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Utilisation of GGBS and Fly Ash as Supplementary Cementitious Materials in Concrete: A Review of Properties and Sustainability

Anand B. Kudoli[1*], Shreyash Bhapkar[1], Srushti Doke[1], Omkar Kangune[1], Swarup Taware[1]

Department of Civil Engineering, Pimpri Chinchwad College of Engineering and Research, Ravet, Pune 412101, Maharashtra, India[1]

*Corresponding Author

Abstract: The production of Portland cement is one of the largest industrial sources of carbon dioxide, and partial replacement of cement clinker by supplementary cementitious materials (SCMs) is the most practical way of reducing the carbon footprint of concrete. Ground granulated blast furnace slag (GGBS) and fly ash are the two SCMs that are available in the largest quantities and are already accepted in standards and practice. This review summarises published research on the use of GGBS and fly ash in concrete. The origin, chemical composition and reaction mechanisms of both materials are first described. Their influence on the fresh properties, compressive and tensile strength, and durability of concrete is then discussed, followed by the role of curing, the use of prediction models, and the environmental and economic benefits. The literature shows that both materials improve workability and long-term strength, refine the pore structure and increase resistance to chloride and sulphate attack, while early-age strength is usually reduced and carbonation resistance may be lower if curing is inadequate. GGBS is latent hydraulic and gains strength faster, whereas fly ash reacts more slowly through the pozzolanic reaction and gives better workability and lower heat of hydration. Adequate moist curing is essential for both. The review concludes that GGBS and fly ash can routinely replace 30–50% and 20–35% of cement respectively in structural concrete, and identifies the need for performance-based mix design, data-driven strength prediction and field durability data as directions for future work.

Keywords: Supplementary cementitious materials; Ground granulated blast furnace slag; Fly ash; Durability; Compressive strength; Sustainable concrete

1. INTRODUCTION

Concrete is the most widely used construction material in the world, and Portland cement is its essential binder. The manufacture of cement clinker requires the calcination of limestone and the burning of fuel at about 1450 °C, and both processes release large quantities of carbon dioxide. Cement production is therefore estimated to account for a significant share, commonly quoted as 5–8%, of global anthropogenic CO_2 emissions [1, 2]. With the demand for infrastructure continuing to rise in developing countries such as India, reducing the carbon intensity of concrete has become an important objective of the construction sector.

Several routes have been proposed, including improved kiln efficiency, alternative fuels, carbon capture and entirely new binders such as alkali-activated materials [3]. Among these, the partial replacement of clinker by supplementary cementitious materials is regarded as the most economically viable and immediately applicable solution [2]. SCMs are finely divided materials that, when used together with Portland cement, contribute to the properties of hardened concrete through hydraulic or pozzolanic activity [4]. Their use reduces the clinker content of concrete and, in many cases, improves its long-term performance [5].

Ground granulated blast furnace slag and fly ash are industrial by-products of the steel and thermal power industries respectively. Both are produced in very large quantities, are covered by national and international standards, and have the longest record of use among all SCMs [6, 7]. Although many studies have examined them individually, practising engineers and students often need a concise comparison of how each material affects the main properties of concrete and what precautions are needed in practice. The objective of this paper is to provide such a review. Section 2 describes the origin and chemistry of GGBS and fly ash; Sections 3–5 discuss fresh, mechanical and durability properties; Section 6

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considers curing and prediction models; Section 7 summarises the sustainability benefits; and Section 8 presents conclusions and future research needs.

2. ORIGIN, COMPOSITION AND REACTION MECHANISMS

2.1 Ground granulated blast furnace slag

GGBS is obtained by rapidly quenching molten iron slag from a blast furnace in water or steam, which produces a glassy, granular material that is then dried and ground to a fineness similar to or higher than that of cement. Its main oxides are CaO, SiO_2, Al_2O_3 and MgO (Table 1). Because of its relatively high calcium content and glassy structure, GGBS is a latent hydraulic material: it reacts slowly with water on its own, but its reaction is activated by the alkaline environment and the calcium hydroxide produced by cement hydration [4]. The reaction products are mainly calcium silicate hydrate (C-S-H) with a lower Ca/Si ratio than in plain cement paste, together with aluminate phases such as hydrotalcite. This leads to a denser microstructure and a finer pore structure in the long term [7].

2.2 Fly ash

Fly ash is the fine residue collected from the flue gases of coal-fired power stations. It consists largely of spherical glassy particles and is classified, according to its calcium content, into low-calcium (Class F) and high-calcium (Class C) types [6]. Indian fly ashes are mostly of the low-calcium type. Low-calcium fly ash is a pozzolan: it has little cementing value by itself, but its amorphous silica and alumina react with the calcium hydroxide released by cement hydration to form additional C-S-H [8]. The reactivity of fly ash depends on its glass content, particle size distribution, unburnt carbon (loss on ignition) and chemical composition [9]. Because the pozzolanic reaction is slow, the contribution of fly ash to strength becomes significant mainly after 28 days.

Table 1. Typical ranges of chemical composition of OPC, GGBS and Class F fly ash (% by mass)

Oxide	OPC	GGBS	Class F fly ash
CaO	60–67	30–45	1–10
SiO_2	17–25	30–40	45–65
Al_2O_3	3–8	8–18	20–30
Fe_2O_3	0.5–6	0.5–2	4–15
MgO	0.5–4	1–15	0.5–3
Nature of reaction	Hydraulic	Latent hydraulic	Pozzolanic

Note: Typical ranges compiled from the reviews of Lothenbach et al. [4], Ahmaruzzaman [6] and Özbay et al. [7]; actual values depend on the source.

3. FRESH PROPERTIES

Both GGBS and fly ash generally improve the workability of fresh concrete. In the case of fly ash, the spherical shape of the particles acts as a 'ball-bearing' that reduces inter-particle friction, so that the water demand for a given slump decreases as the fly ash content increases [9]. GGBS particles are angular, but their smooth, glassy surfaces absorb little water, and the replacement of cement by GGBS usually improves the consistency and pumpability of concrete [7]. Fly ash with a high loss on ignition is an exception: unburnt carbon adsorbs water and air-entraining admixtures and can reduce workability [6].

Setting time is generally extended by both materials, because less clinker is present and the reactions of slag and fly ash are slower than those of cement. The retardation is more marked at high replacement levels and in cold weather, which must be considered in planning formwork removal. On the other hand, the slower reaction lowers the rate of heat evolution, which is a clear advantage in mass concrete, where high temperature gradients can cause thermal cracking [7, 10].

4. MECHANICAL PROPERTIES

4.1 Compressive strength

The effect of GGBS and fly ash on compressive strength depends strongly on age, replacement level and water–binder ratio. At early ages (3–7 days), concretes containing either material are usually weaker than the corresponding plain

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cement concrete, because less clinker is present and the secondary reactions have only started. With continued curing, the strength gap narrows and, in many cases, is reversed. Öner and Akyüz [11] examined a wide range of GGBS contents and reported that compressive strength increased with GGBS content up to an optimum level of approximately 55–59% of the total binder, beyond which strength decreased. Chidiac and Panesar [12] observed that concrete with GGBS developed its mechanical properties more slowly than plain concrete, so that tests carried out at 28 days underestimated its long-term performance.

For fly ash, Siddique [10] studied high-volume Class F fly ash concrete with 40–50% cement replacement and found that, although the 28-day strength was lower than that of the control mix, strength continued to increase significantly up to 365 days, and the concrete was suitable for structural use. Poon et al. [13] showed that high-strength concrete can be produced with large volumes of low-calcium fly ash provided that the water–binder ratio is kept low; under these conditions the fly ash reacted more effectively and the long-term strength was comparable to that of the control. The use of ultra-fine GGBS has been shown to overcome part of the early-strength loss: Teng et al. [14] reported that high-strength concrete containing ultra-fine GGBS had improved mechanical properties and durability compared with plain concrete.

4.2 Tensile and flexural strength

The split tensile and flexural strengths of GGBS and fly ash concretes generally follow the same trend as compressive strength: lower values at early ages and similar or higher values at later ages, due to the densification of the paste and the improvement of the interfacial transition zone between paste and aggregate [7, 10]. Since the tensile capacity of concrete remains low in all cases, combining SCMs with fibres is an attractive option. Fibres bridge cracks and mainly improve post-cracking behaviour, such as flexural toughness and residual strength, rather than compressive strength [15, 16]. Polypropylene fibres, for example, have been reported to increase flexural strength by about 10–50% and to improve crack resistance considerably [17], and their use in SCM-based concrete deserves further study. Bhapkar and Kudoli [18] noted that fibres act mainly after cracking, improving flexural toughness, residual strength and impact energy absorption while changing compressive strength little. Fibre-based enhancement is also relevant at the structural level: Taware and Kudoli [19] reviewed its role in reducing spalling and increasing energy absorption of reinforced concrete under blast loading, but cautioned that material-level improvements must be confirmed at member and system level.

Table 2. Summary of selected studies on GGBS and fly ash concrete

Study	SCM	Main findings
Öner & Akyüz [11]	GGBS	Compressive strength increased with GGBS content up to an optimum of about 55–59% of the binder
Chidiac & Panesar [12]	GGBS	Slower development of mechanical properties; 28-day tests underestimate long-term performance
Teng et al. [14]	Ultra-fine GGBS	Improved strength and durability of high-strength concrete
Barnett et al. [20]	GGBS	Strength development highly sensitive to curing temperature
Siddique [10]	Class F fly ash	40–50% replacement: lower 28-day strength, large gain up to 365 days; suitable for structural use
Poon et al. [13]	Low-calcium fly ash	High-strength concrete with large fly ash volumes is feasible at low water–binder ratio
Nath & Sarker [21]	Fly ash	Lower sorptivity and chloride ion penetration of high-strength concrete
Ramezanianpour & Malhotra [22]	GGBS, fly ash	Poor curing reduced strength and chloride resistance more than in plain concrete

5. DURABILITY PROPERTIES

5.1 Permeability and chloride resistance

The most important durability benefit of GGBS and fly ash is the refinement of the pore structure. The additional C-S-H produced by the slag and pozzolanic reactions fills capillary pores, reduces their connectivity and lowers the permeability of concrete [4]. Permeation properties such as absorption, permeability and diffusion are generally regarded as the most useful general indicators of durability [23]. In addition, the aluminate phases formed by these materials bind chloride

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ions. As a result, concretes containing GGBS or fly ash show markedly lower chloride ion penetration than plain concrete of similar strength, which is particularly valuable for reinforced concrete exposed to marine environments or de-icing salts [7]. Nath and Sarker [21] found that the replacement of cement by fly ash reduced the sorptivity and chloride ion penetration of high-strength concrete, and similar improvements were reported for ultra-fine GGBS by Teng et al. [14].

5.2 Sulphate attack and alkali–silica reaction

The partial replacement of cement by GGBS or fly ash reduces the tricalcium aluminate content of the binder and consumes calcium hydroxide, both of which are involved in sulphate attack. Concretes containing these materials therefore generally show better resistance to sulphate environments [7]. The lower alkali content and the binding of alkalis in low Ca/Si C-S-H also reduce the risk of alkali–silica reaction, which is why SCMs are widely recommended when potentially reactive aggregates are used [4, 5].

5.3 Carbonation

Carbonation is the main durability property that may be adversely affected. Because the pozzolanic and slag reactions consume calcium hydroxide, less alkaline reserve is available to react with atmospheric CO_2, and the depth of carbonation can be greater than in plain concrete, especially at high replacement levels and when curing is short [7]. This effect can be controlled by adequate curing, by limiting the water–binder ratio and by providing sufficient cover to the reinforcement.

Freeze–thaw resistance also requires attention in cold climates. Frost damage develops as internal microcracking and surface scaling [24], and it remains small until the degree of saturation of the concrete exceeds a critical value [25]. Air entrainment, a low water–cement ratio and appropriate supplementary materials are the main design measures for frost resistance [26]. Vishwanath et al. [27] investigated the freeze–thaw resistance of sustainable concrete experimentally and used AI/ML models to predict its performance.

A further practical consideration is that durability tests are commonly performed at 28 days. Since both GGBS and fly ash continue to react long after this age, such tests can underestimate their real benefit [12]. For fibre-reinforced concrete, polypropylene fibres have also been reported to improve resistance to fire, freeze–thaw and chemical attack [17, 28], which suggests that combinations of SCMs and fibres could provide further durability gains. Kangune and Kudoli [29] likewise recommended that durability claims for sustainable concrete be supported by exposure-specific tests using several durability indicators, rather than inferred from strength results.

Table 3. Comparison of the effects of GGBS and fly ash on concrete properties

Property	**GGBS**	**Fly ash (Class F)**
Workability	Improved	Improved (ball-bearing effect)
Setting time	Extended	Extended
Heat of hydration	Reduced	Strongly reduced
Early strength (≤ 7 days)	Reduced (moderately)	Reduced (significantly)
Long-term strength (≥ 90 days)	Similar or higher	Similar or higher
Chloride resistance	Much improved	Much improved
Sulphate resistance	Improved	Improved
Carbonation resistance	May be reduced	May be reduced
Sensitivity to curing	High	High
Typical replacement level	30–50%	20–35%

Note: Qualitative summary based on the studies reviewed in Sections 3–5.

6. CURING AND PREDICTION OF PROPERTIES

6.1 Influence of curing

Because GGBS and fly ash react more slowly than cement, concretes containing them are more sensitive to curing. Ramezanianpour and Malhotra [22] compared different curing regimes for concretes incorporating slag and fly ash and found that inadequate curing reduced compressive strength and resistance to chloride-ion penetration and increased

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porosity, with the effect being more pronounced than for plain concrete. Temperature also plays an important role. Barnett et al. [20] showed that the strength development of GGBS mortars is strongly dependent on curing temperature and reported higher apparent activation energies than for plain cement; elevated temperatures therefore accelerate strength gain, whereas cold conditions delay it. In practice, a longer period of moist curing than that used for plain concrete is recommended for both materials.

6.2 Prediction models

The large number of variables in SCM concrete, including replacement level, fineness, water–binder ratio, age and curing, makes it difficult to predict strength using simple empirical relationships. Yeh [30] was one of the first to show that artificial neural networks could predict the compressive strength of high-performance concrete containing fly ash and slag more accurately than regression models. Since then, a wide range of machine learning techniques has been applied. Chou et al. [31] found that an ensemble of regression trees gave the best accuracy among the data-mining methods they compared, and a systematic review by Nunez et al. [32] reached similar conclusions for modern concrete mixtures. Ben Chaabene et al. [33] critically reviewed these methods for the mechanical properties of concrete and highlighted the importance of data quality and model interpretability. Young et al. [34] showed, using a large industrial dataset, that mixture proportions alone limit the accuracy of strength prediction, whatever the algorithm used. Explainability methods such as SHAP can help to check whether a model has learned physically sensible trends [35]. Kudoli and Bala [36] reviewed machine learning and traditional models for predicting the physical and mechanical properties of cement and cement mortar and showed that hybrid models such as support vector machines combined with genetic algorithms can provide excellent accuracy. Doke and Kudoli [37] extended this discussion to concrete, and concluded that machine learning works best as a screening tool when supported by grouped validation, uncertainty reporting and experimental confirmation. For durability, machine-learning applications remain limited by the scarcity of consistent exposure data [38]. Such tools can reduce the number of trial mixes required when designing GGBS and fly ash concretes.

7. Sustainability and Economic Aspects

The main environmental benefit of GGBS and fly ash is the reduction of clinker content. Since the CO_2 emissions associated with these by-products are very small compared with those of clinker, every tonne of cement replaced reduces emissions almost proportionally [2]. Clinker substitution by SCMs is one of the largest contributors to the reduction potential of the cement industry identified by Miller et al. [1]. At the same time, the use of these materials helps to dispose of industrial wastes that would otherwise require land for storage; this is particularly relevant for fly ash, of which large quantities are produced every year [6, 9]. The performance of such recycled waste materials, however, depends on their processing, replacement ratio and the adjustment of the mix design [39].

Habert and Roussel [40] pointed out that the environmental benefit should be assessed per unit of performance rather than per cubic metre, since a mix with high SCM content that requires more binder to reach the required strength may lose part of its advantage. Mix design strategies should therefore aim at achieving the required strength and durability with the minimum clinker content. Computational optimisation methods can support this by searching for mixtures that balance strength, cost and environmental impact [41]. Economically, GGBS and fly ash are usually cheaper than cement, and their use reduces the cost of concrete, although transport distance and local availability can affect this benefit. Alternative binders such as alkali-activated slag and fly ash may offer further reductions in the future, but blended cements remain the most practical solution at present [3].

8. CONCLUSIONS AND FUTURE SCOPE

Based on the literature reviewed, the following conclusions can be drawn:

(i) GGBS and fly ash are the most widely available and best-understood SCMs. GGBS is latent hydraulic and fly ash is pozzolanic, which explains the faster strength development of GGBS concrete.

(ii) Both materials improve workability, reduce the heat of hydration and extend setting time.

(iii) Early-age strength is reduced, but long-term strength is similar to or higher than that of plain concrete. An optimum GGBS content of about 55–59% has been reported for compressive strength, and high-volume fly ash concrete with 40–50% replacement can be used structurally.

(iv) Both materials refine the pore structure and greatly improve resistance to chloride penetration, sulphate attack and alkali–silica reaction; carbonation resistance may be reduced and must be managed through curing and cover.

(v) Adequate moist curing and attention to curing temperature are essential to realise the benefits of both materials.

(vi) Replacement of 30–50% (GGBS) or 20–35% (fly ash) of cement can significantly reduce the carbon footprint and cost of concrete.

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Future research should focus on performance-based mix design rather than fixed replacement limits, on long-term field data on carbonation and chloride resistance, on data-driven models for predicting strength and durability [36, 37], and on hybrid systems that combine SCMs with fibres to improve tensile behaviour and crack resistance [17, 18].

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