Experimental Investigation of Lightweight Wall Panel Using Cenosphere Incorporated with Ground Granulated Blast Furnace Slag

V. Raguraman *, S. Deepasree *

* Department of Civil Engineering, Sri Shakthi Institute of Engineering and Technology, Coimbatore-641062, Tamil Nadu, India.

* Corresponding Author: vraguramancivil@siet.ac.in

Received: 31-03-2021, Revised: 20-05-2021, Accepted: 25-05-2021, Published: 29-05-2021

Abstract: The secondary form of waste is the major outcome of the various industries. Likewise, Cenosphere and Ground Granulated Blast Furnace Slag (GGBS) are the waste material obtained from thermal power plants and the steel industry. This waste requires a large land area for disposal. In such cases, these can be used in the construction field. This paper investigated the lightweight wall panel made with cenosphere and GGBS as a replacement for cementitious material. Cenosphere was replaced at 5%, 10%, 15%, 20%, 25% and 30% respectively by weight of cement and GGBS was at 15% constant replacement of cement. The properties of wall panels such as compressive strength, flexural strength, and water absorption have been studied. The flexural behavior was carried out by inhibition of fiber into the matrix. The samples were tested at 7, 14, and 28 days respectively. The SEM analysis of the cenosphere has been carried out. The results infer an increase in the percentage of cenosphere does not impart strength to the mix. Therefore, 15% of constant replacement of GGBS to the mass of cement stabilize the strength which was lost due to the addition of the cenosphere. On an overall view, it was recommended that the strength loss of mixture due to the addition of the cenosphere can be alleviated by GGBS and nevertheless a secure value of strength can be gained.

Keywords: Cenosphere, Ground Granulated Blast furnace slag, lightweight wall panel, mechanical properties, fiber, water absorption.

1. Introduction

Lightweight structures have made considerable attention in society as well as from researchers. The use of lightweight structures results in lower self-weight, reduced area of cross-
section, and also economic conditions. A decrease in self-weight results in a smaller cross-section of the member. It helps in easy fabrication, transportation, installation in the case of precast structures and also reduces the cost. Generally, lightweight concrete is made by incorporating lightweight aggregates such as shale [1–3], clay [4] and expanded perlite [5–8], pumice. Lightweight fillers affect the strength parameter by associating some issues such as lower mechanical strength, brittle behavior, increased air voids, permeability, and emission of CO2. Lightweight structures offer durability to chemical and frost attacks and have a lesser permeability [9]. Lightweight structures provide high resistance to fire and improve thermal installation [10]. Expanded perlite is utilized as a filler material in creating a lightweight concrete with a compressive and flexural strength values in a range of 2.8-11.98 N/mm² and 0.7-3.5 N/mm² [6]. Expanded glass was also used as a filler material with a compressive strength of 28-30 N/mm² [11]. Fly-ash cenosphere as a lightweight material in the construction field not only reduces the disposal of the waste but also enhances the hardened properties due to its similar range of chemical composition [12,13] used Polyethylene terephthalate (PET) as a lightweight aggregate which results in reduced volumetric weight but hardened properties resemble the normal concrete. Generally, lightweight concrete is categorized under class II which renders the concrete with a lower weight. [14] used recycled plastic aggregate as a filler material results in a reduction of chloride penetration up to 13%. Compressive strength was also reduced and suggested non-structural buildings. The lightweight fillers for lightweight structures depends on the availability, storage and composition of material. Masonry walls are commonly used in construction field with quiet deficiencies when subjected to uncertain loadings [15–17] improved the masonry wall without a steel reinforcement. The reinforced walls having a higher self-weight compared to unreinforced. [18–21] used ferro cement wall panel which results in crack resistance, improved mechanical strength, ductility, and energy absorption. [22,23] used expanded polystyrene beads as a filler in making a sandwich panel which reduced the compressive and flexural strength due to the increased percentage of expanded polystyrene. Cenosphere is a hollow spherical particle obtained from coal-burning power plants. Nearly 700 million tons of ash were produced from thermal power plants in China in 2015, which is double the time greater production than in 2005 [24]. Cenosphere is a residual waste, where the size is relatively greater than fly-ash of size (10–400 µm) [25]. In the present scenario, lightweight panels are extensively used in the structural field. Cenosphere is obtained from fly-ash, where its concentration varies from 0.02 to 4.90 by a percentage of weight. But, mostly it limits between 0.3 to 1.5 by a percentage of weight [26–28]. The cenosphere is a by-product of fly ash that comes under class F fly ash. The cenosphere is spherical in shape and grey in color. [29] stated that nearly 70% of the cenosphere has a size of range 45 to 150 µm. The spherical shape has classified into two types such as single ring-like structure and network-like structure. A higher percentage of the cenosphere comes under a single structure. The pH of the cenosphere is neutral in solution. The thermal conductivity of the cenosphere is lower compared to cement. The fly-ash cenosphere is spherical particles with a smooth textured surface [30]. The size of the cenosphere (i.e) size in microns depends on the
grade of the cenosphere. The sizes such as 1-100 µm [30], 1-300 µm [31], 1-400 µm [32–34], 1-600 µm [35]. [35] stated that a high percentage of the cenosphere has a size range of 20 to 300µm. As the grade decreases, the fineness of the material increases. The density of the cenosphere is around 300-800 kg/m³. [36] used cenosphere as an aggregate in making lightweight concrete. Cenosphere is used as a filler material in the construction field. Using a cenosphere, a lightweight concrete achieved a strength of 60 MPa [8]. [7] reported that finer particles enhance durability properties. The autogenous shrinkage can also be eliminated, by promoting the durability properties of concrete [37–39]. Ground Granulated Blast furnace slag (GGBS) also enhances the properties of cement. [40] GGBS can be used as an alternative to ordinary Portland cement. The properties of GGBS highly enhancing the corrosion resistance [40–43] and durability [44–46]. The particles of GGBS are finely in nature which inhibits the bond [47–51] and controls the permeability in concrete [52–55] studied the performance of RC beam using GGBS. When GGBS was added up to 40% of replacement to cement, there is slight decrease in compressive strength with time. Alternatively, there is a contrast in the strength development when GGBS added below 30%. Also, it controls the steel reinforcement from corrosion [56–59] higher the percentage of GGBS, higher the tensile strength. The outcome of this study reduces the consumption of cementitious material thereby contribution of CO2 emission can be reduced. Lightweight structures are made by using secondary waste which meet the strength parameter similar to that of conventional. This study is the first attempt in making a lightweight wall panel using a secondary form of waste such as cenosphere and Ground Granulated Blast furnace slag.

**Experimental Details**

**Materials used**

The materials used in this study are cement, cenosphere, and GGBS.

**Cement**

The ordinary Portland cement (OPC) is used conforming to the code IS 1226-1987. It is commonly made of limestone, shells, clay, and silica sand. The properties of OPC are tabulated in table 1.

**Cenosphere**

Cenosphere is obtained from fly-ash as a by-product. It is a hollow, inert material comprised largely of silica and alumina. It has been used as a filler material in lightweight construction. The SEM images of the cenosphere have been shown in figure 1. The porous structure in a cementitious material when added with the cenosphere can be viewed. The porosity occurs at 43%, whereas 70% of cenosphere in weight fraction with a water-binder ratio of 0.70 [33].
This is due to the fact that spherical particle of the cenosphere leaves more air voids and also possess a lower iso-static strength. The pozzolanic reaction takes place in the cementitious material where the particles consume themselves thereby increasing the calcium-silicate-hydrate gel. The reaction of the cenosphere in a cementitious material composite is the reason for enhancing the greater strength with reduced unit weight. The interfacial property between the cenosphere and the cementitious matrix can be seen with the crack growth in figure 2(b). The shell of the cenosphere is not cracked, alternatively, it passes through the weaker zone of the particle. This infers that the cenosphere has a better bond with the cementitious material. Cenosphere has predominantly silica and alumina content (i.e) 45 to 80% of total ash is silicious and aluminous material [60]. Therefore, the cenosphere is also knowns as alumino-silicate [31,61–65]. The cenosphere depends on Fe₂O₃. Therefore, the
lesser the Fe₂O₃ higher will be the cenosphere [61]. [66] discuss the phase minerals in the cenosphere. The minerals such as rutile, quartz, calcite, mullite, alumino-silicate. But quartz and mullite are the high percentages of minerals present in the cenosphere [31,62]. The cenosphere has roughly comparable properties of fly-ash since it is a by-product of fly-ash obtained from coal consumption [12]. The presence of silica results in high strength whereas alumina for quick setting property and also lowers the clinker temperature [67]. The chemical composition of the cenosphere has been tabulated in table 1.

Figure. 2 SEM images of cenosphere : (a) [32] (b) [32] (c) [35] (d) [32,69] (e) [32] (f) [33]

Ground Granulated Blast furnace slag

Ground Granulated Blast furnace slag (GGBS) is a secondary form of waste obtained from the steel industry. It is a cementitious material and rich in calcium silicate hydrate. It advances the strength, durability, and appearance of concrete. The properties of GGBS are tabulated in table 1.

Mix proportioning

A total of 7 samples were made including the control mix. A mix consist of cement, cenosphere and GGBS with different proportions of cenosphere such as 5%, 10%, 15%, 20%, 25%, 30% respectively with constant 15% of GGBS. Table 2 shows the mixed proportioning of
A mortar cube of size $70.6 \times 70.6 \times 70.6 \text{ mm}^3$ and a panel of size $459.13 \times 304.79 \times 76.2 \text{ mm}^3$ was cast and cured under room temperature.

**Table 2** Mix proportion of mortar at 15% constant replacement of GGBS to a mass of cement

| Mix | % of cenosphere | Cement (gm) | Cenosphere (gm) | Sand (gm) |
|-----|----------------|-------------|-----------------|-----------|
| M1  | 0              | 1010        | -               | 3255      |
| M2  | 5              | 838.3       | 50.5            | 3255      |
| M3  | 10             | 787.8       | 101             | 3255      |
| M4  | 15             | 737.3       | 151.5           | 3255      |
| M5  | 20             | 686.8       | 202             | 3255      |
| M6  | 25             | 636.3       | 252.5           | 3255      |
| M7  | 30             | 583.8       | 303             | 3255      |

**Results and Discussion**

**Compressive Strength of Mortar by Using Cenosphere**

The cenosphere having a low density with high compressive strength compared to normal concrete. Contradictory, [68] concluded that the addition of the cenosphere may decrease the strength so that it can be stabilized by the addition of silica fume. The property of nano-silica is to improve the interfacial transition zone in concrete, thereby obtaining an early-age strength and attains a high compressive strength [69-72] stated that a slight decrease in the strength of the mortar even at low density and low thermal conductivity of the cenosphere. 65] stated that strength loss in mortar can be strengthened by improving the interfacial property by using the cenosphere. The compressive strength of mortar cube specimen of size $70.6 \times 70.6 \times 70.6 \text{ mm}^3$ has been taken and tested at 7 days, 14 days, and 28 days respectively as shown in figure 3.

![Figure 3. Mortar cubes](image)
The cenosphere has been replaced as cementitious material at 5%, 10%, 15%, 20%, 25%, and 30% respectively by the weight of cement. The test results are discussed in table 3 and figure 4. The test outcome at 7 days strength indicates that the strength of mixture M1, M2, M3, M4, M5, M6, and M7 decreases by 5.69%, 8.6%, 14.12%, 19.9%, 21.86%, and 27.5% in contrast with M1. The test outcome at 14 days strength indicates that the strength of mixture M1, M2, M3, M4, M5, M6, and M7 decreases by 6.7%, 11.1%, 13.3%, 19.2%, 21.15%, and 28.9% in contrast with M1. The test outcomes at 28 days strength indicates that the strength of
mix M1, M2, M3, M4, M5, M6 and M7 decreases by 3.5%, 5.3%, 8.8%, 15.85%, 17.5%, and 19.8% in contrast with M1. From the outcomes, it infers that addition of cenosphere decreases the compressive strength of mortar.

**Compressive Strength of Mortar At 15% Constant Replacement of GGBS**

The compressive strength of mortar cubes has been tested as shown in figure 3.3 at 7 days, 14 days, and 28 days respectively. The cenosphere has been replaced as cementitious material at 5%, 10%, 15%, 20%, 25%, and 30% respectively by weight of cement in addition to 15% constant replacement of GGBS. The test outcomes are discussed in table 4 and figure 6. The test results at 7 days strength show that the strength of mixture M1, M2, M3, M4, M5, M6, and M7 increases by 2.85%, 11.42%, 14.28%, 20%, 28.57%, and 31.42% in contrast with M1.

![Figure 5. UTM machine under loading](image)

**Figure 5. UTM machine under loading**

| SI.no | Mix | % of Cenosphere | Area (mm^2) | Compressive strength (N/mm^2) |
|-------|-----|-----------------|-------------|--------------------------------|
|       |     |                 |             | 7 days | 14 days | 28 days |
| 1     | M1  | 0               | 4984.36     | 35     | 45      | 57      |
| 2     | M2  | 5               | 4984.36     | 48     | 46      | 59      |
| 3     | M3  | 10              | 4984.36     | 39     | 48      | 59      |
| 4     | M4  | 15              | 4984.36     | 40     | 51      | 61      |
| 5     | M5  | 20              | 4984.36     | 42     | 53      | 62      |
| 6     | M6  | 25              | 4984.36     | 45     | 54      | 63      |
| 7     | M7  | 30              | 4984.36     | 46     | 56      | 65      |

**Table 4** Compressive strength of mortar at constant 15% replacement of GGBS with Cenosphere.
Figure 6. Compressive strength of mortar (15% of GGBS)

The test results at 14 days strength show that the strength of mixture M1, M2, M3, M4, M5, M6, and M7 increases by 2.22%, 6.66%, 13.33%, 17.77%, 20%, and 26.66% in contrast with M1. The test results at 28 days strength show that the strength of mixture M1, M2, M3, M4, M5, M6, and M7 increases by 1.75%, 3.5%, 7.01%, 8.77%, 10.52%, and 14.03% in contrast with M1. From the test results, it infers that as discussed in table 3, the replacement of cement by cenosphere without adding any other admixture weakens the mortar. To overcome such effects, constant replacement of GGBS at 15% improves and stabilizes the strength of mortar.

Flexural Strength of Mortar

Generally, lightweight structures are brittle. Cenosphere has been incorporated into cementitious material with fiber such as polyethylene fiber [73], steel fiber [74], and polypropylene fiber. In this study, fiberglass mesh has been used. The flexural behavior of mortar was tested at 7 days, 14 days, and 28 days respectively. The cenosphere has been replaced at various percentages such as 5%, 10%, 15%, 20%, 25%, and 30% respectively by the weight of cement. The test results are discussed in table 5 and figure 7. The test outcomes at 7 days strength indicate that the strength of mixture M1, M2, M3, M4, M5, M6, and M7 increases by 17.24%, 20.68%, 31.03%, 34.48%, 34.48%, and 34.48% in contrast with M1. The test outcomes at 14 days strength indicate that the strength of mixture M1, M2, M3, M4,
M5, M6, and M7 increases by 9.75%, 17.07%, 26.82%, 34.14%, 36.58%, and 36.58% in contrast with M1.

![Flexural strength of mortar](image)

**Figure 7.** Flexural strength of mortar

| SL.no | Mix | % of Cenosphere | Flexural strength (N/mm²) |
|-------|-----|----------------|--------------------------|
|       |     |                | 7 days | 14 days | 28 days |
| 1     | M1  | 0              | 2.9    | 4.1     | 5.5     |
| 2     | M2  | 5              | 3.4    | 4.5     | 5.7     |
| 3     | M3  | 10             | 3.5    | 4.8     | 6.2     |
| 4     | M4  | 15             | 3.8    | 5.2     | 6.9     |
| 5     | M5  | 20             | 3.9    | 5.5     | 7.0     |
| 6     | M6  | 25             | 3.9    | 5.6     | 7.1     |
| 7     | M7  | 30             | 3.9    | 5.6     | 7.2     |

The test outcomes at 28 days strength indicate that the strength of mixture M1, M2, M3, M4, M5, M6, and M7 increases by 3.63%, 12.72%, 25.45%, 27.27%, 29.09%, and 30.9% in contrast with M1. From the test outcomes, it infers that mortar is good in compression however vulnerable to tension. Therefore, inhibition of fiber into the matrix improves flexural strength.

**Water Absorption of panel**

Water absorption of the panel has been tested and the values are discussed in table 6. The water absorption was found to be 1.65% which is categorized under vitrified.
is the one that is resistant to water and provides high durability.

\[
\text{Water absorption} = \frac{M_2 - M_1}{M_1} \times 100 = \frac{4900 - 4820}{4820} \times 100 = 1.65\%
\]

Table 6. Water absorption of panel

| SI.no | M1  | M2  | Water absorption % |
|-------|-----|-----|---------------------|
| 1     | 4820| 4900| 1.65                |

Wall panel

The wall panel of size 459.13 × 304.79 × 76.2 mm³ has been made. The wall panel has been tested against the mechanical properties. The mold of the sample has shown in figure 8. Figure 9 shows the prototype of the wall panel.
Conclusion

This study has been carried out with the mortar cubes which can be produced with a blend of cenosphere and GGBS as a replacement for cement. The material properties have been analyzed. Cenosphere is a by-product of fly-ash which resembles the properties of fly-ash material. It has a hollow spherical particle. Generally, spherical particles aid strength to the mortar or concrete. In this research, the mechanical properties of the mortar have been tested. From the test results, the following conclusions are made:

1. The cenosphere was replaced with cement. The compressive strength infers that an increase in the percentage of cenosphere decreases the strength compared to the conventional mix.

2. To stabilize the strength loss caused by the cenosphere and also to improve the strength, a constant 12% replacement of GGBS has to be made.

3. The cenosphere and GGBS were replaced to cement up to 30% and 12% respectively. According to a strength basis, the cenosphere improves the strength up to 30% of replacement. Beyond 30% of the cenosphere, decreases the strength.

4. Therefore, it is suggested to replace the cenosphere as a cementitious material up to 30% to the mass of cement.

5. Generally, the concrete is strong in compression however vulnerable in tension. To improve the tensile property, the fiber is placed in the mix to improve the flexural strength.

6. The water absorption test has been taken and the specimen was categorized under vitrified. Therefore, it possesses high durability and water resistance.

7. The test on mortar cubes discovered that strength loss of cement occurs due to the replacement of the cenosphere. However, the loss of strength can be stabilized by adding GGBS.

References

[1] R. De Gennaro, A. Langella, M. D’Amore, M. Dondi, A. Colella, P. Cappelletti, M. De’Gennaro, Use of zeolite-rich rocks and waste materials for the production of structural lightweight concretes, Applied Clay Science, 41(2008) 61–72. https://doi.org/10.1016/j.clay.2007.09.008

[2] A. Lotfy, K.M.A. Hossain, M. Lachemi, Lightweight self-consolidating concrete with expanded shale aggregates: Modelling and optimization, International Journal of Concrete Structures and Materials volume, 9 (2015) 185–206. https://doi.org/10.1007/s40069-015-0096-5

[3] Y. Ke, A.L. Beaucour, S. Ortola, H. Dumontet, R. Cabrillac, Influence of volume fraction and characteristics of lightweight aggregates on the mechanical properties of...
concrete, Construction and Building Materials, 23 (2009) 2821–2828. https://doi.org/10.1016/j.conbuildmat.2009.02.038

[4] S. Chandra, L. Berntsson, (2002) Lightweight aggregate concrete, Elsevier, 450.

[5] Z. Lu, B. Xu, J. Zhang, Y. Zhu, G. Sun, Z Li, Preparation and characterization of expanded perlite/paraffin composite as form-stable phase change material, Solar Energy, 108 (2014) 460–466. https://doi.org/10.1016/j.solener.2014.08.008

[6] M. Lanzón, P.A. García-Ruiz, Lightweight cement mortars: Advantages and inconveniences of expanded perlite and its influence on fresh and hardened state and durability, Construction and Building Materials, 22 (2008) 1798–1806. https://doi.org/10.1016/j.conbuildmat.2007.05.006

[7] K. Sudalaimani, M. Shammugasundaram, Influence of ultrafine natural steatite powder on setting time and strength development of cement, Advances in Smart Materials and Applications, 2014 (2014) 1-7. http://dx.doi.org/10.1155/2014/532746

[8] K.S. Chia, M.H. Zhang, J.Y.R. Liew, (2011) High-strength ultra-lightweight cement composite-material properties, In Proceedings of the Proceedings of 9th international symposium on high performance concrete design, verification & utilization, Rotorua, New Zealand,

[9] Z. Li, (2011) Advanced Concrete Technology, John Wiley Sons.

[10] 213, A.C.I.C. Guide for structural lightweight-aggregate concrete.; American Concrete Institute, 2003.

[11] P. Spiesz, Q.L. Yu, H. J. H. Brouwers, Development of lightweight mortars targeted on the high strength, low density and low permeability, In Proceedings of the International Conference on Advances in Cement and Concrete Technology (ACCTA) Held in South Africa; 2013; p. 285e292.

[12] A. Hanif, Z. Lu, Z. Li, Utilization of fly ash cenosphere as lightweight filler in cement-based composites—a review, Construction and Building Materials, 144 (2017) 373–384. https://doi.org/10.1016/j.conbuildmat.2017.03.188

[13] F. Casanova-del-Angel, J.L. Vázquez-Ruiz, Manufacturing light concrete with PET aggregate, International Scholarly Research Notices, 2012 (2012) 1-11. https://doi.org/10.5402/2012/287323

[14] A.M. Hameed, B.A.F. Ahmed, Employment the plastic waste to produce the light weight concrete, Energy Procedia, 157 (2019) 30–38. https://doi.org/10.1016/j.egypro.2018.11.160

[15] M. Bruneau, State-of-the-art report on seismic performance of unreinforced masonry buildings, Journal of Structural Engineering, 120 (1994) 230–251.

[16] D.P. Abrams, T.J. Paulson, Modeling earthquake response of concrete masonry building structures, Structural Journal, 88 (1991) 475–485.

[17] W.A. Thanoon, Y. Yardim, M.S. Jaafer, J. Noorzaei, Structural behaviour of ferrocement–brick composite floor slab panel, Construction and Building Materials, 24 (2010) 2224–2230. https://doi.org/10.1016/j.conbuildmat.2010.04.034

[18] C.B. Cheah, M. Ramli, Load capacity and crack development characteristics of HCWA–DSF high strength mortar ferrocement panels in flexure, Construction and
[19] K.N. Lakshmikandhan, Experimental and evaluation study on ferrocement infilled RC framed structures, In Proceedings of the Proceese of International Conference on recent advances in concrete and construction technology, 79 (2005) 833843.

[20] S. A Majeed, N. M. Mahmood, Flexural Behavior of Flat and Folded Ferrocement Panels, Al-Rafidain Engineering Journal (AREJ), 17 (2009) 1-11. http://dx.doi.org/10.33899/rengj.2009.43268

[21] J.A. Peter, N. Lakshmanan, P. Sivakumar, N.P. Rajamane, A novel precast roofing scheme for affordable housing, Indian Concrete Journal, 84 (2010) 34.

[22] D.S. Babu, K.G. Babu, T.H. Wee, Properties of lightweight expanded polystyrene aggregate concretes containing fly ash, Cement and Concrete Research, 35 (2005) 1218-1223. https://doi.org/10.1016/j.cemconres.2004.11.015

[23] Y. Xu, L. Jiang, J. Xu, Y. Li, Mechanical properties of expanded polystyrene lightweight aggregate concrete and brick, Construction and Building Materials, 27 (2012) 32–38, https://doi.org/10.1016/j.conbuildmat.2011.08.030

[24] J. Ding, S. Ma, S. Shen, Z. Xie, S. Zheng, Y. Zhang, Research and industrialization progress of recovering alumina from fly ash: A concise review, Waste Management, 60 (2017) 375–387. https://doi.org/10.1016/j.wasman.2016.06.009

[25] S.P. McBride, A. Shukla, A. Bose, Processing and characterization of a lightweight concrete using cenospheres, Journal of Materials Science, 37 (2002) 4217–4225. http://dx.doi.org/10.1023/A:1020056407402

[26] E. V. Fomenko, N.N. Anshits, L.A. Solovyov, O.A. Mikhaylova, A.G. Anshits, Composition and morphology of fly ash cenospheres produced from the combustion of Kuznetsk coal, Energy & fuels, 27 (2013) 5440–5448. https://doi.org/10.1021/ef400754c

[27] E. V. Sokol, N.V. Maksimova, N.I. Volkova, E.N. Nigmatulina, A.E. Frenkel, Hollow silicate microspheres from fly ashes of the Chelyabinsk brown coals (South Urals, Russia), Fuel Processing Technology, 67(2000) 35–52. https://doi.org/10.1016/S0378-3820(00)00084-9

[28] S.V. Vassilev, C.G. Vassileva, Mineralogy of combustion wastes from coal-fired power stations, Fuel Processing Technology, 47 (1996) 261–280. https://doi.org/10.1016/0378-3820(96)01016-8

[29] L. Ng, H. Wu, D. Zhang, Characterization of ash cenospheres in fly ash from Australian power stations, Energy Fuels, 21 (2007) 3437–3445. https://doi.org/10.1021/ef700340k

[30] S. Diamond, Particle morphologies in fly ash, Cement and Concrete Research, 16 (1986) 569–579. https://doi.org/10.1016/0008-8846(86)90095-5

[31] P.K. Kolay, D.N. Singh, Physical, chemical, mineralogical, and thermal properties of cenospheres from an ash lagoon, Cement and Concrete Research, 31 (2001) 539–542. http://dx.doi.org/10.1016/S0008-8846(01)00457-4
[32] A. Hanif, Z. Lu, S. Diao, X. Zeng, Z. Li, Properties investigation of fiber reinforced cement-based composites incorporating cenosphere fillers, Construction and Building Materials, 140 (2017) 139–149. http://dx.doi.org/10.1016/j.conbuildmat.2017.02.093

[33] A. Hanif, S. Diao, Z. Lu, T. Fan, Z. Li, Green lightweight cementitious composite incorporating aerogels and fly ash cenospheres–Mechanical and thermal insulating properties, Construction and Building Materials 116 (2016) 422–430. https://doi.org/10.1016/j.conbuildmat.2016.04.134

[34] A. Hanif, P. Parthasarathy, Z. Li, Utilizing fly ash cenosphere and aerogel for lightweight thermal insulating cement-based composites, International Journal of Civil and Environmental Engineering, 11 (2017) 84-90. https://doi.org/10.5281/zenodo.1339802

[35] X. Huang, R. Ranade, Q. Zhang, W. Ni, V.C. Li, Mechanical and thermal properties of green lightweight engineered cementitious composites, Construction and Building Materials, 48 (2013) 954–960. https://doi.org/10.1016/j.conbuildmat.2013.07.104

[36] F. Blanco, P. García, P. Mateos, J. Ayala, Characteristics and properties of lightweight concrete manufactured with cenospheresm, Cement and Concrete Research, 30 (2000) 1715–1722. https://doi.org/10.1016/S0008-8846(00)00357-4

[37] P. Lura, J. Bisschop, On the origin of eigenstresses in lightweight aggregate concrete, Cement and Concrete Composites, 26 (2004) 445–452. https://doi.org/10.1016/S0958-9465(03)00072-6

[38] D.P. Bentz, W.J. Weiss, (2011) Internal curing: a 2010 state-of-the-art review, NIST Interagency/Internal Report (NISTIR), US Department of Commerce, National Institute of Standards and Technology, Gaithersburg. https://doi.org/10.6028/NIST.IR.7765

[39] R. Henkensiefken, T. Nantung, J. Weiss, (2008) Reducing restrained shrinkage cracking in concrete: examining the behavior of self-curing concrete made using different volumes of saturated lightweight aggregate, In Proceedings of the National concrete bridge conference, St. Louis, MO;

[40] R. Siddique, R. Bennacer, Use of iron and steel industry by-product (GGBS) in cement paste and mortar, Resources, Conservation and Recycling, 69 (2012) 29–34. https://doi.org/10.1016/j.resconrec.2012.09.002

[41] A. Cheng, R. Huang, J.K. Wu, C.-H. Chen, Influence of GGBS on durability and corrosion behavior of reinforced concrete, Materials Chemistry and Physics, 93 (2005) 404–411. https://doi.org/10.1016/j.matchemphys.2005.03.043

[42] İ.B. Topçu, A.R. Boğa, Effect of ground granulate blast-furnace slag on corrosion performance of steel embedded in concrete, Materials & Design, 31 (2010) 3358–3365. https://doi.org/10.1016/j.matdes.2010.01.057

[43] L. Bertolini, Steel corrosion and service life of reinforced concrete structures, Structure and Infrastructure Engineering, 4 (2008) 123–137. https://doi.org/10.1080/15732470601155490
[44] Ş.C. Bostancı, M. Limbachiya, H. Kew, Portland slag and composites cement concretes: engineering and durability properties, Journal of Cleaner Production, 112 (2016) 542–552. https://doi.org/10.1016/j.jclepro.2015.08.070

[45] V. Baroghel-Bouny, M. Dierkens, X. Wang, A. Soive, M. Saillio, M. Thiery, B. Thauvin, Ageing and durability of concrete in lab and in field conditions: investigation of chloride penetration, Journal of Sustainable Cement-Based Materials, 2 (2013) 67–110. https://doi.org/10.1080/21650373.2013.797938

[46] G.J. Osborne, Durability of Portland blast-furnace slag cement concrete, Cement and Concrete Composites, 21 (1999) 11–21. https://doi.org/10.1016/S0958-9465(98)00032-8

[47] Z. Chen, Y. Yang, Y. Yao, Quasi-static and dynamic compressive mechanical properties of engineered cementitious composite incorporating ground granulated blast furnace slag, Materials & Design, 44 (2013) 500–508. https://doi.org/10.1016/j.matdes.2012.08.037

[48] S.J. Barnett, M.N. Soutsos, S.G. Millard, J.H. Bungey, Strength development of mortars containing ground granulated blast-furnace slag: Effect of curing temperature and determination of apparent activation energies, Cement and Concrete Research, 2006, 36, 434–440. doi: 10.1016/j.cemconres.2005.11.002

[49] S.E. Chidiac, D.K. Panesar, Evolution of mechanical properties of concrete containing ground granulated blast furnace slag and effects on the scaling resistance test at 28 days, Cement and Concrete Composites, 30 (2008) 63–71. https://doi.org/10.1016/j.cemconcomp.2007.09.003

[50] P. Dinakar, K.P. Sethy, U.C. Sahoo, Design of self-compacting concrete with ground granulated blast furnace slag, Materials and Design, 43 (2013) 161–169. https://doi.org/10.1016/j.matdes.2012.06.049

[51] C.J. Tsai, R. Huang, W.-T. Lin, H.-N. Wang, Mechanical and cementitious characteristics of ground granulated blast furnace slag and basic oxygen furnace slag blended mortar, Materials and Design, 60 (2014) 267–273. https://doi.org/10.1016/j.matdes.2014.04.002

[52] K.H. Mo, U.J. Alengaram, M.Z. Jumaat, M.Y.J. Liu, J. Lim, Assessing some durability properties of sustainable lightweight oil palm shell concrete incorporating slag and manufactured sand, Journal of Cleaner Production, 112 (2016) 763–770. https://doi.org/10.1016/j.jclepro.2015.06.122

[53] E. Garcia-Taengua, M. Sonebi, P. Crossett, S. Taylor, P. Deegan, L. Ferrara, A. Pattarini, Performance of sustainable SCC mixes with mineral additions for use in precast concrete industry, Journal of Sustainable Cement-Based Materials, 5 (2016) 157–175. https://doi.org/10.1080/21650373.2015.1024297

[54] D. Chithra, M. Nazeer, (2012) Strength and chloride permeability studies on ground granulated blast furnace slag admixed medium strength concrete, In Proceedings of the 2012 international conference on green technologies (ICGT), IEEE, 103–106.

[55] R.A. Hawileh, J.A. Abdalla, F. Fardmanesh, P. Shahsana, A. Khalili, Performance of reinforced concrete beams cast with different percentages of GGBS replacement to
cement, Archives of Civil and Mechanical Engineering, 17 (2017) 511–519. http://dx.doi.org/10.1016/j.acme.2016.11.006

[56] A. Islam, U.J. Alengaram, M.Z. Jumaat, I.I. Bashar, the development of compressive strength of ground granulated blast furnace slag-palm oil fuel ash-fly ash based geopolymer mortar, Materials & Design, 56 (2014) 833–841. https://doi.org/10.1016/j.matdes.2013.11.080

[57] S. Teng, T.Y.D. Lim, B.S. Divsholi, Durability and mechanical properties of high strength concrete incorporating ultra fine ground granulated blast-furnace slag, Construction and Building Materials, 40 (2013) 875–881. https://doi.org/10.1016/j.conbuildmat.2012.11.052

[58] A. Oner, S. Akyuz, An experimental study on optimum usage of GGBS for the compressive strength of concrete, Cement and Concrete Composites, 29 (2007) 505–514. https://doi.org/10.1016/j.cemconcomp.2007.01.001

[59] S. Kumar, R. Kumar, A. Bandopadhyay, T.C. Alex, B.R. Kumar, S.K. Das, S.P. Mehrotra, Mechanical activation of granulated blast furnace slag and its effect on the properties and structure of portland slag cement, Cement and Concrete Composites, 30 (2008) 679–685. https://doi.org/10.1016/j.cemconcomp.2008.05.005

[60] A. Hanif, Z. Lu, Y. Cheng, S. Diao, Z. Li, Effects of different lightweight functional fillers for use in cementitious composites, International Journal of Concrete Structures and Materials, 11 (2017) 99–113. https://doi.org/10.1007/s40069-016-0184-1

[61] S. Ghosal, S.A. Self, Particle size-density relation and cenosphere content of coal fly ash, Fuel, 74 (1995) 522–529. https://doi.org/10.1016/0016-2361(95)98354-H

[62] K.V. Joseph, F. Francis, J. Chacko, P. Das, G. Hebbar, Fly ash cenosphere waste formation in coal fired power plants and its application as a structural material—a review, International Journal of Engineering Research & Technology (IJERT), 2 (2013) 1236–1260.

[63] Noor-ul-Amin, A multi-directional utilization of different ashes. RSC Advances, 4 (2014) 62769–62788. https://doi.org/10.1039/C4RA06568A

[64] G. Majkrzak, J. Watson, M. Bryant, K. Clayton, (2007) Effect of cenospheres on fly ash brick properties, world of coal ash (WOCA), Kentuck, USA.

[65] V. Tiwari, A. Shukla, A. Bose, Acoustic properties of cenosphere reinforced cement and asphalt concrete, Applied Acoustics, 65 (2004) 263–275. https://doi.org/10.1016/j.apacoust.2003.09.002

[66] S. V. Vassilev, R. Menendez, M. Diaz-Somoano, M.R. Martinez-Tarazona, Phase-mineral and chemical composition of coal fly ashes as a basis for their multicomponent utilization. 2. Characterization of ceramic cenosphere and salt concentrates, Fuel, 83 (2004) 585–603. https://doi.org/10.1016/j.fuel.2003.10.003

[67] M.S. Shetty, A.K. jain, (2005) Concrete technology, S. chand Co Ltd, 420–453.

[68] C. Wang, J. Liu, H. Du, A. Guo, Effect of fly ash cenospheres on the microstructure and properties of silica-based composites, Ceramics International, 38 (2012) 4395–4400. https://doi.org/10.1016/j.ceramint.2012.01.044
[69] J.-Y. Wang, K.-S. Chia, J.-Y.R. Liew, M.-H. Zhang, Flexural performance of fiber-reinforced ultra-lightweight cement composites with low fiber content, Cement and Concrete Composites, 43 (2013) 39-47. https://doi.org/10.1016/j.cemconcomp.2013.06.006

[70] K. Senthamarai Kannan, L. Andal, M. Shammugasundaram, An investigation on strength development of cement with cenosphere and silica fume as pozzolanic replacement, Advances in Materials Science and Engineering, 2016 (2016) 1-6. http://dx.doi.org/10.1155/2016/9367619

[71] M. Stefanidou, I. Papayianni, Influence of nano-SiO2 on the Portland cement pastes, Composites Part B: Engineering, 43 (2012) 2706–2710. https://doi.org/10.1016/j.compositesb.2011.12.015

[72] S.W.M. Supit, F.U.A. Shaikh, Durability properties of high-volume fly ash concrete containing nano-silica, Materials and Structures, 48 (2015) 2431–2445. https://doi.org/10.1617/s11527-014-0329-0

[73] L.P. Singh, S.R. Karade, S.K. Bhattacharyya, M.M. Yousuf, S. Ahalawat, Beneficial role of nanosilica in cement based materials-A review, Construction and Building Materials, 47 (2013) 1069–1077. https://doi.org/10.1016/j.conbuildmat.2013.05.052

[74] M.-R. Wang, D.-C. Jia, P.-G. He, Y. Zhou, Microstructural and mechanical characterization of fly ash cenosphere/metakaolin-based geopolymeric composites, Ceramics International, 37 (2011) 1661–1666. https://doi.org/10.1016/j.ceramint.2011.02.010

[75] Y. Wu, J.-Y. Wang, P.J.M. Monteiro, M.-H. Zhang, Development of ultra-lightweight cement composites with low thermal conductivity and high specific strength for energy efficient buildings, Construction and Building Materials, 87 (2015) 100–112. https://doi.org/10.1016/j.conbuildmat.2015.04.004

Acknowledgements: NIL

Conflict of interest: NIL

About The License: © 2021 The Authors. This work is licensed under a Creative Commons Attribution 4.0 International License which permits unrestricted use, provided the original author and source are credited.