Yehualaw, M.C. Liao, Y.F. Chao, HPC produced with CDW as a partial replacement for fine and coarse aggregates using the Densified Mixture Design Algorithm (DMDA) method: Mechanical properties and stability in development. Constr. Build. Mater. **270**, 121441 (2021). DOI: https://doi.org/10.1016/j.conbuildmat.2020.121441

[4] N. Zhang, H. Duan, T.R. Miller, V.W.Y. Tam, G. Liu, J. Zuo, Mitigation of carbon dioxide by accelerated sequestration in concrete debris. Renew. Sustain. Energy Rev. **117**, 109495 (2020). DOI: https://doi.org/10.1016/j.rser.2019.109495

[5] F.A. Shilar, S.V. Ganachari, V.B. Patil, T.M.Y Khan, S. Javed, R.U. Baig, Optimization of Alkaline Activator on the Strength Properties of Geopolymer Concrete. Poly. **14** (12), (2022). DOI: https://doi.org/10.3390/polym14122434

[6] W.W.A. Zailani, M.M.A.B. Abdullah, M.F. Arshad, R.A. Razak, M.F.M. Tahir, R.R.M.A. Zainol, M. Nabialek, A.V. Sandu, J.J. Wysłocki, K. Błoch, Characterisation at the Bonding Zone between Fly Ash Based Geopolymer Repair Materials (GRM) and Ordinary Portland Cement Concrete (OPCC). Mater. **14** (1), 56 (2021). DOI: https://doi.org/10.3390/ma14010056

[7] M. Ibrahim, W.M.W. Ibrahim, M.M.A.B. Abdullah, M. Nabialek, R. Putra Jaya, M. Setkit, R. Ahmad, B. Jeż, Synthesis of Metakaolin Based Alkali Activated Materials as an Adsorbent at Different Na2SiO3/NaOH Ratios and Exposing Temperatures for Cu2+ Removal. Mater. **16** (3), 1221 (2023). DOI: https://doi.org/10.3390/ma16031221

[8] S.R. Abdila, M.M.A.B. Abdullah, R. Ahmad, S.Z. Abd Rahim, M. Rychta, I. Wnuk, M. Nabiałek, K. Muskalski, M.F. Mohd Tahir, Syafwandi, M. Isardi, M. Gucwa, Evaluation on the Mechanical Properties of Ground Granulated Blast Slag (GGBS) and Fly Ash Stabilized Soil via Geopolymer Process. Mater. **14** (11), 2833 (2021). DOI: https://doi.org/10.3390/ma14112833

[9] B.W. Chong, R. Othman, R. Putra Jaya, M.R.M. Hasan, A.V. Sandu, M. Nabiałek, B. Jeż, P. Pietrusiewicz, D. Kwiatkowski, P. Postawa, M.M.A.B. Abdullah, Design of Experiment on Concrete Mechanical Properties Prediction: A Critical Review. Mater. **14** (8), 1866 (2021). DOI: https://doi.org/10.3390/ma14081866

[10] M.H. Yazid, M.A. Faris, M.M.A.B. Abdullah, M. Nabiałek, S.Z.A. Rahim, M.A.A.M. Salleh, M. Kheimi, A.V. Sandu, A. Rylski, B. Jeż, Contribution of Interfacial Bonding towards Geopolymers Properties in Geopolymers Reinforced Fibers: A Review. Mater. **15** (4), 1496 (2022). DOI: https://doi.org/10.3390/ma15041496

[11] A. Anamika, P.V. Ramana, GGBS:Fly-Ash evaluation and mechanical properties within high strength concrete. Mater. Today: Proceed. **50** (5), 2404-2410 (2022). DOI: https://doi.org/10.1016/j.matpr.2021.10.257

[12] K. Zulkifly, H. Cheng-Yong, L. Yun-Ming, R. Bayuaji, M.M.A.B. Abdullah, S. Bin Ahmad, T. Stachowiak, J. Szmidla, J. Gondro, B. Jeż, and et al., Elevated-Temperature Performance, Combustibility and Fire Propagation Index of Fly Ash-Metakaolin Blend Geopolymers with Addition of Monoaluminium Phosphate (MAP) and Aluminum Dihydrogen Triphosphate (ATP), Mater. **14** (8), 1973 (2021). DOI: https://doi.org/10.3390/ma14081973

[13] H. Upadhyay, M. Mungule, K.K.R. Iyer, Issues and challenges for development of geopolymer concrete. Mater. Today: Proceed. **65** (2), 1575-1581 (2022). DOI: https://doi.org/10.1016/j.matpr.2022.04.520

[14] J.V.M. Raman, V. Ramasamy, Various treatment techniques involved to enhance the recycled coarse aggregate in concrete: A review. Mater. Today: Proceed. **45** (7), 6356-6363 (2021). DOI: https://doi.org/10.1016/j.matpr.2020.10.935

[15] O.F. Ebenezer, T.K. John, J.B. Adewumi, L. Jian, A comprehensive review on the use of recycled concrete aggregate for pavement construction: Properties, performance, and sustainability. Clean. Mater. **9**, 100199 (2023). DOI: https://doi.org/10.1016/j.clema.2023.100199

[16] A.L. Almutairi, B.A. Tayeh, A. Adesina, H.F. Isleem, A.M. Zeyad, Potential applications of geopolymer concrete in construction: A review. Case Stud. Const. Mater. **15**, e00733 (2021). DOI: https://doi.org/10.1016/j.cscm.2021.e00733

[17] C.H.L. Dickson, A.R. Rafiza, Y. Zarina, A. Mohd Mustafa Al Bakri, C. Jitrin, T.P. Vu, M. Rosnita, A. Ikmal Hakem, Investigation of influence factors and surface treatment on palm oil boiler ash (POBA) based geopolymer artificial aggregate: Impregnation vs. coating method. J. Build. Eng. **66**, 105936 (2023). DOI: https://doi.org/10.1016/j.jobe.2023.105936

[18] British Standards Institution, BS 812-112 Methods for determination of aggregate impact value (AIV). 1, 14 (1990).

[19] N. Hui Teng, H. Cheng Yong, M.M.A.B. Abdullah, N. Yong Sing, R. Bayuaji, Study of Fly Ash Geopolymer and Fly Ash/Slag Geopolymer in Term of Physical and Mechanical Properties. Europ. J. Mater. Sci. Eng. **5** (4) 187-198 (2020). DOI: https://doi.org/10.36868/ejmse.2020.05.04.187

[20] H.S. Gokce, D. Hatungimana, K. Ramyar, Effect of fly ash and silica fume on hardened properties of foam concrete. Const. Build. Mater. **194**, 1-11 (2019). DOI: https://doi.org/10.1016/j.conbuildmat.2018.11.036

[21] P. Duan, C. Yan, W. Zhou, Compressive strength and microstructure of fly ash based geopolymer blended with silica fume under thermal cycle. Cem. Concr. Compos. **78**, 108-119 (2017). DOI: https://doi.org/10.1016/j.cemconcomp.2017.01.009

[22] A.C.A. Muller, K.L. Scrivener, J. Skibsted, A.M. Gajewicz, P.J. McDonald, Influence of silica fume on the microstructure of cement pastes: new insights from 1H NMR relaxometry. Cem. Concr. Res. **74**, 116-125 (2015). DOI: https://doi.org/10.1016/j.cemconres.2015.04.005

[23] C. Peiliang, M. Linna, Using silica fume for improvement of fly ash/slag based geopolymer activated with calcium carbide residue and gypsum. Constr. Build. Mater. **275**, 122171 (2021). DOI: https://doi.org/10.1016/j.conbuildmat.2020.122171

[24] American Concrete Institute, ACI 213R-87 Guide for Structural Lightweight Aggregate Concrete. 1-27 (2014).