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Compressive Strength of Concrete When Exposed to Elevated Temperature – A Review

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Abstract: Concrete is a composite material which is made of cement, aggregates and water. Fire resistance is one of the key considerations in concrete design. The exposure of high temperature such as fire incident will cause severe damage on physical and mechanical properties of concrete. Supplementary cementitious material (SCM) such as Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) are widely used in construction industry as partial replacement in concrete. This study aims to review and compare the strength performance of concrete with different percentage of FA and GGBS replacement range from 0% to 100% replacement with control sample which exposed to high temperature range from 27℃ to 1000℃. Graphical method was conducted to analyze the compressive strength of concrete with different percentage replacement of FA and GGBS after exposure to temperature range from 27℃ to 1000℃. ASTM Standard code was mostly referred by the previous researchers for compressive strength testing. It was found that the incorporation of SCM has significant influence on concrete strength at high temperature at later age. Inclusion of 20% FA was found to have an effect on compressive strength of concrete while incorporation of GGBS was found to reduce the compressive strength of concrete at early age due to slower heat of hydration than Portland cement. Incorporation of low percentage of FA (20% - 40%) and high percentage of GGBS (50% - 100%) showed favorable results in improving concrete residual compressive strength at high temperature range of 200℃ to 400℃ compared to Ordinary Portland Cement (OPC) concrete.

Keywords: Fly Ash, Ground Granulated Blast Furnace Slag, Compressive Strength, High Temperature

1. Introduction

Concrete is a composite material composed of cement, aggregates and water. Utilization of concrete widely in concrete sector making it one of the most vital building materials [1]. Ordinary Portland cement (OPC) has historically been used as a concrete binder. However, cement manufacturing is associated with significant greenhouse gas emissions. Therefore, it is essential for development of alternative binders from industrial by products to reduce the carbon footprint of concrete production [2]. Concrete with pozzolanic elements is widely utilized for environmentally safe, sustainable and eco-

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friendly applications all over the world [3]. Pozzolanas are found to have chemical components that react as the chemical reaction that is released during the cement hydration process to form cement materials. Calcium hydroxide (CH) was removed from the mixture as the chemical components of cement and pozzolanas reaction. Removal of CH from concrete mixture has increased the concrete's resilience to harsh environments. This chemical reaction increases the strength of concrete and affects other properties, including durability and thermal resistance [4].

Even though concrete is considered as a fire-resistance product, the exposure to high temperature such as fire incident will cause severe damage on concrete structure as well as its mechanical properties. As the temperature increased, concrete will lose its strength to withstand load which will cause catastrophic failure on concrete structure when exposed to high temperature. It was found that the components in the concrete mixture inevitably impact the high temperature resistance of concrete [5]. This statement is aligned with Shah & Ahmad [6] which stated that since concrete has various thermal characteristics, moisture content and porosity, its fire resistance capability is complex. When concrete is subjected to high temperatures, the effect on compressive strength and elastic modulus, cracking, spalling and decrease in yield strength, ductility and tensile strength were obtained [5].

The incorporation of supplemental cement replacement (SCM) was discovered to have an effect on concrete when exposed to high temperatures. Many prior studies have been conducted on the influence of temperature on concrete using supplementary cementitious material as a concrete binder. It was discovered that the inclusion of SCM resulted in better performance, such as residual strength and durability at high temperatures than Portland cement concrete depending on the type of binder [7]–[12]. Slag replacement was discovered to achieved a significant and beneficial reduction in the amount of Ch and improved the mechanical properties after exposure to temperatures above 400℃[13]. On the other hand, more research on concrete mixture including various percentages of mineral additives is required in order to get a general conclusion on the influence of mineral additives at high temperature [14].

A lot of research were conducted on the effect of high temperature on concrete, however there is less studies mentioned on optimal replacement of SCM in concrete that can improve the performance of concrete at high temperature. It is crucial to study the effect of percentage replacement of SCM on the strength of concrete for designing a building structure that can withstand the high temperatures. The performance of ordinary concrete and concrete with replacement material at elevated temperature can be evaluated and compared to improve the safety of the concrete structure.

This study aims to review and analyze the optimum percentage of supplementary cement replacement on concrete strength at high temperature. The review focused on the performance of concrete with and without Fly Ash (FA) or Ground Granulated Blast Furnace Slag (GGBS) replacement. The compressive strength of concrete with different percentage replacement of FA and GGBS in concrete at the age of 28 days under room temperature and after exposure to high temperature range from 27℃ to 1000℃ were investigated. Concrete without any cement replacement is representing as control sample for comparison.

2. Fly Ash Replacement on Compressive Strength of Concrete at High Temperature

The compressive strength of concrete with different percentage of FA at room temperature and after high temperature exposure were analyzed.

2.2 Concrete at Room Temperature

Compressive strength of concrete with percentage of FA replacement in range 0% to 90% at room temperature for 28 days were analyzed. About 5 out of 9 studies that used percentage replacement from 0% to 40% of fly ash shows increases in compressive strength of concrete with replacement of 10 to 40% of FA as compared to control sample. In all studies, it can be seen that replacement of FA in concrete more than 40% tend to reduce the compressive strength of concrete [15], [11], [16], [17], [18], [19], [20], [21], [22], [1] and [5]. As compared, the highest compressive strength of concrete is 121.38 MPa with 20% of FA replacement [19].

When cement is partially replaced by FA, an improvement of strength is due to recrystallization of calcium carbonate and the formation of extra calcium silicate hydrate (C-S-H) gel in cement matrix, generated by interactions between calcium hydroxide (CH) and FA which lower both the transitional zone and the matrix [23].

2.3 Concrete at High Temperature

Figure 1 to Figure 3 show the compressive strength of concrete with and without replacement of FA after exposure to high temperature in range of 27℃ to 1000℃. The result for compressive strength incorporated with fly ash was divided into two ranges of percentage replacement which are 10 to 45% (low percentage) and 50 to 90% (high percentage) replacement.

In Figure 1, it can be seen in few previous studies found that the compressive strength of control samples increased gradually after exposure to temperature up to 400℃. Most previous studies discovered a slightly decrease or no significant changes in compressive strength at this temperature. The insignificant changes in compressive strength below 300℃ is due to improvement in unhydrated cement grains hydration caused by internal autoclaving condition [24]. After exposure to temperature above 400℃, the compressive strength of concrete decreased significantly. The highest strength of control sample at 400℃ is 89.49 MPa and at 800℃ is 30.28 MPa [18]. Similar trend can be seen in Figure 2 which is compressive strength of concrete with 50 to 90% of FA replacement. The highest compressive strength of concrete for concrete with high percentage replacement of FA is 66.84 MPa with 60% of FA replacement [18] and 17.66 MPa with 50 % of FA replacement [21].

The compressive strength of concrete with low percentage of FA replacement as shown in Figure 3 shows significant increase after exposure to temperature up to 400℃. However, the compressive strength of concrete decreases after exposure to temperature above 400℃. As compared for all studies, the highest compressive strength of concrete at 400℃ is 105.26 MPa with 20% of FA replacement and at 800℃ is 30.28 MPa [18].

The gain in compressive strength of concrete containing fly ash at temperature up to 400℃ was attributed to additional calcium silicate hydrate (CSH) gel that promotes to densification of concrete internal structure [21]. The reduction in compressive strength of concrete beyond 400℃ caused by dehydration of CSH and break down of calcium hydroxide (CH). Low percentage replacement of FA in concrete shows prominent effect on compressive strength at temperature up to 400℃ followed by control sample and high percentage of FA replacement. Therefore, it can be concluded that, replacing Ordinary Portland Cement with low percentage of FA enhance the compressive strength of concrete at high temperature.

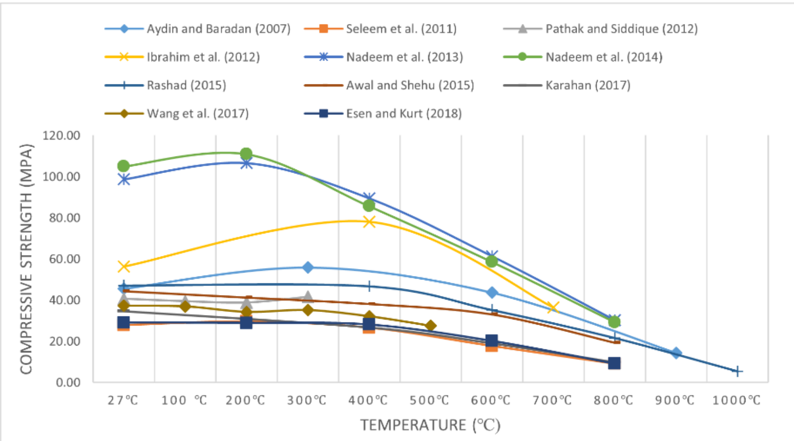

Figure 1: Compressive Strength of FA Control Sample

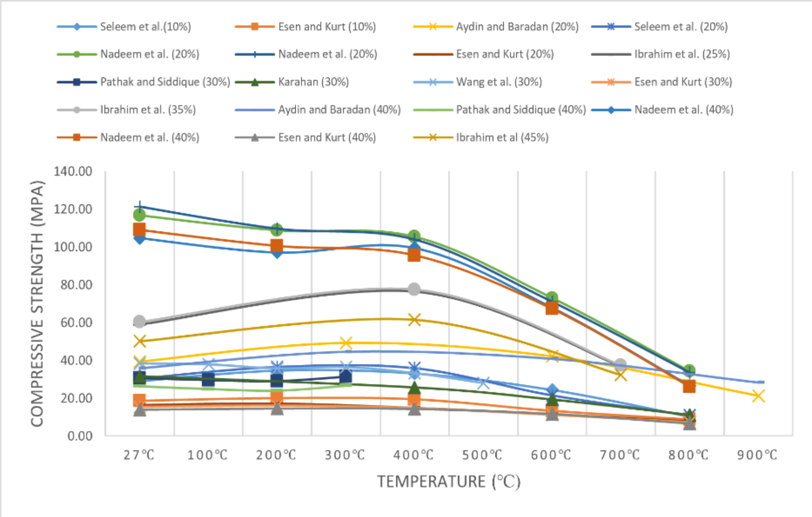

Figure 2: Compressive Strength of 10% to 40% FA Replacement

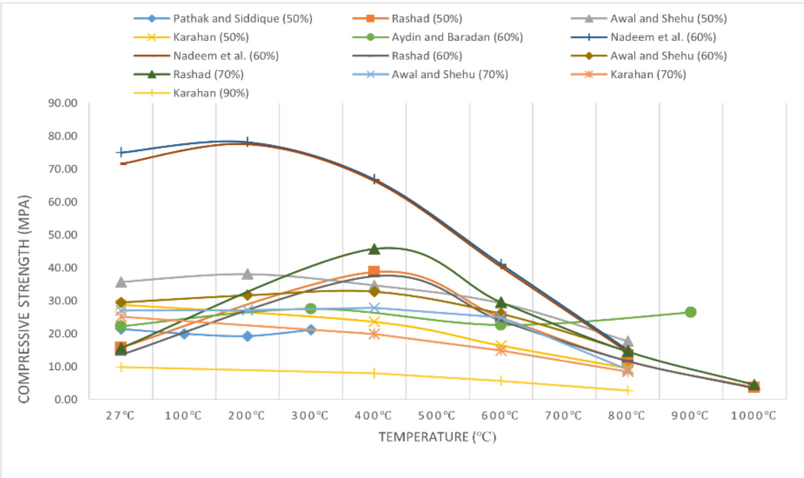

Figure 3: Compressive Strength of 50% to 90% FA Replacement

3. GGBS Replacement on Compressive Strength

The compressive strength of concrete with different percentage of GGBS replacement at room temperature and after high temperature exposure were analyzed.

3.1 Concrete at room Temperature

Compressive strength of concrete incorporated with various percentage of GGBS replacement at the age of 28 days at room temperature were analyzed. Only 40% of the total number of studies showed an increase in compressive strength of concrete incorporated with GGBS in range of 10 to 50% replacement. Accordingly, as the percentage replacement of GGBS increased, the compressive strength of concrete at the early age also decreases[25], [7], [11], [26], [27], [28], [6], [22], [29], [30]. It was found that the highest compressive strength of concrete is 67.90 MPa with the use of 20% of GGBS replacement [31]. The compressive strength of concrete which contained of GGBS generally will increase after 28 days was due to the slower generation of heat of hydration than Portland cement at an early stage of curing [32].

3.2 Concrete at High Temperature

Figure 4 to Figure 6 shows the compressive strength of concrete with and without GGBS replacement after exposure to high temperature from 27°C to 1000°C. The result for compressive strength of concrete with GGBS replacement was divided into two ranges, low percentage (5- 40%) and high percentage replacement (50- 100%).

In Figure 4, compressive strength of control concrete drop at 100°C then increased slightly at temperature up to 300°C. Then after exposure to temperature 900°C, the compressive strength decreases significantly, the compressive strength of concrete incorporated with low percentage of GGBS replacement as shown in Figure 5 decreases when exposed to 100°C. An apparent increase in compressive strength was observed at temperature up to 400°C. As shown in Figure 6, concrete with high percentage replacement of GGBS loss its compressive strength at 100°C then increases at 200°C. The compressive strength of concrete falls again after exposure to temperature 300°C. The compressive strength of concrete after exposure to temperature above 400°C for all percentage replacement remarkably decrease. However, concrete with high percentage replacement of GGBS in concrete (50% to 100%) has the highest compressive strength compared to control sample and low percentage of GGBS replacement after exposure to temperature up to 1000°C.

The highest compressive strength for all range of GGBS replacement at 800°C were 35 MPa with GGBS replacement of 50% [25] followed by 30% of GGBS replacement with compressive strength of 30 MPa [29] and lastly 29.85 MPa which has no GGBS replacement [6].

Heating cause decrease in compressive strength at 100°C due to stress created at the interface between aggregate and hardened cement paste [27]. The increase in compressive strength from 200°C to 300°C was caused by evaporation of free water as the cement gel layers moved closer together [6], [7]. In conclusion, from the result obtained, high percentage of GGBS replacement in concrete is beneficial to improve concrete strength exposed to high temperature.

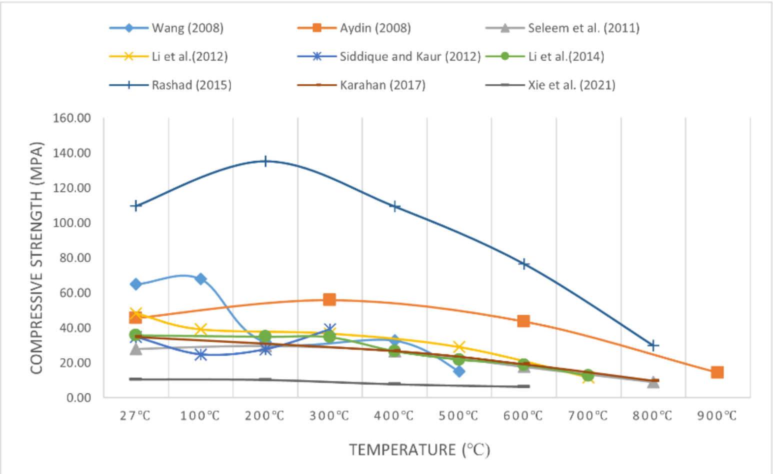

Figure 4: Compressive Strength of GGBS Control Sample

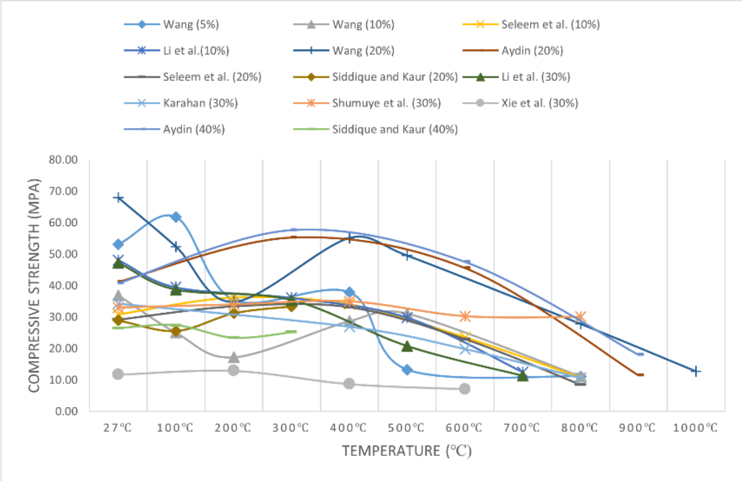

Figure 5: Compressive Strength of 5% to 40% GGBS Replacement

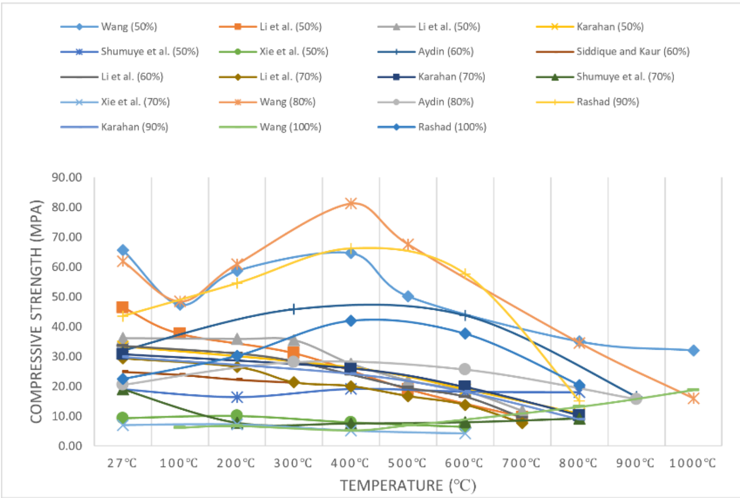

Figure 6: Compressive Strength of 50% to 100% of GGBS Replacement

4. Conclusion

To conclude, the incorporation of 10% to 40% of fly ash increase the early strength of concrete at room temperature due to recrystallization of calcium carbonate and formation of extra calcium silicate hydrate (CSH) gel. Compressive strength of concrete regardless of percentage of GGBS replacement is lower than compressive strength of control sample due to slower generation of heat of hydration at early stage of curing. After temperature exposure, it can be concluded that low percentage of FA replacement which is 10% to 40% of FA has better performance in compressive strength at high temperature than control sample and high percentage replacement of FA. Meanwhile, for GGBS replacement in concrete, the high percentage replacement which is 50% to 100% shows higher compressive strength at high temperature range between 200°C to 400°C than control sample. The increase in compressive strength is due to evaporation of free water from hydrated cement paste that result in higher Van Der Waal's forces.

This study only focusing on the impact of percentage replacement of FA and GGBS in concrete on compressive strength of concrete at high temperature. For further research, it is recommended to take into accounts other factor such as the optimum water to binder ratio and the cooling method before testing for compressive strength on the optimum percentage of FA and GGBS replacement in concrete to enhance the concrete performance at high temperature range from 27°C to 400°C.

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References

[1] W. Wang, Y. Meng, and D. Wang, "Effect of Rice Husk Ash on High-Temperature Mechanical Properties and Microstructure of Concrete," vol. 66, pp. 157–164, 2017, doi: 10.15255/KUI.2016.054.

[2] P. K. Sarker, S. Kelly, and Z. Yao, "Effect of fire exposure on cracking, spalling and residual strength of fly ash geopolymer concrete," *Mater. Des.*, vol. 63, pp. 584–592, 2014, doi: 10.1016/j.matdes.2014.06.059.

[3] T. C. Madhavi and P. K. Ram Kumar, "Effects of Temperature on concrete," *ARPN J. Eng. Appl. Sci.*, vol. 11, no. 9, pp. 5990–5992, 2016.

[4] P. . Nimlyat and E. . Datok, "Performance of Concrete at Elevated Temperatures: Utilizing A Blended Ordinary Portland Cement (Opc)/ Saw Dust Ash (Sda) As Binder," *IOSR J. Mech. Civ. Eng.*, vol. 9, no. 3, pp. 01–10, 2013, doi: 10.9790/1684-0930110.

[5] Y. Esen and A. Kurt, "Effect of High Temperature in Concrete for Different Mineral Additives and Rates," *KSCE J. Civ. Eng.*, vol. 22, no. 4, pp. 1288–1294, 2017, doi: 10.1007/s12205-017-1224-3.

[6] A. M. Rashad, "An investigation on very high volume slag pastes subjected to elevated temperatures," *Constr. Build. Mater.*, vol. 74, pp. 249–258, 2015, doi: 10.1016/j.conbuildmat.2014.10.019.

[7] S. Aydin, "Development of a high-temperature-resistant mortar by using slag and pumice," *Fire Saf. J.*, vol. 43, no. 8, pp. 610–617, 2008, doi: 10.1016/j.firesaf.2008.02.001.

[8] M. F. Nuruddin, N. M. Azmee, and C. K. Yung, "Effect of fire flame exposure on ductile self-compacting concrete (DSCC) blended with MIRHA and fly ash," *Constr. Build. Mater.*, vol. 50, pp. 388–393, 2014, doi: 10.1016/j.conbuildmat.2013.09.038.

[9] A. M. Rashad, "An exploratory study on high-volume fly ash concrete incorporating silica fume subjected to thermal loads," *J. Clean. Prod.*, vol. 87, no. 1, pp. 735–744, 2015, doi: 10.1016/j.jclepro.2014.09.018.

[10] S. Al Razib and F. I. Rahman, "Elevating the Effect of Temperature on Compressive and Tensile Strength of Concrete with Admixture," *Int. J. Adv. Struct. Geotech. Eng.*, vol. 6, no. 1, pp. 12–20, 2017.

[11] H. E. H. Seleem, A. M. Rashad, and T. Elsokary, "Effect of elevated temperature on physico-mechanical properties of blended cement concrete," *Constr. Build. Mater.*, vol. 25, no. 2, pp. 1009–1017, 2011, doi: 10.1016/j.conbuildmat.2010.06.078.

[12] J. Zhou, D. Lu, Y. Yang, Y. Gong, B. Yu, and B. Yan, "Physical and Mechanical Properties of High-Strength Concrete Modified with Supplementary Cementitious Materials after Exposure to Elevated Temperature up to 1000 ◦C," *Materials (Basel).*, vol. 13, no. 532, pp. 1–13, 2020, doi: 10.3390/ma13030532.

[13] A. Mendes, J. Sanjayan, and F. Collins, "Phase transformations and mechanical strength of OPC/Slag pastes submitted to high temperatures," *Mater. Struct. Constr.*, vol. 41, no. 2, pp. 345–350, 2008, doi: 10.1617/s11527-007-9247-8.

[14] M. J. Rukavina, D. Bjegovic, and I. Gabrijel, "Mechanical Properties of Self-Compacting Concrete with Different Mineral Aditives After High Temperature Exposure," *J. Struct. Fire*

Eng., vol. 6, no. 3, pp. 177–184, 2015.

[15] S. Aydin and B. Baradan, “Effect of pumice and fly ash incorporation on high temperature resistance of cement based mortars,” *Cem. Concr. Res.*, vol. 37, no. 6, pp. 988–995, 2007, doi: 10.1016/j.cemconres.2007.02.005.

[16] N. Pathak and R. Siddique, “Effects of elevated temperatures on properties of self-compacting-concrete containing fly ash and spent foundry sand,” *Constr. Build. Mater.*, vol. 34, pp. 512–521, 2012, doi: 10.1016/j.conbuildmat.2012.02.026.

[17] R. K. Ibrahim, R. Hamid, and M. R. Taha, “Fire resistance of high-volume fly ash mortars with nanosilica addition,” *Constr. Build. Mater.*, vol. 36, pp. 779–786, 2012, doi: 10.1016/j.conbuildmat.2012.05.028.

[18] A. Nadeem, S. Ali, and T. Yiu, “Mechanical performance , durability , qualitative and quantitative analysis of microstructure of fly ash and Metakaolin mortar at elevated temperatures,” *Constr. Build. Mater.*, vol. 38, pp. 338–347, 2013, doi: 10.1016/j.conbuildmat.2012.08.042.

[19] A. Nadeem, S. A. Memon, and T. Y. Lo, “The performance of Fly ash and Metakaolin concrete at elevated temperatures,” *Constr. Build. Mater.*, vol. 62, pp. 67–76, 2014, doi: 10.1016/j.conbuildmat.2014.02.073.

[20] A. M. Rashad, “An investigation of high-volume fly ash concrete blended with slag subjected to elevated temperatures,” *J. Clean. Prod.*, vol. 93, pp. 47–55, 2015, doi: 10.1016/j.jclepro.2015.01.031.

[21] A. S. M. A. Awal and I. A. Shehu, “Performance evaluation of concrete containing high volume palm oil fuel ash exposed to elevated temperature,” *Constr. Build. Mater.*, vol. 76, pp. 214–220, 2015, doi: 10.1016/j.conbuildmat.2014.12.001.

[22] O. Karahan, “Transport properties of high volume fly ash or slag concrete exposed to high temperature,” *Constr. Build. Mater.*, vol. 152, pp. 898–906, 2017, doi: 10.1016/j.conbuildmat.2017.07.051.

[23] A. Al- Hamrani, M. Kucukvar, W. Alnahhal, M. Elsadig, and C. O. Nuri, “Green Concrete for a Circular Economy : A Review on Sustainability, Durability and Structural Prooperties.,” *Materials (Basel).*, no. 14, p. 351, 2021, doi: https://doi.org/10.3390/ma14020351.

[24] Q. Ma, R. Guo, Z. Zhao, Z. Lin, and K. He, “Mechanical properties of concrete at high temperature — A review,” *Constr. Build. Mater.*, vol. 93, pp. 371–383, 2015, doi: 10.1016/j.conbuildmat.2015.05.131.

[25] H. Y. Wang, “The effects of elevated temperature on cement paste containing GGBFS,” *Cem. Concr. Compos.*, vol. 30, no. 10, pp. 992–999, 2008, doi: 10.1016/j.cemconcomp.2007.12.003.

[26] Q. Li, Z. Li, and G. Yuan, “Effects of elevated temperatures on properties of concrete containing ground granulated blast furnace slag as cementitious material,” *Constr. Build. Mater.*, vol. 35, pp. 687–692, 2012, doi: 10.1016/j.conbuildmat.2012.04.103.

[27] R. Siddique and D. Kaur, “Properties of concrete containing ground granulated blast furnace slag (GGBFS) at elevated temperatures,” *J. Adv. Res.*, vol. 3, no. 1, pp. 45–51, 2012, doi: 10.1016/j.jare.2011.03.004.

[28] Q. Li, G. Yuan, Z. Xu, and T. Dou, “Effect of elevated temperature on the mechanical properties of high-volume GGBS concrete,” *Mag. Concr. Res.*, vol. 66, no. 24, pp. 1277–1285, 2014, doi: 10.1680/macr.14.00142.

[29] E. D. Shumuye, J. Zhao, and Z. Wang, “Effect of fire exposure on physico-mechanical and microstructural properties of concrete containing high volume slag cement,” *Constr. Build.*

Mater., vol. 213, pp. 447–458, 2019, doi: 10.1016/j.conbuildmat.2019.04.079.

[30] J. Xie, J. Zhao, J. Wang, P. Huang, and J. Liu, "Investigation of the high-temperature resistance of sludge ceramsite concrete with recycled fine aggregates and GGBS and its application in hollow blocks," *J. Build. Eng.*, vol. 34, no. November 2020, p. 101954, 2021, doi: 10.1016/j.jobe.2020.101954.

[31] H. Y. Wang, "The effects of elevated temperature on cement paste containing GGBFS," *Cem. Concr. Compos.*, vol. 30, no. 10, pp. 992–999, 2008, doi: 10.1016/j.cemconcomp.2007.12.003.

[32] T. Ibrahim and F. Satuk Bugra, "Several properties of mineral admixtured lightweight mortars at elevated temperatures," *FIRE Mater.*, 2010, doi: 10.1002/fam.