CONSTRUCTION
e-ISSN: 2785-8731
VOL. 2, ISSUE 2, 93 – 103
DOI: https://doi.org/10.15282/construction.v2i2.8710

REVIEW ARTICLE

Green Concrete: An Eco-Friendly Alternative to the OPC Concrete

A. Fuzail Hashmi[1,*], M. S. Khan[2], M. Bilal[1], M. Shariq[2] and A. Baqi[2]

[1]Civil Engineering Section, University Polytechnic, Aligarh Muslim University, India.
[2]Department of Civil Engineering, Aligarh Muslim University, India.

ABSTRACT – The popularity of concrete has resulted in the considerable consumption of natural resources and significant emission of CO_2 gas into the atmosphere. The key constituents of the concrete are the cement and the natural aggregates. These major concrete elements are recommended to be replaced with other materials to solve sustainability issues. Hence, by-products like pulverized granular blast-furnace slag, fly ash, rice husk ash, silica fume, recycled coarse aggregates etc., are added to the concrete to utilize the waste products and produce sustainable concrete. Cement manufacturing accounts for 8 to 10% of total global CO_2 emissions. The construction industry is progressively adopting green concrete use in buildings because of its inherent benefits and limitations of traditional concrete. Green concrete is available in a variety of forms such as high-volume fly ash concrete, alkali-activated concrete, recycled aggregate concrete, ultra-high performance concrete, geopolymer concrete etc. Green concrete has various environmental, technical, and economic advantages i.e., greater durability, enhanced workability, and pumpability, decreased permeability, controlled bleeding, higher acid resistance, and decreased plastic shrinkage cracking. These properties encourage faster concrete production, shorter curing times, lower construction costs, earlier project completion, lower maintenance costs, and longer service life of construction projects. This review article aims to comprehensively explain the fresh, hardened, and durability properties of green concrete and knowledge gaps in green concrete. The literature revealed that further research is needed to accurately assess the long-term properties, notably creep and shrinkage behaviour of structural or reinforced elements of green concrete.

ARTICLE HISTORY
Received: 19th Sept. 2022
Revised: 01st Nov. 2022
Accepted: 21st Nov. 2022

KEYWORDS
Green concrete
Waste material
Sustainability
Mechanical properties
Durability

INTRODUCTION

Concrete has a significant environmental effect since it consumes substantial natural resources and emits roughly one tonne of CO_2 per tonne of Portland cement (OPC) produced [1]. Growing populations are likely one of the most influential aspects of increased concrete consumption [2]. This substantial expansion stresses natural resources and necessitates commercial and industrial infrastructure. Cement output is expected to reach 4 billion tonnes annually by 2030 [3]. Cement manufacturing accounts for almost 5% of global anthropogenic greenhouse gas emissions [4]. Because of the negative environmental impact, new materials are needed to curb the wasteful use of natural resources or reuse by-products from manufacturing and farming.

Nowadays, the term "Green" refers to the entire environment, which is an essential aspect on a global scale. Green concrete is described as concrete that contains at least one component made from waste, whose manufacturing process does not harm the environment, or which has great results and life cycle sustainability. Researchers have made considerable attempts to arrive at alternatives capable of significantly lowering high energy consumption and environmental impacts during the cement manufacturing processes, such as adopting the concept of ecological sustainability and green chemistry. The current high demand for natural resources to satisfy infrastructure demands has provided enormous prospects for green infrastructural development utilizing waste materials [5-8]. These waste materials, which may be classified as agricultural, industrial, or municipal waste, serve as supplemental cementitious materials and are illustrated in Fig. 1. The utilization of these wastes not only makes the concrete sustainable but also helps in solving the problem of waste disposal. Green concrete is the principle of incorporating environmental considerations into concrete in terms of raw material procurement, mix formulation, structural design, building, and maintenance of concrete structures [9].

Conventional concrete has intrinsic limitations, such as excessive utilization of natural raw materials, limited early-age strength properties, and environmental pollution [10-12]. On the other hand, green concrete has several advantages, such as improved concrete characteristics, longer strength, lower shrinkage rate, reduced CO_2 emissions, and natural resource conservation etc [13]. Conventional concrete mainly comprises four basic components - cement, aggregates, water, and additives. Engineers' primary focus is on finding ways to reduce the world's cement industry's carbon footprint, as well as the massive use of aggregates. Carbon dioxide emissions are present at all stages of the OPC manufacturing and application processes. Energy-intensive processes like extracting limestone from quarries and the chemical decomposition of limestone calcium carbonate (main ingredient of cement) to lime (calcium oxide) contribute CO_2

***CORRESPONDING AUTHOR** | A. Fuzail Hashmi | ✉ fuzailhashmi.amu@gmail.com emissions to the environment. Burning fossil fuels during the manufacturing process, which is required to heat raw materials to 1400 C in the rotating kiln, significantly contributes to harmful emissions [14].

The fresh and hardened qualities of concrete are enhanced if the waste materials are efficiently used in the concrete. Biajawi et al. [15] observed that waste materials and by-products like coal bottom ash, rice husk ash, coconut shells, plastic, glass, wood etc., are effectively used in the concrete. According to Biajawi et al.[16], concrete and mortar may be made sustainable by including recycled resources like coal bottom ash. Cement production's massive impact on the economy is mitigated, and a sustainable, functional green environment is created to achieve national wealth. Fly ash shortens the curing time for mass concrete structures without affecting long-term strength and improved workability [17-21]. Rice husk ash lessens the water absorption of concrete [22,23] and improves the durability and chemical resistance [24-29]. The addition of rice husk ash in the concrete also increased early age strength and improved the microstructure by reducing the size of the interfacial transition zone between the paste and the aggregate [30-32]. Using silica fume in concrete has several advantages i.e., better flexural and compressive strengths, greater pozzolanic activity, and multi-range macro-porosity characteristics [33]. It is used to make high-porosity cement foams and high-strength lightweight concrete owing to its macroporosity properties. Load-bearing capacity, durability, and resistance to impact are improved by using silica fume [34]. Using metakaolin as a pozzolan is useful in concrete since it greatly enhances the pore structure. It may increase permeability and resistance against alkali-silica reactions while considerably boosting early-age strength in blended cement products [35]. Ground granular blast-furnace slag (GGBFS), fly ash, and municipal solid waste ash significantly reduce linear shrinkage, porosity, and heat of hydration and improvement in the bending toughness and ductility [36-37]. Adding glass scraps to the concrete enhances compressive strength and resilience to high and low temperatures [38,39]. However, there are limitations to employing these by-products, and choosing one relies on several factors, such as mechanical and chemical qualities, availability, and cost. Some key barriers to green concrete application in construction are poor standards of locally accessible materials, elevated building costs, and technical obstacles [40]. Energy-efficient technology advancements and innovative cement formulations are necessary, along with technical recommendations, to produce sustainable green concrete [41].

Many environmental and financial benefits are associated with plastic waste in concrete, but a few drawbacks hamper its widespread usage. Harvesting plastic waste before recycling is a severe restriction. Plastic waste from diverse streams is usually polluted with plastics and other pollutants [42]. Plastic wastes are formed of various grades and kinds of plastic, which may produce non-isotropic construction performance. Complex compositions of certain plastics render typical recycling procedures unsuitable for their reuse, resulting in garbage in the marine environment. Plastic wastes are inappropriate for use in situations where a high toughness and modulus of elasticity are required due to their low density. Because of its low density, plastic waste needs to be compressed to fit into smaller trucks, which drives up transportation costs [43]. Plastics have low surface energy. Thus, they don't work very well for situations like plastic waste embedded in a composite, where strong mechanical bonding is required. Reduced mechanical performance of the final composite may arise from insufficient bonding. There is currently no accepted standard for implementing plastic waste in the building industry. Construction applications, such as plastic waste in cementitious composites, have been the subject of substantial research but are not yet standardized commercially [44].

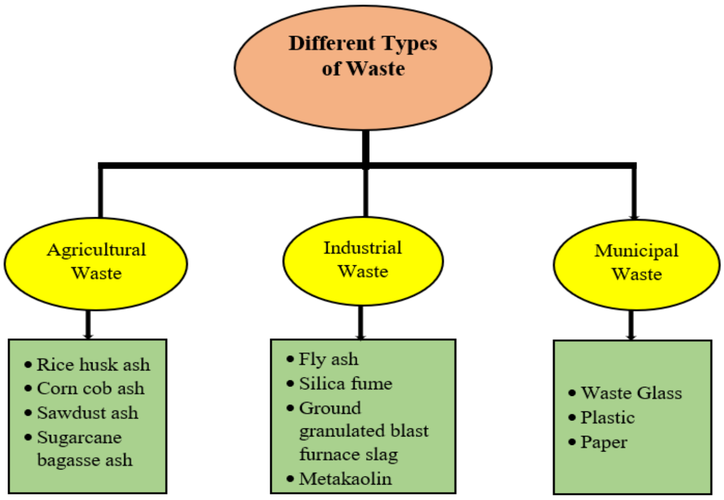

Figure 1. Wastes obtained from different sectors.

This study aims to contribute to green concrete by reviewing the literature on the sustainability, strength, fresh and hardened properties, and durability properties of green concrete to ascertain that it can be used as an eco-friendly structural material in place of Portland cement. The present paper attempted to review the concrete containing fly ash, rice husk ash, silica fume, GGBFS, glass, plastics, etc., as a cement replacement. This study also provides insights into the performance of green concrete in terms of elevated temperature, acid and chemical attack, chloride ion penetration, and freezing and thawing exposures.

FRESH PROPERTIES OF GREEN CONCRETE

Water requirement and slump

The freshness and consistency of concrete before it hardens can be obtained with the help of a slump test. This test aims to determine how easily freshly made concrete can be poured. The simple nature of the test's setup and execution has contributed to its widespread adoption. Slump testing is done in the field to ensure consistency in varying loads of concrete.

Good workable fly ash concrete at a low water-binder ratio can be obtained with a superabundant dosage of superplasticizer [45]. Slump values increased with increasing fly ash replacements of cement [46,47] because fly ash has a higher specific surface area and lower specific gravity than Portland cement. Slump appeared to reduce with increasing rice husk ash [48]. However, Abalaka [49] reported a rise in a slump with increasing rice husk ash by cement substitution of 5%. Hunchate et al. [50] observed that slump increased when 10% silica fume was added to cement substitution. Amarkhail [51] found that slump values decreased beyond 15% silica fume cement replacement. Slump values appeared to grow with increasing GGBFS levels, as reported by Karri et al. [52] and Arivalagan [53]. Rice husk ash's high water absorption is responsible for the decline in slump values as a result of which superplasticizer is commonly used to improve workability in concrete. The macro-mesoporous structure of rice husk ash and silica fume, together with the pore volume of concrete, contribute to their large specific surface area and water absorption capacity, all of which contribute to slump reduction. The fineness, the water-cement ratio, and the cement replacement ratio all have a role in reducing the slump [54]. Slump values considerably decrease if waste materials like glass and plastics are added to the concrete [55]. The slump values decrease if the cement is replaced by agriculture or municipal wastes. However, some industrial waste enhances the slump values when mixed appropriately. Improvement or reduction in the slump values on the addition of different types of wastes to the concrete is shown in Table 1.

Setting time, Workability, Segregation and Bleeding

The time that cement and other cementitious materials have to set before they can be moved, placed, or compacted is called the setting time. The setting time for GGBFS-based geopolymers varies with calcium concentration, particle size, and Si/Al molar ratios [56]. Ravina and Mehta [57] reported a delay in concrete setting time ranging from 20 to 240 minutes depending on the kind and quantity of fly ash used. Sulphate and available alkali levels of fly ash affect the length of time it takes for the material to set.

Fresh concrete workability is the ease with which it may be handled, placed, compacted, and finished. The workability of geopolymer concrete decreased due to the rapid reaction of calcium and the angular and spherical morphologies of fly ash particles [58]. According to Duval and Kadri [59], 10% silica fume may be used as a substitute for cement without compromising the workability of the concrete.

Fly ash based concrete reportedly shows high deformability and stability [60]. Reduced water content resulted in a prolonged time to flow. A higher fly ash content reduces the segregation index, whereas a higher superplasticizer dose causes the opposite effect. Shen [61] found that paste viscosity and yield stress may be increased while dynamic segregation is decreased with smaller aggregate size, continuous aggregate gradation, lower aggregate density, and greater paste viscosity. Bleeding occurs when water moves to the top of freshly poured concrete and may be seen on the surface. Bleeding has undesirable consequences, one of which is that concrete characteristics might be unpredictable. Wainwright and Ait-Aider [62] claim that bleeding is affected by the cement's particle size distribution, the fine concentration in the concrete mix, and the cement's reactivity. There was no noticeable difference in bleeding when the authors compared the concrete containing GGBFS and OPC to 100% OPC concrete. The different properties of fresh concrete are presented in Table 1.

Table 1. Effect of different types of waste on fresh properties of concrete.

Waste material	Slump values	Workability	Setting time	Segregation and bleeding
Fly ash	Increased [46,47]	Improved [63]	Setting time increased [63,64]	Reduced [60,61]
Silica Fume	Increased at lower replacement but decreased at higher replacement [50]	Improved when lesser percentage is added [59]	Prolonged the setting time [66]	Reduced [59]
GGBFS	Increased [52, 53]	Decreased [58]	Setting time delayed [56]	Higher content of GGBFS increased the segregation and bleeding [58]

Table 2. Effect of different types of waste on fresh properties of concrete (cont.)

Waste material	Slump values	Workability	Setting time	Segregation and bleeding
Metakaolin	Decreased with the increment of metakaolin in concrete [67]	Workability of concrete reduced [64,65]	Setting time reduced [64,67]	Reduced [67]
Agriculture waste (Rice husk ash, sawdust ash etc)	Decreased [48, 54]	Workability Reduced [54]	Increased [69]	Reduced [69]
Domestic waste (glass, plastic)	Decreased [55]	Workability Reduced [55,68]	Increased [55]	Segregation and bleeding increases with higher waste content [55]

MECHANICAL PROPERTIES OF GREEN CONCRETE

Compressive strength

The concrete's compressive strength is an essential attribute in the design of concrete structures and is utilized for quality monitoring in the field. Fly ash as a cement replacement material in concrete slowed the hydration process and decreased the concrete's compressive strength. Although, due to the pozzolanic activity of fly ash, the compressive strength increases later in the curing process [70,71]. At 40%, 45%, and 50% incorporation, fly ash lowered the compressive strength of concrete by 28%, 33%, and 37%, respectively [72]. Hashmi et al. [73] reported that High volume fly ash (HVFA) concrete has low early age strength, but with respect to concrete age, adequate strength can be obtained due to the pozzolanic behaviour of fly ash particles. Unlike fly ash, silica fumes improved concrete's compressive strength due to its high pozzolanacity, reactivity, and small silica fume particles. Due to the finer particle size of silica fumes, adding 6%, 10%, and 15% of the silica fumes enhanced the compressive strength of concrete by 12%, 16%, and 20%, respectively [74]. The incorporation of rice husk ash up to 15% enhanced the compressive strength of concrete because of micro filling and pozzolanic properties. However, the increased rice husk ash content further reduced compressive strength [75,76]. The concrete with rice husk ash had more compressive strength than the control mix. According to the previous research, compressive strength of concrete reduces with an increase in the percentage of GGBFS content in the concrete. However, few studies showed a slight improvement in compressive strength at lower cement replacement [77,78]. Despite this, the compressive strength of concrete with 50% GGBFS was 11% lower than the control mix [77]. Fig. 2 illustrates the compressive strength of green concrete prepared using different waste materials at 7, 28, and 90 days. The highest compressive strength is achieved in concrete containing silica fume. Fly ash reduced the compressive strength of concrete and retarded the hydration process. Likewise, the incorporation of GBBFS showed the same impact on the strength of concrete, while at 50% cement replacement, GBBFS caused the threshold reduction to the compressive strength. However, silica fume increases concrete's compressive strength due to its fine particle size and pozzolanic content. Rice husk increased the compressive strength only up to 15% cement replacement.

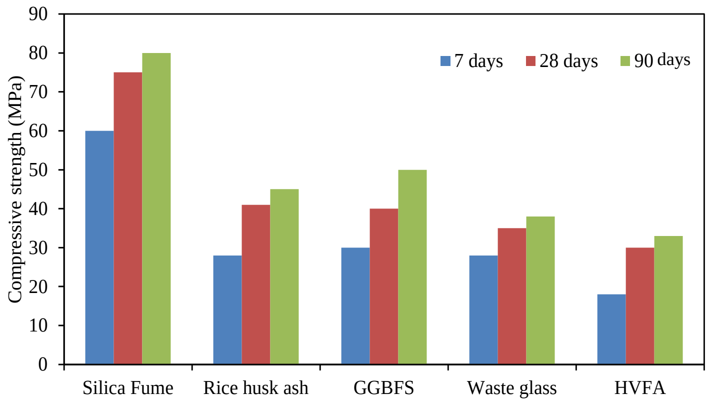

Figure 2. Compressive strength for different waste materials utilized in green concrete [79-81].

Modulus of Elasticity

Modulus of elasticity is defined as the ratio of the stress applied to the strain produced at the applied stress. Similar to the compressive strength, a distinct trend was observed in the modulus of elasticity when different cement replacement materials were incorporated into concrete. A decrease in the modulus of elasticity was also noticed as the fly ash substitution increased. The modulus of elasticity of concrete decreased by 30%, 33%, and 36% due to the addition of

40%, 45%, and 50% fly ash content in the concrete [73]. The modulus of elasticity follows the same trend as that of compressive strength. Silica fumes fill the voids formed in the concrete, forming a more compact structure, leading to a high stress-strain rate under loading, thus enhancing the modulus of elasticity of concrete [82]. Incorporating 6%, 10%, and 15% silica fumes as cement substitutes in the concrete increased the modulus of elasticity by 3.2%, 7.5%, and 10.75%, respectively [74]. Unlike the flexural strength and compressive strength, the modulus of elasticity of concrete was enhanced up to 5% rice husk ash content and then decreased when the rice husk ash concentration was increased further [76]. At 5% rice husk ash, the modulus of elasticity reached its peak value of 32 MPa [76]. Likewise, the compressive strength, splitting tensile strength of concrete, and modulus of elasticity of concrete are also reduced with the increase of GGBFS content in the concrete [83]. At room temperature, the modulus of elasticity of concrete containing 20%, 40%, and 60% GGBFS was 22.5%, 39.98%, and 41.7% lesser than the control mix [84]. The addition of silica fume and rice husk to concrete has increased its modulus of elasticity. Only 5% rice husk incorporation enhances the modulus of elasticity of concrete. However, the addition of fly ash and GBBFS decreased the modulus of elasticity.

Flexural Strength

Flexural strength of concrete is one of the deficient properties of concrete, hence efforts are made to increase it. Past studies revealed that increasing the percentage of fly ash in the concrete reduced the flexural strength of the concrete as compared to the control mix. The 40%, 45%, and 50% replacement of cement by fly ash reduced the flexural strength of concrete by 33.3%, 42.5%, and 50%, respectively, as compared to the control mix [73]. Unlike fly ash and GBBFS, the inclusion of silica fume and rice husk ash up to the optimal concentration increased the flexural strength of concrete. According to the studies, the flexural strength of concrete increases with increases in silica content in concrete, whereas this increment was noted only up to a 15% replacement further increase in silica content, which showed a slight reduction in flexural strength. A concrete mix containing 20% silica has 24.4% less flexure strength than a concrete mix containing 15% silica [85]. In the case of rice husk ash, the improvement in flexural strength was only observed up to 5% content. The addition of 5% husk ash increased the flexural strength of concrete by 12%, but subsequent additions of husk ash began to reduce the flexural strength [86]. However, as the GGBFS percentage in the concrete increases, the flexural strength starts to decrease. Most of the researchers concluded that the flexural strength of concrete increased up to 50% of GBBS-cement replacement. The flexural strength of concrete with GGBFS reached its highest value of 6.28 MPa at 50% GGBFS content. When the GGBFS content was increased to 60%, the flexural strength decreased by 18% as compared 50% GGBFS concrete mix [77]. Fly ash and GBBFS have a detrimental influence on the flexural strength of concrete, similar to compressive strength and modulus of elasticity; however, the inclusion of rice husk and silica content increased the flexural strength of concrete.

DURABILITY PROPERTIES OF GREEN CONCRETE

Water Absorption and Porosity

Bulk density decreases when the percentage of recycled glass powder in a material rises, while water absorption decreases [87]. Both the water absorption and the porosity of geopolymer concrete were reduced with the addition of cement, as reported by Aliabdo et al. [81]. Waste glass powder's pore filling and pozzolanic activity caused water absorption and voids ratio to decrease with increasing amounts of waste glass powder added. Binici's [88] research showed that alkali activation temperatures decrease water absorption. However, the percentage reduction varies from material to material, as shown in Fig. 3. Water absorption and apparent porosity are said to change with curing ages and fly ash cement, as reported by Tian and Zhang [89]. This indicates that the mechanical performance of green concrete is affected by the ratio of supplemental cementitious material (SCM) to cement, as well as the apparent porosity and water absorption of the SCM. Regardless of the water-cement ratio, Hesami et al. [28] found that increasing husk ash mixed with glass and steel fibres reduced porosity. The authors suggested that a rice husk ash content of 8–10% and a water-cement ratio of 0.33 is optimal. According to Momtazi and Zanoosh [90], RHA-cement composites made using waste rubber tyres and polypropylene fibre (PPF) may be utilized to lessen water absorption. Fly ash, GGBFS , and silica fume all work together or independently to make concrete less porous and hence more water resistant. Immersed concrete absorbs less water when treated with GGBFS than micro silica [91]. Steel slag impacts the early-age hydration of cement [92] negatively. The variation of water absorption for different wastes i.e. GGBFS, silica fume, and fly ash are depicted in Fig. 3.

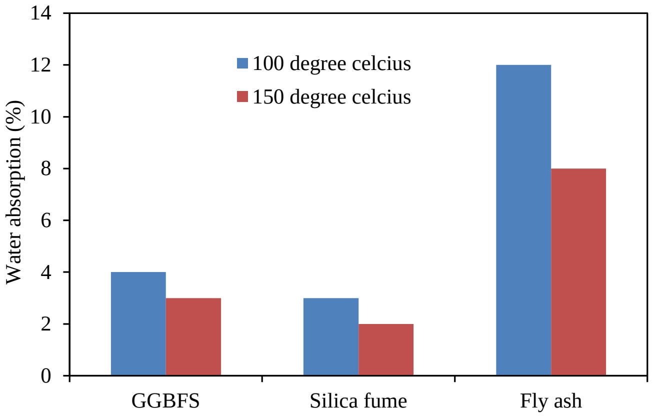

Figure 3. Water absorption for different materials at varying temperatures [81].

Elevated temperatures

Poon et al. [93] tested the effectiveness of metakaolin as a replacement for OPC in eight regular and high-strength concrete mixes at temperatures up to 800 ^{0}C. Metakaolin was used at 0%, 5%, 10%, and 20%. The test samples were heated at high temperatures in an automated electric furnace. The metakaolin concrete mixes achieved higher compressive strength than the OPC, fly ash, and silica fumes concrete up to 400 ^{0}C but then experienced a sharp reduction in compressive strength, severe cracking, and explosive spalling after being heated above 400 ^{0}C [94]. This was attributed to the dense micro-structure of the metakaolin concrete mixes, which allowed pore pressure to build up by steam. Nevertheless, the mixture containing 5% metakaolin outperformed similar concrete without spalling at failure throughout a wide temperature range [93]. High-performance concrete mixtures containing between 5 and 20 percent metakaolin and between 20 and 60 percent fly ash were tested for their mechanical and durability properties at high temperatures [95]. The concrete mixtures were heated to temperatures between 27 and 800 degrees Celsius, then cooled either slowly in the air or quickly in water. Overwhelmingly, the loss of compressive strength was found to be more pronounced after exposure to 400 C, followed by rapid cooling. For all mixtures tested between 400 and 600 C, the sorptivity and chloride permeability values dramatically increased with increasing temperature. However, the Metakaolin specimens showed greater resistance to water penetration than the fly ash and cement concrete specimens at room temperature. However, at temperatures of 600 degrees Celsius and above, the 20% fly ash mixture had the lowest sorptivity. Rashad and Sadek [96] fired 70% GGBFS paste to 400, 600, 800, and 1000 ^{0}C for 2 hours to increase its compressive strength. The authors proposed a weighted replacement ratio of 2- 10% of metakaolin for the GGBFS. Their findings showed that compressive strength was improved before and after being subjected to high temperatures. Compared to a control mixture, the residual compressive strength of pastes containing 2%, 4%, 6%, 8%, and 10% metakaolin were 10%, 15%, 20%, 27%, and 35% greater at 800 to 1000 ^{0}C.

Siddique and Kaur [97] examined the mechanical behaviour of concrete subjected to temperatures up to 350 C, where the OPC was substituted by weight with 20%, 40%, and 60% of GGBFS. The authors reported that after 28 and 56 days of curing at 100, 200, and 350 degrees Celsius, the concrete's compressive strength, splitting tensile strength, and elastic modulus were all 40% lower than the control mix stored at 27 degrees Celsius. The 20% GGBFS mixture performed best among the GGBFS mixtures and was shown to be amenable to use in nuclear structures. The performance of GGBFS in concrete exposed to high temperatures (150-700 ^{0}C) for 90 days was investigated by Li et al. [98] using replacement ratios of 10%, 30%, and 50% by weight of OPC. Greater carbonation depth was seen in GGBFS-containing mixes. Lower compressive strength was seen at temperatures over 400 °C, with the trend becoming more evident as the temperature was raised. Compressive strength decreases by 40%, 38%, 56%, and 59% at 500 °C for concrete containing 0%, 10%, 30%, and 50% of GGBFS, respectively. In addition, concretes containing 10%, 30%, and 50% GGBFS saw a greater decline in elastic modulus compared to the unheated specimens (by 22%, 25%, and 27%, respectively) when exposed to heat. The effect of temperature on the compressive strength of concrete containing different types of waste materials is shown in Fig. 4.

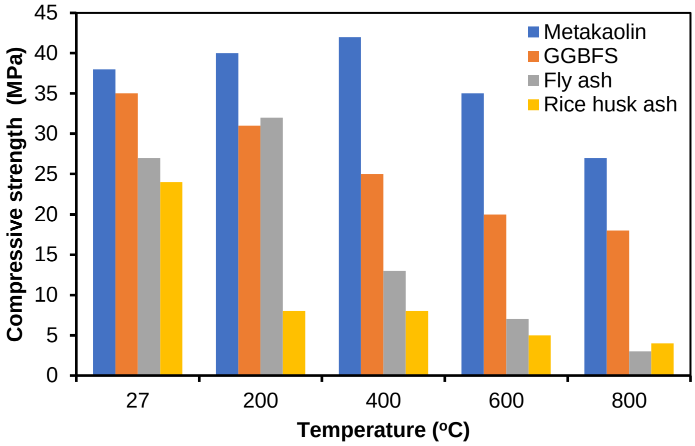

Figure 4. Temperature effect on the compressive strength of concrete subjected to high temperatures [96-99].

Acid attack, chloride ion penetration and Freezing and Thawing

Li and Zhao [100] investigated the short- and long-term sulphate resistance of three concrete mixes: standard cement concrete, fly ash concrete, and concrete containing 25% fly ash and 15% GGBFS. In terms of sulphate attack resistance after 50 weeks of exposure, GGBFS + fly ash concrete outperformed conventional and fly ash concrete.

Mc Carthy and Dhir [101] tested the chloride diffusion, permeability, and absorption of concrete containing 45% fly ash as a cement component to assess its durability. A 100 mm 25 mm deep concrete cylinder was immersed in 5 M NaCl and 5 M $Ca(OH)_2$ solutions at 20 C and then subjected to a chloride diffusion test. However, a concrete core of 54 mm in diameter and 50 mm in depth was subjected to a permeability test, which included monitoring the airflow rates through the specimen at different intake pressures. Overall, the durability performance of fly ash concrete was superior to that of cement concrete, while the performance of fly ash concrete was comparable to that of cement concrete for carbonation depth.

The effects of adding 0, 5, 10, 15, and 20% metakaolin and silica fume to concrete were studied by Kim et al. [102]. Chloride ion permeability and other properties decreased with increasing amounts of metakaolin and silica fume. Concrete mixtures containing 0% and 10% metakaolin or silica fume retain their relative dynamic elastic modulus after freezing and thawing for up to 300 cycles. In order to determine how well concrete would hold up against carbonation, it was exposed to accelerated circumstances for 7, 14, 28, and 56 days at 30 ºC and 60% relative humidity. Mortar specimens containing 15% metakaolin or silica fume had a 20% decrease in compressive strength when subjected to a 2% acid solution for 56 days, compared to the control mix.

The influence of fly ash and silica fume on chloride permeability, electric resistivity, and water absorption in concrete was investigated by Sabet et al. [103]. Their investigation revealed that the chloride diffusion coefficient was decreased when 10% and 20% fly ash were included in the mix and then exposed to a NaCl solution for 90 days. The most remarkable improvement was the 10% and 20% silica fume concrete.

Wang et al. [104] studied the effects of sulphate attack and freezing-thawing cycles on the durability of concrete containing silica fume at 5%, 8%, and 11% by weight to replace the OPC, and fly ash at 10%, 15%, and 25% by weight. Samples of prismatic concrete were submerged in 5% and 10% sodium sulphate solutions and subjected to 175 cycles of freezing and thawing. The findings showed that the durability of concrete was greatly enhanced by adding up to 25% fly ash and between 5% and 8% silica fume.

SCOPE FOR FUTURE RESEARCH

More research is needed on the reinforced structural elements of green concrete, such as beams, slabs, columns, etc., particularly at high temperatures. The long-term shrinkage and creep characteristics of commercially processed green concrete should also be studied, including experimental findings compared to conventional i.e. OPC concrete. In order to expand the available database of green concrete, the authors recommend doing more experimental and analytical studies on reinforced green concrete structural elements using a variety of conditions and mix designs. The study on green concrete mix design and performance assessment must be accomplished to design, build, and effectively expand concrete industries.

CONCLUDING REMARKS

The present paper reviewed the fresh and hardened properties as well as the durability properties of green concrete. A literature review revealed that extensive work had been carried out on green concrete utilizing different waste materials, but limited study is available related to the long-term behaviour of structural elements prepared using green concrete. The important conclusions derived from the past studies are summarized below:

- Green concrete is one of the most efficient, cost-effective, innovative, and environmentally friendly methods to improve the performance of concrete structures. It is recommended that green concrete be utilized in large-scale worldwide infrastructure projects.
- Higher percentages of rice husk ash and agricultural waste reduce the slump values and workability of concrete.
- The silica fume effectively gained higher early strength than the control mix. At later ages, the GGBFS and fly ash concrete reported higher compressive strength and further increased with concrete age.
- The literature revealed that green concrete containing silica fume and low percentages of rice husk ash could achieve good mechanical strength.
- Compressive strength in concrete mixtures that included GGBFS, fly ash, or silica fume dropped dramatically at temperatures over 400 degrees Celsius. Pozzolanic cement pastes have a far lower sorptivity than Portland cement paste. Concrete containing metakaolin has shown good compressive strength at elevated temperatures.
- Long-term sulphate resistance of GGBFS and fly ash containing concrete was higher than that of traditional cement concrete. Carbonation depth was shown to rise with cementitious concentration and to be greater in the green concrete mix compared to the control mix.
- The current review offers considerable updated information on the fresh, hardened, and durability aspects of green concrete. It will benefit designers, practicing engineers, and researchers working in the field of sustainable construction.

REFERENCES

[1] Meyer, C. The greening of the concrete industry. Cem. Concr. Compos. 2009, 31, 601–605.

[2] Khan, A.A.; Arshad, S.; Mohsin, M. Population Growth and Its Impact on Urban Expansion: A Case Study of Population Growth and Its Impact on Urban Expansion: A Case Study of Bahawalpur, Pakistan. Univers. J. Geosci. 2014, 2, 229–241.

[3] Klee, H. The cement sustainability initiative. In Proceeding of Institution of Civil Engineers Engineering Sustainability; Institute of Civil Engineers: London, UK, 2004.

[4] Hendriks, C.A.;Worrell, E.; De Jager, D.; Blok, K.; Riemer, P. Emission reduction of greenhouse gases from the cement industry. In Proceedings of the IEA Greenhouse Gas R&D Programme, Interlaken, Switzerland, August 30–2 September 2000.

[5] Mehta, R. Siddique, An overview of geopolymers derived from industrial by-products, Constr. Build. Mater. 127 (2016) 183–198.

[6] J.K. Prusty, S.K. Patro, S. Basarkar, Concrete using agro-waste as fine aggregate for sustainable built environment–A review, Int. J. Sustainable Built Environ. 5(2) (2016) 312–333.

[7] A.M. Rashad, D.M. Sadek, An investigation on Portland cement replaced by high-volume GGBS pastes modified with micro-sized metakaolin subjected to elevated temperatures, Int. J. Sustainable Built Environ. (2016).

[8] A.O. Sojobi, Evaluation of the performance of eco-friendly lightweight interlocking concrete paving units incorporating sawdust wastes and laterite, Cogent Eng. 3 (1) (2016) 1255168.

[9] R. Jin, Q. Chen, An investigation of current status of "green" concrete in the construction industry, 49th ASC Annual International Conference Proceedings, 2013.

[10] A. Baikerikar, A Review on Green Concrete, J. Emerging Technol. Innovative Res. 1 (6) (2014) 472–474.

[11] O.M. Jensen, P.F. Hansen, Autogenous deformation and RH-change in perspective, Cem. Concr. Res. 31 (12) (2001) 1859–1865.

[12] D. Thorpe, Y. Zhuge, Advantages and disadvantages in using permeable concrete pavement as a pavement construction material, Assoc. Res. Constr. Manage. 6 (8) (2010) 1341–1350.

[13] R. Woodward, N. Duffy, Cement and concrete flow analysis in a rapidly expanding economy: Ireland as a case study, Resour. Conserv. Recycl. 55 (4) (2011) 448–455.

[14] Turner, L.K.; Collins, F.G. Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer OPC cement concrete. Constr. Build. Mater. 2013, 43, 125–130.

[15] AlBiajawi MI, Embong R, Muthusamy K. An overview of the utilization and method for improving pozzolanic performance of agricultural and industrial wastes in concrete. Materials Today: Proceedings. 2021 Mar 22.

[16] Al Biajawi MI, Embong R, Muthusamy K, Ismail N, Obianyo II. Recycled coal bottom ash as sustainable materials for cement replacement in cementitious Composites: A review. Construction and Building Materials. 2022 Jul 4;338:127624.

[17] Hela, R.; Tazky, M.; Bodnarova, L. Possibilities of determination of optimal dosage of power plant fly ash for concrete. J. Teknol. 2016, 78, 59–64.

[18] Li, G. Properties of high-volume fly ash concrete incorporating nano-SiO2. Cem. Concr. Res. 2004, 34, 1043–1049.

[19] Ravina, D.; Mehta, P.K. Properties of fresh concrete containing large amounts of fly ash. Cem. Concr. Res. 1986, 16, 227–238.

[20] Ahmaruzzaman, M. A review on the utilization of fly ash. Prog. Energy Combust. Sci. 2010, 36, 327–363.

[21] Gamage, N.; Liyanage, K.; Fragomeni, S.; Setunge, S. Overview of different types of fly ash and their use as a building and construction material. In Proceedings of the International Conference of Structural Engineering, Construction and Management, Kandy, Sri Lanka, 15–17 December 2011.

[22] Mahmud, H.B.; Malik, M.F.A.; Kahar, R.A.; Zain, M.F.M.; Raman, S.N. Mechanical Properties and Durability of Normal and Water Reduced High Strength Grade 60 Concrete Containing Rice Husk Ash. J. Adv. Concr. Technol. 2009, 7, 21–30.

[23] Zareei, S.A.; Ameri, F.; Dorostkar, F.; Ahmadi, M. Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: Evaluating durability and mechanical properties. Case Stud. Constr. Mater. 2017, 7, 73–81.

[24] Singh, B. Rice husk ash. InWaste and Supplementary Cementitious Materials in Concrete; Siddique, R., Cachim, P., Eds.;Woodhead Publishing: Cambridge, UK, 2018; pp. 417–460.

[25] Reddy, D.V.; Diana, A.; Marcelina Alvarez, B.S. Rice Husk Ash as a Sustainable Concrete Material for the Marine Environment. In Proceedings of the Sixth LACCEI International Latin American and Caribbean Conference for Engineering and Technology, Tegucigalpa, Honduras, 4–6 June 2008; Partnering to Success: Engineering, Education, Research and Development. LACCEI: Boca Raton, FL, USA, 2008.

[26] Nehdi, M.; Duquette, J.; El Damatty, A. Performance of rice husk ash produced using a new technology as a mineral admixture in concrete. Cem. Concr. Res. 2003, 33, 1203–1210.

[27] Vigneshwari, M.; Arunachalam, K.; Angayarkanni, A. Replacement of silica fume with thermally treated rice husk ash in Reactive Powder Concrete. J. Clean. Prod. 2018, 188, 264–277.

[28] Deb, P.S.; Nath, P.; Sarker, P.K. The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. Mater. Des. 2014, 62, 32–39.

[29] Crossin, E. The greenhouse gas implications of using ground granulated blast furnace slag as a cement substitute. J. Clean. Prod. 2015, 95, 101–108.

[30] S. Hesami, S. Ahmadi, M. Nematzadeh, Effects of rice husk ash and fiber on mechanical properties of pervious concrete pavement, Constr. Build. Mater. 53 (2014) 680–691.

[31] E. Mohseni, F. Naseri, R. Amjadi, M.M. Khotbehsara, M.M. Ranjbar, Microstructure and durability properties of cement mortars containing nano-TiO2 and rice husk ash, Constr. Build. Mater. 114 (2016) 656–664.

[32] F. Zunino, M. Lopez, Decoupling the physical and chemical effects of supplementary cementitious materials on strength and permeability: a multi-level approach, Cement Concr. Compos. 65 (2016) 19–28.

[33] E. Papa, V. Medri, D. Kpogbemabou, V. Morinière, J. Laumonier, A. Vaccari, S. Rossignol, Porosity and insulating properties of silica-fume based foams, Energy Build. 131 (2016) 223–232.

[34] Z. Zhang, B. Zhang, P. Yan, Comparative study of effect of raw and densified silica fume in the paste, mortar and concrete, Constr. Build. Mater. 105 (2016) 82–93.

[35] Mansour AM, Al Biajawi MI. The effect of the addition of metakaolin on the fresh and hardened properties of blended cement products: A review. Materials Today: Proceedings. 2022 Jul 9.

[36] Lam, C.H.K.; Lp, A.W.M.; John Patrick, B.; Gordon, M. Use of IncinerationMSWAsh: A Review. Sustainability 2010, 2, 1943–1968.

[37] Topcu, I.B.; Unverdi, A. Properties of High Content Ground Granulated Blast Furnace Slag Concrete. In Proceedings of the 3rd International Sustainable Buildings Symposium, Dubai, UAE, 15–17 March 2017;

[38] Lee, H.; Hanif, A.; Usman, M.; Sim, J.; Oh, H. Performance evaluation of concrete incorporating glass powder and glass sludge wastes as supplementary cementing material. J. Clean. Prod. 2018, 170, 683–693.

[39] M.K. Dash, S.K. Patro, A.K. Rath, Sustainable use of industrial-waste as partial replacement of fine aggregate for preparation of concrete–A review, Int. J. Sustainable Built Environ. 5 (2) (2016) 484–516.

[40] J.H. Wesseling, A. van der Vooren, Lock-in of mature innovation systems, The transformation toward clean concrete in the Netherlands, Lund University, CIRCLE-Center for Innovation, Research and Competences in the Learning Economy, 2016.

[41] M.S. Imbabi, C. Carrigan, S. McKenna, Trends and developments in green cement and concrete technology, Int. J. Sustainable Built Environ. 1 (2) (2012) 194–216.

[42] Awoyera PO, Adesina A. Plastic wastes to construction products: Status, limitations and future perspective. Case Studies in Construction Materials. 2020 Jun 1;12:e00330.

[43] Jambeck J, Hardesty BD, Brooks AL, Friend T, Teleki K, Fabres J, Beaudoin Y, Bamba A, Francis J, Ribbink AJ, Baleta T. Challenges and emerging solutions to the land-based plastic waste issue in Africa. Marine Policy. 2018 Oct 1;96:256-63.

[44] Singh N, Hui D, Singh R, Ahuja IP, Feo L, Fraternali F. Recycling of plastic solid waste: A state of art review and future applications. Composites Part B: Engineering. 2017 Apr 15;115:409-22.

[45] H.A. Alaka, L.O. Oyedele, High volume fly ash concrete: The practical impact of using superabundant dose of high range water reducer, J. Build. Eng. 8 (2016) 81–90.

[46] L. Yijin, Z. Shiqiong, Y. Jian, G. Yingli, The effect of fly ash on the fluidity of cement paste, mortar, and concrete, in: International workshop on Sustainable Development and Concrete Technology, Beijing, China, 2004, pp. 339–345.

[47] S. Mukherjee, S. Mandal, U. Adhikari, Comparative study on physical and mechanical properties of high Slump and zero slump high volume fly ash concrete (HVFAC), Global NEST J. 20 (10) (2013) 1–7.

[48] B. Keertana, S. Gobhiga, Experimental study of concrete with partial replacement of cement with rice husk ash and fine aggregate with granite dust, IRACST-Eng. Sci. Technol.: Int. J. 6 (1) (2016) 36–41.

[49] A. Abalaka, Strength and some durability properties of concrete containing rice husk ash produced in a charcoal incinerator at low specific surface, Int. J. Concr. Struct. Mater. 7 (4) (2013) 287–293.

[50] S.R. Hunchate, S. Chandupalle, V.G. Ghorpode, R. Venkata, Mix design of high performance concrete using silica fume and superplasticizer, Pan 18 (1.8) (2014) 100.

[51] N. Amarkhail, Effects of silica fume on properties of high strength concrete, Int. J. Tech. Res. Appl. 32 (2015) 13–19.

[52] S.K. Karri, G.R. Rao, P.M. Raju, Strength and Durability Studies on GGBS Concrete, SSRG Int. J. Civil Eng. 2 (2015).

[53] S. Arivalagan, Sustainable studies on concrete with ggbs as a replacement material in cement, Jordan J. Civil Eng. 8 (3) (2014) 263–270.

[54] H.T. Le, K. Siewert, H.-M. Ludwig, Alkali silica reaction in mortar formulated from self-compacting high performance concrete containing rice husk ash, Constr. Build. Mater. 88 (2015) 10–19.

[55] A. Ikpong, D. Okpala, Strength characteristics of medium workability ordinary Portland cement-rice husk ash concrete, Build. Environ. 27 (1) (1992) 105–111.

[56] H. Xu, W. Gong, L. Syltebo, K. Izzo, W. Lutze, I.L. Pegg, Effect of blast furnace slag grades on fly ash based geopolymer waste forms, Fuel 133 (2014) 332–340.

[57] D. Ravina, P.K. Mehta, Properties of fresh concrete containing large amounts of fly ash, Cem. Concr. Res. 16 (2) (1986) 227–238.

[58] P.S. Deb, P. Nath, P.K. Sarker, The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature, Mater. Des. 62 (2014) 32–39.

[59] R. Duval, E. Kadri, Influence of silica fume on the workability and the compressive strength of high-performance concretes, Cement Concr. Res. 28(4) (1998) 533–547.

[60] N. Bouzoubaa, M. Lachemi, Self-compacting concrete incorporating high volumes of class F fly ash: preliminary results, Cement Concr. Res. 31 (3) (2001) 413–420.

[61] L. Shen, Role of Aggregate Packing in Segregation Resistance and Flow Behavior of self-Consolidating Concrete, University of Illinois at Urbana-Champaign, 2007.

[62] P. Wainwright, H. Ait-Aider, The influence of cement source and slag additions on the bleeding of concrete, Cem. Concr. Res. 25 (7) (1995) 1445–1456.

[63] Hashmi AF, Shariq M, Baqi A. Use of HVFA Concrete for Sustainable Development: A Comprehensive Review on Mechanical and Structural Properties. Arabian Journal for Science and Engineering. 2022 May 12:1-24.

[64] Liu T, Li C, Li L, Fan W, Dong Y, Liang H, Yang H. Effect of fly ash and metakaolin on properties and microstructure of magnesium oxysulfate cement. Materials. 2022 Feb 11;15(4):1334.

[65] Muduli R, Mukharjee BB. Effect of incorporation of metakaolin and recycled coarse aggregate on properties of concrete. Journal of cleaner production. 2019 Feb 1;209:398-414.

[66] Xu X, Lin X, Pan X, Ji T, Liang Y, Zhang H. Influence of silica fume on the setting time and mechanical properties of a new magnesium phosphate cement. Construction and Building Materials. 2020 Feb 28;235:117544.

[67] Pillay DL, Olalusi OB, Awoyera PO, Rondon C, Echeverría AM, Kolawole JT. A review of the engineering properties of metakaolin based concrete: Towards combatting chloride attack in coastal/marine structures. Advances in Civil Engineering. 2020 Oct 5;2020.

[68] Almeshal I, Tayeh BA, Alyousef R, Alabduljabbar H, Mohamed AM. Eco-friendly concrete containing recycled plastic as partial replacement for sand. Journal of Materials Research and Technology. 2020 May 1;9(3):4631-43.

[69] Gastaldini AL, Isaia GC, Saciloto AP, Missau F, Hoppe TF. Influence of curing time on the chloride penetration resistance of concrete containing rice husk ash: A technical and economical feasibility study. Cement and Concrete Composites. 2010 Nov 1;32(10):783-93.

[70] Al-Manaseer AA, Dalal TR. Concrete containing plastic aggregates. Concrete international. 1997 Aug 1;19(8):47-52.

[71] Sumer M. Compressive strength and sulfate resistance properties of concretes containing Class F and Class C fly ashes. Construction and Building Materials. 2012 Sep 1;34:531-6.

[72] Siddique R. Performance characteristics of high-volume Class F fly ash concrete. Cement and Concrete Research. 2004 Mar 1;34(3):487-93.

[73] Hashmi AF, Shariq M, Baqi A. An investigation into age-dependent strength, elastic modulus and deflection of low calcium fly ash concrete for sustainable construction. Construction and Building Materials. 2021 May 10;283:122772.

[74] Mazloom M, Ramezanianpour AA, Brooks JJ. Effect of silica fume on mechanical properties of high-strength concrete. Cement and Concrete Composites. 2004 May 1;26(4):347-57.

[75] Chopra D, Siddique R. Strength, permeability and microstructure of self-compacting concrete containing rice husk ash. Biosystems engineering. 2015 Feb 1;130:72-80.

[76] Kannan V, Ganesan K. Chloride and chemical resistance of self compacting concrete containing rice husk ash and metakaolin. Construction and Building Materials. 2014 Jan 31;51:225-34.

[77] Mohan A, Hayat MT. Characterization of mechanical properties by preferential supplant of cement with GGBS and silica fume in concrete. Materials Today: Proceedings. 2021 Jan 1;43:1179-89.

[78] Krishna BR, Kumar KH, Kumar TM, Likitha I. Properties of GGBS concrete under various curing conditions. International Journal. 2020 Apr;8(4).

[79] W. Xu, Y.T. Lo, D. Ouyang, S.A. Memon, F. Xing, W. Wang, X. Yuan, Effect of rice husk ash fineness on porosity and hydration reaction of blended cement paste, Constr. Build. Mater. 89 (2015) 90–101.

[80] E. Mohseni, M.M. Khotbehsara, F. Naseri, M. Monazami, P. Sarker, Polypropylene fiber reinforced cement mortars containing rice husk ash and nano-alumina, Constr. Build. Mater. 111 (2016) 429–439.

[81] A.A. Aliabdo, A.E.M.A. Elmoaty, A.Y. Aboshama, Utilization of waste glass powder in the production of cement and concrete, Constr. Build. Mater. 124 (2016) 866–877.

[82] Bhanja S, Sengupta B. Influence of silica fume on the tensile strength of concrete. Cement and concrete research. 2005 Apr 1;35(4):743-7.

[83] Ganesh P, Murthy AR. Tensile behaviour and durability aspects of sustainable ultra-high performance concrete incorporated with GGBS as cementitious material. Construction and Building Materials. 2019 Feb 10;197:667-80.

[84] Siddique R, Kaur D. Properties of concrete containing ground granulated blast furnace slag (GGBFS) at elevated temperatures. Journal of Advanced Research. 2012 Jan 1;3(1):45-51.

[85] Amudhavalli NK, Mathew J. Effect of silica fume on strength and durability parameters of concrete. International journal of engineering sciences & emerging technologies. 2012 Aug;3(1):28-35.

[86] Adnan ZS, Ariffin NF, Mohsin SM, Lim NH. Performance of rice husk ash as a material for partial cement replacement in concrete. Materials Today: Proceedings. 2022 Jan 1;48:842-8.

[87] A. Parghi, M.S. Alam, Physical and mechanical properties of cementitious composites containing recycled glass powder (RGP) and styrene butadiene rubber (SBR), Constr. Build. Mater. 104 (2016) 34–43.

[88] H. Binici, Engineering properties of geopolymer incorporating slag, fly ash, silica sand and pumice, Adv. Civ. Environ. Eng 1 (3) (2013) 108–123.

[89] H. Tian, Y. Zhang, The influence of bagasse fibre and fly ash on the long-term properties of green cementitious composites, Constr. Build. Mater. 111 (2016) 237–250.

[90] A.S. Momtazi, R.Z. Zanoosh, The effects of polypropylene fibers and rubber particles on mechanical properties of cement composite containing rice husk ash, Procedia Eng. 10 (2011) 3608–3615.

[91] Ding, S.; Liang, X.; Zhang, Y.; Fang, Y.; Zhou, J.; Kang, T. Capillary Water Absorption and Micro Pore Connectivity of Concrete with Fractal Analysis. Crystals 2020, 10, 892.

[92] Zhuang, S.; Wang, Q. Inhibition mechanisms of steel slag on the early-age hydration of cement. Cem. Concr. Res. 2021, 140, 106283.

[93] Poon, C.S.; Azhar, S.; Anson, M.;Wong, Y.L. Performance of metakaolin concrete at elevated temperatures. Cem. Concr. Compos. 2003, 25, 83–89.

[94] Phan, L.T.; Carino, N.J. Fire performance of high strength concrete: Research needs. Adv. Technol. Struct. Eng. 2000, 1–8.

[95] Zareei, S.A.; Ameri, F.; Dorostkar, F.; Ahmadi, M. Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: Evaluating durability and mechanical properties. Case Stud. Constr. Mater. 2017, 7, 73–81.

[96] Rashad, A.M.; Sadek, D.M. An investigation on Portland cement replaced by high-volume GGBS pastes modified with micro-sized metakaolin subjected to elevated temperatures. Int. J. Sustain. Built Environ. 2017, 6, 91–101.

[97] Siddique, R.; Kaur, D. Properties of concrete containing ground granulated blast furnace slag (GGBFS) at elevated temperatures. J. Adv. Res. 2012, 3, 45–51.

[98] Li, Q.; Li, Z.; Yuan, G. Effects of elevated temperatures on properties of concrete containing ground granulated blast furnace slag as cementitious material. Constr. Build. Mater. 2012, 35, 687–692.

[99] Khan MS, Shariq M, Akhtar S, Masood A. Performance of high-volume fly ash concrete after exposure to elevated temperature. Journal of the Australian Ceramic Society. 2020 Jun;56(2):781-94.

[100] Li, G.; Zhao, X. Properties of concrete incorporating fly ash and ground granulated blast-furnace slag. Cem. Concr. Compos. 2003, 25, 293–299.

[101] McCarthy, M.J.; Dhir, R.K. Development of high volume fly ash cements for use in concrete construction. Fuel 2005, 84, 1423–1432.

[102] Kim, H.S.; Lee, S.H.; Moon, H.Y. Strength properties and durability aspects of high strength concrete using Korean metakaolin. Constr. Build. Mater. 2007, 21, 1229–1237.

[103] Sabet, F.A.; Libre, N.A.; Shekarchi, M. Mechanical and durability properties of self consolidating high performance concrete incorporating natural zeolite, silica fume and fly ash. Constr. Build. Mater. 2013, 44, 175–184.

[104] Wang, D.; Zhou, X.; Meng, Y.; Chen, Z. Durability of concrete containing fly ash and silica fume against combined freezing-thawing and sulfate attack. Constr. Build. Mater. 2017, 147, 398–406.